

INTRODUCTION TO ENGINEERING DRAWING AND DESIGN



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Introduction to Engineering Drawing and Design

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Preface

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This course and its ancillary materials were made possible through an Illinois SCOERs Subgrant awarded to Edoarda Corradi Dell'Acqua at Illinois Institute of Technology. The materials created for Introduction to Engineering Drawing and Design (CAE 100) and Introduction to AutoCAD Drawing and Design (CAE 101), a high enrollment two-course sequence for undergraduate students.

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6: Peer Review

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Course Introduction

Introduction

This resource is designed for engineering students entering their first engineering graphics classes, but it is also accessible to anyone interested in learning the fundamentals of technical drawing. It is articulated into four modules:

- **Module A** introduces the foundations of technical drawing and standards, covering line types, units of measurement and scale, drawing tools, and geometric constructions.
- **Modules B and C** focus on parallel projections, including orthographic projections, section views, auxiliary views, and cabinet and cavalier projections.
- **Module D** explores fabrication and 3D printing. An additional **Appendix A** is provided for instructors interested in integrating 3D printing into their courses.

While the modules are designed to build on one another, each can also be read independently. When relevant, earlier sections are referenced to help readers navigate the material and connect concepts.

This Open Educational Resource (OER) incorporates a variety of learning tools—lecture notes, images, interactive elements, instructional videos, and exercises—intended to support different learning styles. Interactive visualizations and augmented reality (AR) content have been created using *My AR Studio*. QR codes are included with the interactive elements to allow readers to access visualizations on external devices and to generate AR experiences. Please note that interactive objects are available only in the online version of this book and will not appear in downloaded PDFs.

By offering multiple methods of visualization, the authors aim to provide a resource that helps learners strengthen their spatial visualization skills and complements existing Open Educational Resources (OER) in engineering graphics and technical drawing.

CHAPTER OVERVIEW

1: Module A - Fundamentals

- 1.1: Graphic Representation
- 1.2: Line types
- 1.3: Drawing tools
- 1.4: Units of measurement and scale
- 1.5: Geometric elements
- 1.6: Geometric constructions and tangencies
- 1.7: Exercises

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1.1: Graphic Representation

Learning Objectives

By the end of this section, learners will be able to

- Differentiate between artistic and technical drawing by identifying their distinct purposes and applications.
- Explain the role of Technical Drawing in Engineering Design.

Graphic representation as a form of communication.

Humans have historically used drawings and graphic representations to tell stories, communicate information, ideas, emotions, and abstract concepts. Graphic representation has evolved into two primary forms: artistic drawings and technical drawings. This course focuses on technical drawings.



Figure 1.1.1: Petroglyphs at Petrified Forest National Park (Arizona). Picture from the author's private collection, August 2024.

Definition: Artistic and technical drawing

Artistic drawing is a visual form of expression that emphasizes creativity, emotional depth, and personal interpretation of the world. Guided by the artist's unique perspective, it seeks to convey ideas, evoke emotions, or provoke thought in the viewer.

Technical drawing is a form of graphic representation used to accurately and objectively describe objects, systems, or structures. It communicates all necessary details and specifications in a standardized format, enabling objects, systems, or structures to be manufactured, constructed, or analyzed.

The role of technical drawings

Engineers, architects, and professionals in many other fields rely on technical drawings to design, detail, and communicate their work.

Technical drawings serve three primary purposes:

1. Visualization
2. Communication
3. Documentation

Different types of technical drawings, such as freehand sketches, orthographic projections, and 3D models, are used at various stages of the engineering design process. The engineering design process can be divided into three main stages:

1. Problem identification and ideation

2. Refinement and analysis
3. Manufacturing and construction

During the initial phase, technical sketches help quickly communicate ideas and potential solutions generated to address the defined need. More detailed drawings are developed in the refinement and analysis stage, where solutions are compared and tested. Finally, before manufacturing or construction begins, production drawings and construction documents are created to fully specify and detail a product, machine, structure, or system.

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1.2: Line types

Learning Objectives

By the end of this section, learners will be able to

1. Identify common line types used in technical drawings.
2. Explain the purpose and application of various line types in technical drawings.
3. Interpret technical drawings accurately by understanding the meaning of each line type.

The language of technical drawing

Technical drawing is a form of communication. Like a language, it has its grammar and rules. Being familiar with these rules is essential for creating and interpreting a drawing correctly. Unlike other languages, technical drawings are universally understood—for example, a drawing created in the U.S. can be easily shared with professionals in different countries without requiring a “translation.”

The initial lectures of this course introduce foundational concepts in technical drawing and drawing standards—including line types, measurement systems, and scale—which will support learners' understanding of the subsequent modules.

Line types:

Technical drawings consist of different line types, each having a precise meaning. For example, visible lines, also called object lines, represent visible edges of an object, while hidden lines represent edges that are hidden from that view. Line types are characterized by line weight (thin or thick lines) and style, such as continuous or dashed lines. To correctly create and interpret a technical drawing, it is essential to know the meaning of the different line types composing the drawing.

This lecture introduces 10 different line types, describing their characteristics of line weight and style, and their meaning. At this stage of the course, some of this information may seem abstract. As learners progress through this course, they will become familiar with different line types. The material presented in this lecture will serve as a foundation for upcoming modules on orthographic projections, multiview drawings, and section views. It will be referenced as new line types are introduced and applied.

The correct use of line types not only ensures that drawings are clear and easy to read, but it also allows for a correct interpretation of the drawing. The following examples demonstrate the importance of using different line types in technical drawings.

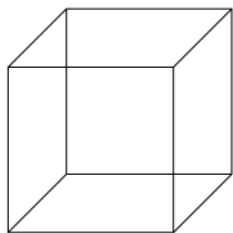


Figure 1.2.1: Sketch of a box using a single line type—a visible line (thick and continuous).

The sketch above represents a box. The drawing was created using only one line type: a thick, continuous line. This line type is called a visible or object line, and it is used to depict visible edges. However, if the box is a solid object, not all edges should be visible from this view. To interpret the drawing correctly, visible and hidden edges should be distinguished using two different line types. Although this example clearly depicts a box, it has two different interpretations, depending on which edges are considered to be hidden.

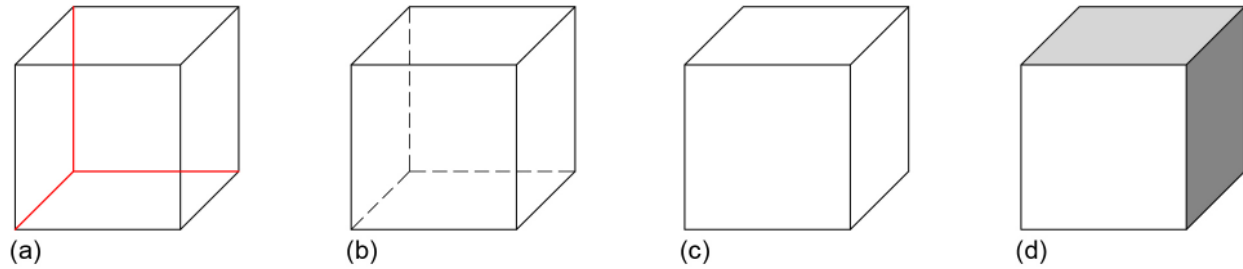


Figure 1.2.2: Interpretation 1: The front, right-side, and top surfaces of the object are visible.

In this first interpretation, the line type of the three edges highlighted in red in Figure 1.2.2(a) is changed to a hidden line in Figure 1.2.2(b)—a thin, dashed line representing edges of the object that are not visible in that view. In this interpretation, the box is rotated so that the front, right side, and top surfaces of the box are visible, as shown in Figures 1.2.2(c) and (d).

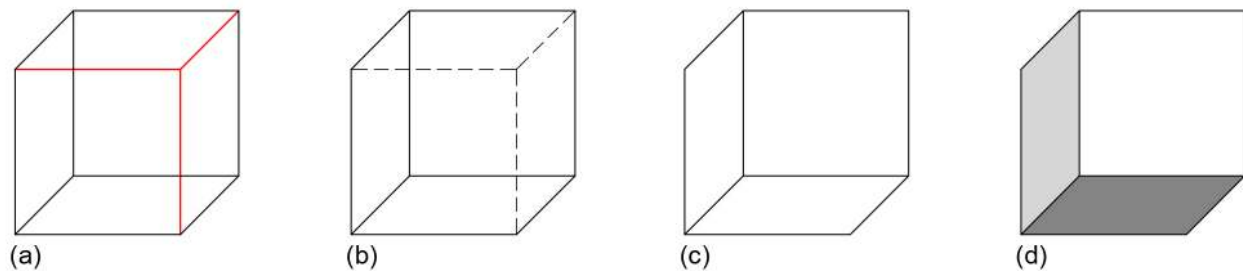


Figure 1.2.3: Interpretation 2: The front, left-side, and bottom surfaces of the object are visible.

The images above illustrate a second interpretation. As in the previous example, the line type of the three edges highlighted in red in Figure 1.2.3(a) is changed from a visible line to a hidden line in Figure 1.2.3(b). In this case, the front, left-side, and bottom surfaces are visible. It may take a moment to adjust to the new orientation.

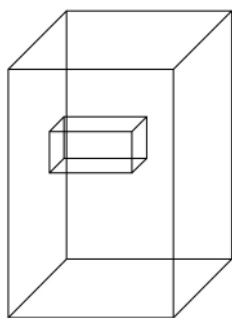


Figure 1.2.4: Sketch of two overlapping boxes using a single line type (visible line).

The image above illustrates a more complex object to highlight further the importance of distinguishing between different line types in technical drawings.

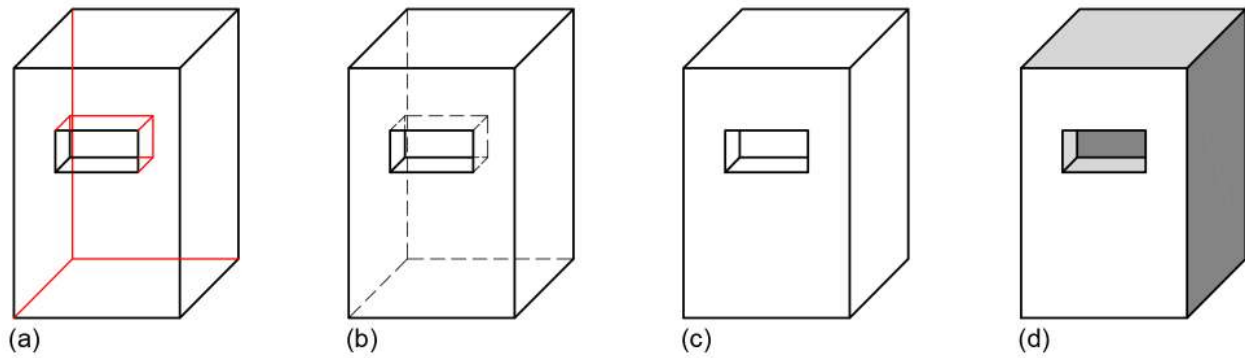


Figure 1.2.5: Interpretation 1: Large box with a smaller one carved into its front face.

By changing the line type of the edges highlighted in red in Figure 1.2.5(a) from visible to hidden lines (Figure 1.2.5(b)), the sketch now represents a large box with a smaller one carved into its front face.

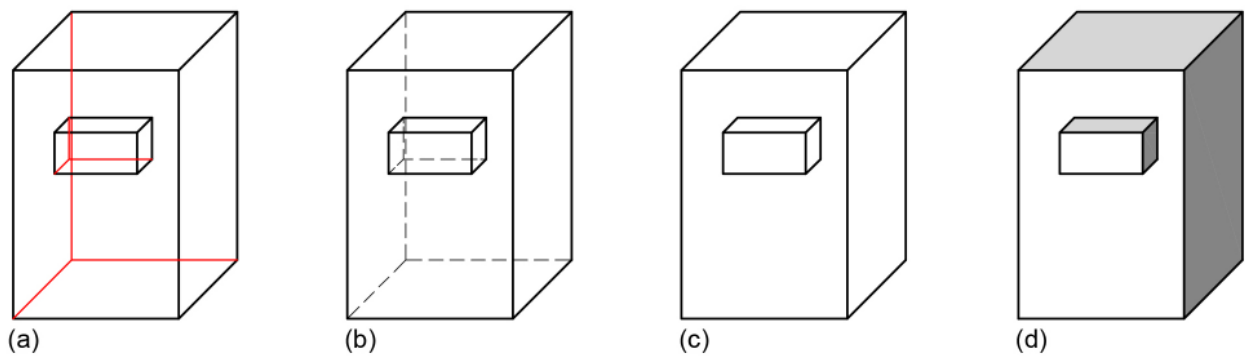


Figure 1.2.6: Interpretation 2: Large box with smaller box protruding from the front face.

Similarly, changing the red-highlighted edges in Figure 1.2.6(a) from visible to hidden lines—see Figure 1.2.6(b)—transforms the interpretation into a larger box with a smaller box protruding from the front.

Note

Please note that these sketches are cabinet projections. While hidden lines are typically omitted in cabinet projections, they are included in these examples to help visualize and understand hidden edges. Cabinet projections are covered in [Module C, section 3.4](#).

In addition to visible and hidden lines, technical drawings include many other line types, such as center lines, cutting plane lines, section lines, dimension lines, and extension lines. Some of these lines represent actual features of the object (e.g., visible and hidden lines), while others provide additional information, such as information about geometry (center lines), dimensions (dimension lines), surface differentiation (section lines), or the extent of movement of a feature (phantom lines).

List of line types

Below is a list of 10 different line types, accompanied by illustrations and brief descriptions.

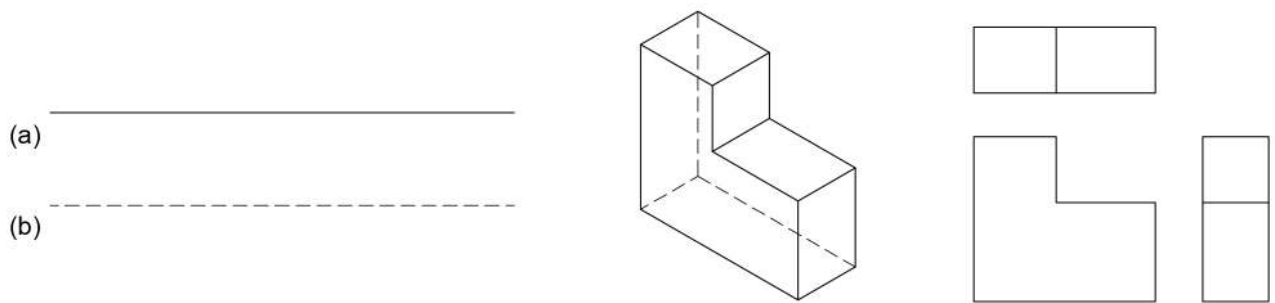


Figure 1.2.7: Visible line (a) and hidden line (b).

Visible lines (a), also called object lines, are thick (0.7mm) and continuous lines and represent the visible edges of an object. Hidden lines (b) are thin (0.3mm) and dashed lines that indicate edges that are hidden in the current view.

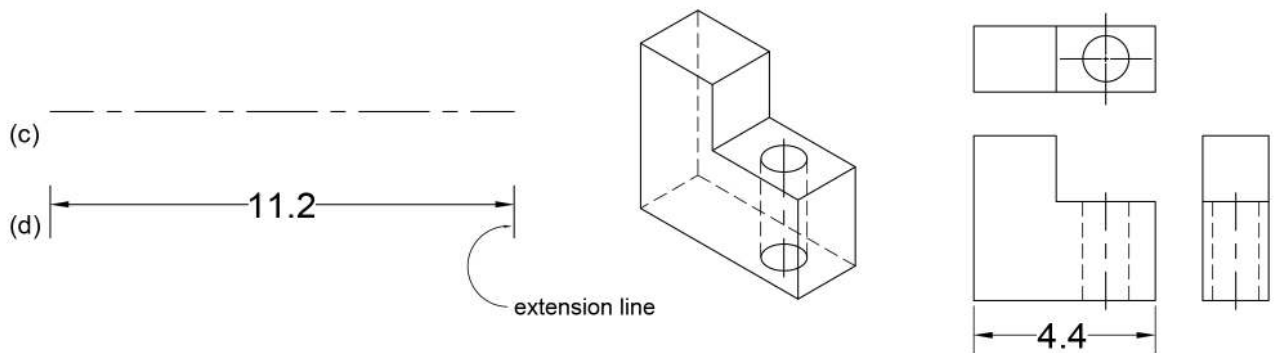


Figure 1.2.8: Center line (c), dimension and extension line (d).

Center Lines (c) are thin, dashed lines used to indicate the central axes of circular features or geometries. Unlike hidden lines, center lines consist of alternating long and short dashes and extend beyond the edges of the object. Dimension lines are thin, continuous lines with arrows or ticks at the ends that include a numerical value indicating the length (dimension) of a feature. Extension lines extend from the object's edge or a central line to the dimension line, helping to define the limits of the measured part.

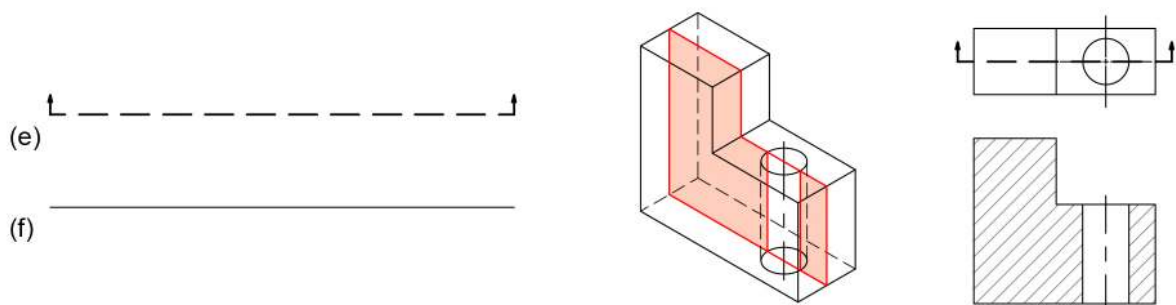


Figure 1.2.9: Cutting plane line (e) and section line (f).

Cutting plane lines (e) are used to describe where a section is cut through an object and the direction of sight. They are thick, dashed lines with arrows on the ends showing the line of sight. Section lines (f) are thin, continuous diagonal lines used to identify

the surfaces of an object that lie on the cutting plane.

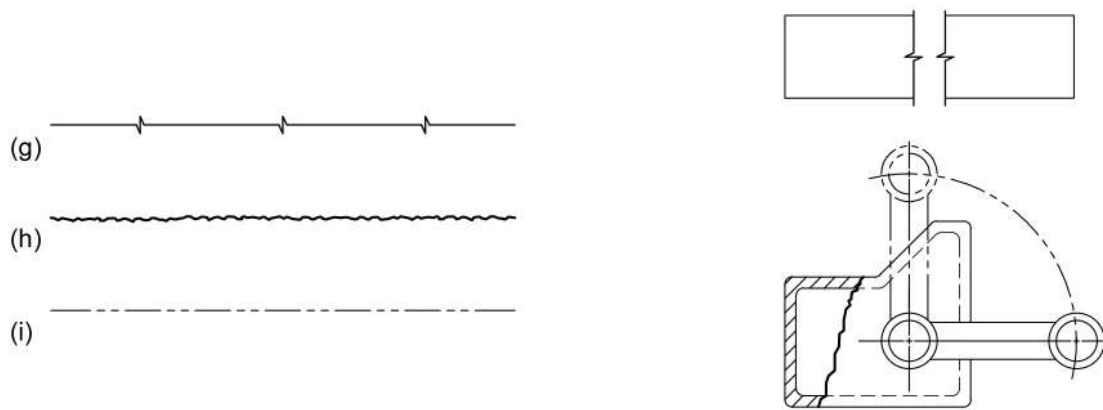


Figure 1.2.10: Long break line (g), short break line (h), and phantom line (i).

Long break lines (g) are used to shorten the representation of a continuous object or feature, similar to the use of ellipses (i.e. ...) in writing. Short break lines (h) are thick, irregular lines used in broken sections to show only a portion of an object in a sectional view. Phantom lines (i) are thin, dashed lines that indicate the range or extent of motion of a moving feature.

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1.3: Drawing tools

Learning Objectives

By the end of this section, learners will be able to

1. Describe the graphite grading scale of pencils and its relevance to line quality in technical drawing.
2. Use a T-square to draw horizontal and vertical lines.
3. Draw lines at 90, 45, 30, and 60-degree angles using drafting triangles.
4. Construct lines at various angles using a combination of two triangles or a triangle and a T-square.
5. Use a compass to create circles and arcs in technical drawings.

Hand drawing tools

Learning how to draw by hand is a valuable skill for engineering students, even though most engineering and architecture firms today primarily use computer-based drawing tools. Computer Aided Design (CAD) offers several advantages over hand drawing: it makes it easier to share, save, copy, store, and edit drawings. However, the ability to create a quick sketch on-site or during the early stages of design remains important. Furthermore, hand drawing can help support the learning process and the development of spatial visualization skills.

This section defines and explains how to choose and use tools commonly used in hand drawing, including pencils, a T-square, drafting triangles, and a compass.

The pencil

The pencil is the primary tool used in hand drawing. Pencils come with leads of varying hardness grades. Harder pencil leads deposit less material on the paper, resulting in lighter lines and are more appropriate for technical drawings, as they reduce smudging and help keep the sheet clean. In contrast, softer leads leave more material on the paper, producing darker lines. Pencils with softer leads are generally used in artistic drawings to create shades and greater contrast.

Information about the lead type is typically printed on the pencil's body. Leads with different levels of thickness and softness can be purchased for mechanical pencils.

Graphite pencil lead grades		
Hard leads	Medium leads	Soft leads
9H, 8H, 7H, 6H, 5H, 4H	3H, 2H, H, F, HB, B	2B, 3B, 4B, 5B, 6B, 7B

Table 1.3.1: Classification of pencil lead grades.



Figure 1.3.1: Pencil with HB lead grade.

The T-square

A T-square is a T-shaped drawing tool designed for creating horizontal lines. Used in combination with triangles, it enables the drawing of lines at various angles. The correct use of a T-square involves aligning the shorter side of the T, called the head, against the edge of the drafting table. By maintaining this alignment and sliding the T-square along the edge, it is possible to draw a series of parallel horizontal lines.

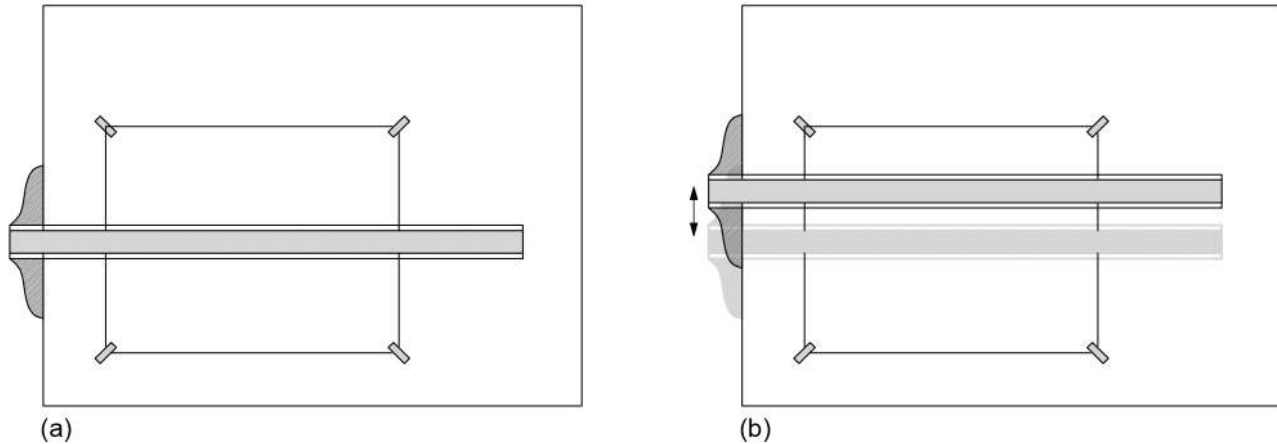


Figure 1.3.2: T-square with head aligned to the edge of the drafting table.

Drafting triangles

Drafting triangles are drawing tools used to create lines at specific angles. The two most common types are the 45-degree triangle, which has two 45-degree angles and one 90-degree (right) angle, and the 30/60 triangle, which has angles of 30, 60, and 90 degrees. Because both types include a right angle, they can be used to draw vertical lines by placing the side of the triangle with the right angle against the T-square, as shown in Figure 1.3.3.

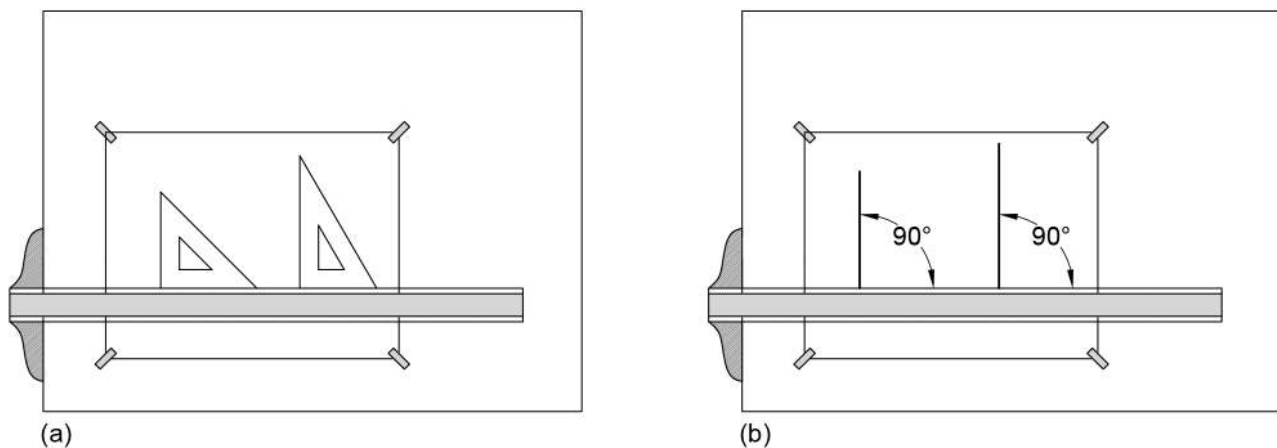


Figure 1.3.3: 90-degree sides of a 45-degree triangle and a 30/60 triangle are aligned with a T-square in (a) to draw vertical lines shown in (b).

To draw a line at a 45-degree angle, the 45-degree triangle can be used in combination with a T-square or another triangle, as illustrated in Figure 1.3.4. The T-square provides a horizontal reference, while the triangle is used to draw the inclined line. In the example, the triangle is positioned to draw a line sloping upward to the right. The opposite side can be used to draw a line sloping in the other direction.

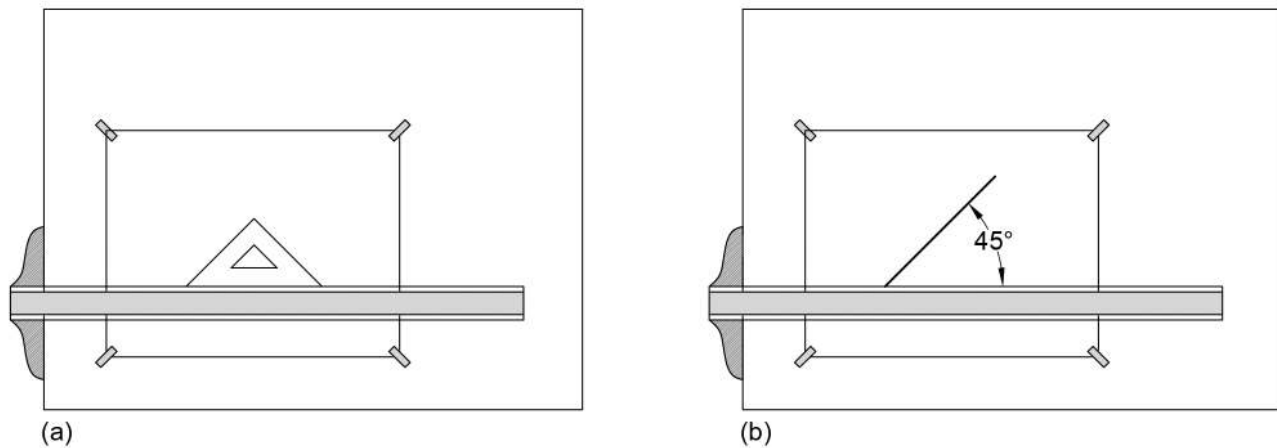


Figure 1.3.4: 45-degree triangle used in combination with a T-square (a) to draw lines at a 45-degree angle as shown in (b).

To draw a line at a 30-degree angle, the 30/60 drafting triangle can be used in combination with a T-square or another triangle, as shown in Figure 1.3.5. Similar to the previous example, the T-square provides a horizontal reference, while the triangle is used to draw the inclined line. In this example, the triangle is positioned to draw a line sloping upward to the right. The triangle can be flipped to draw a line sloping in the opposite direction.

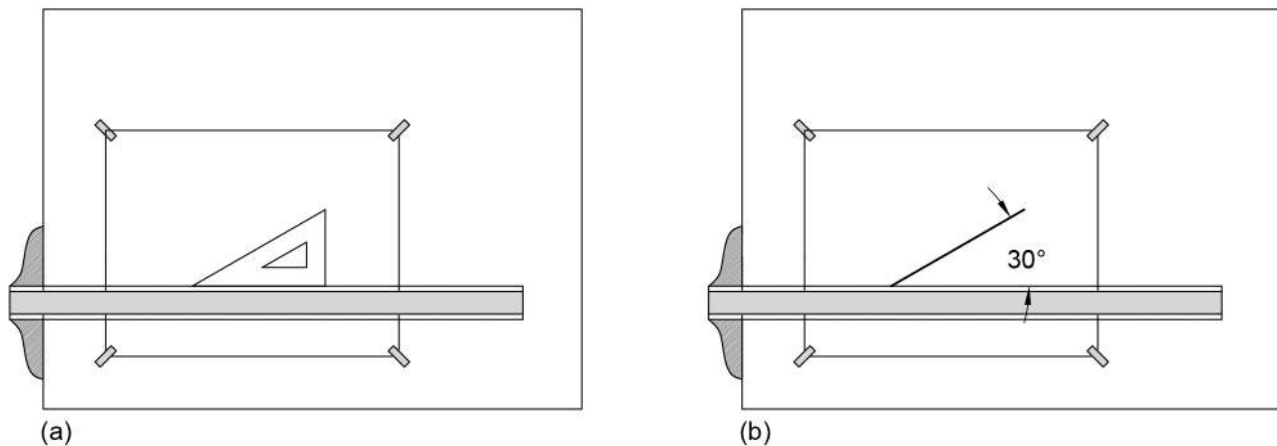


Figure 1.3.5: 30/60 degree triangle used in combination with a T-square (a) to draw a line at a 30-degree angle as shown in (b).

A similar process can be used to construct a line at a 60-degree angle, as illustrated in Figure 1.3.5. In the example below, the 30/60 triangle is positioned on the T-square with the 60-degree angle on the left and the right angle on the right. Similar to the previous examples, the triangle is positioned to draw a line sloping upward to the right. The triangle can be flipped to draw a line sloping in the opposite direction.

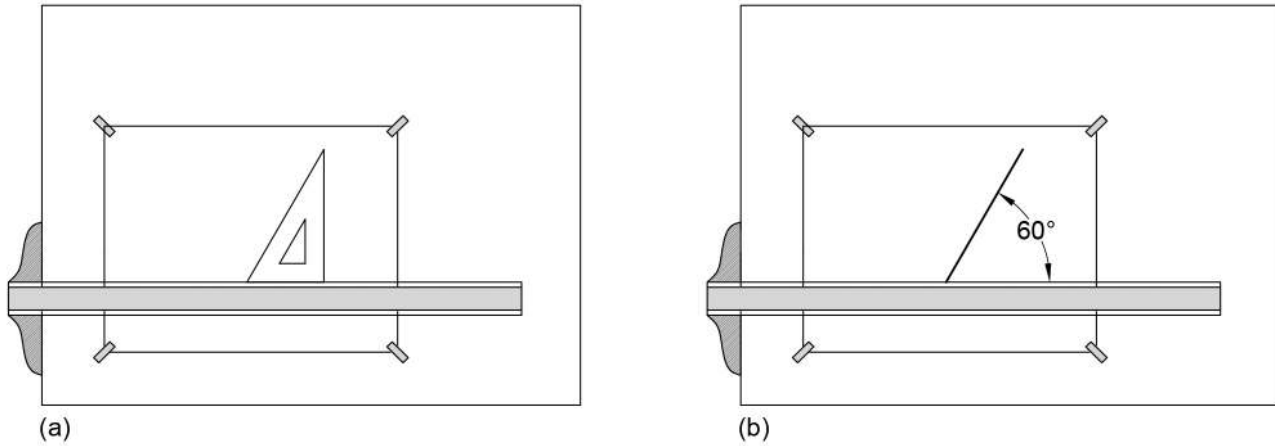


Figure 1.3.6: 30/60 degree triangle used in combination with a T-square (a) to draw a line at a 60-degree angle as shown in (b).

When used in combination, the drafting triangles enable the construction of lines at 15-degree increments, as shown in Figure 1.3.7.

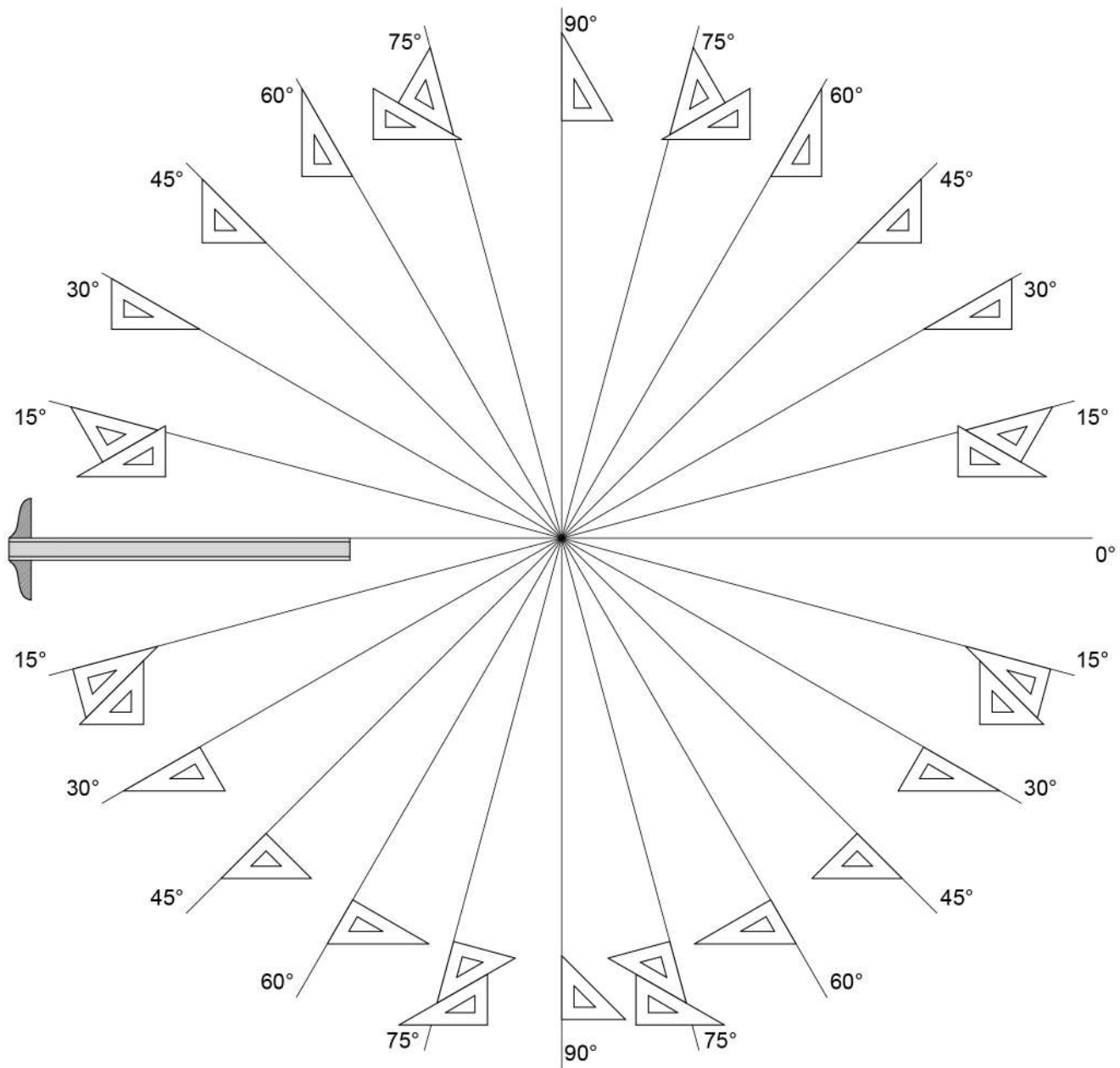


Figure 1.3.7: Drafting triangle wheel.

The compass

The compass is a drawing tool used to create circles or arcs in technical drawings. It has two legs—one with a pointed tip that anchors the center, and the other with a graphite tip that draws the circle or arc.

Scales

Depending on their size, objects must be represented at a reduced or enlarged scale in a drawing while maintaining their proportions. For example, large structures like buildings or bridges need to be drawn at a reduced scale, while very small objects, such as computer chips, have to be enlarged to show detailed features. Scales, or scaled rulers, are drawing tools used to reduce or enlarge the size of objects in technical drawings. [Section 1.4](#) describes the engineer's scale, the architect's scale, and the metric scale.

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1.4: Units of measurement and scale

Learning Objectives

By the end of this section, learners will be able to

1. Describe the two primary systems of measurement: U.S customary units and the metric system.
2. Specify the scale of a technical drawing.
3. Apply the engineer's, architect's, and metric scale rulers for drawing and measurement.
4. Create a scaled drawing of an object or a specific view.
5. Measure dimensions on a scaled drawing.

This section covers two measurement systems: U.S. customary units and the International System of Units (SI Units). Engineers need to be familiar with both systems and their conversions. Below are some conversion factors for reference.

1. The **U.S. customary system** is commonly used in the United States and includes units of length such as feet, inches, and yards.
2. Most of the world works with **SI Units**, which use units like millimeters, centimeters, meters, and kilometers.

U.S. customary units

Units: yards (yd), feet (ft), inches (in)

- 1 yd = 3 ft
- 1 ft = 12 in

The metric system (SI Units, International system of units)

Units: millimeters (mm), centimeter (cm), decimeter (dm), meter (m), kilometer (km)

- 1 mm = 0.001m (1/1000 meter)
- 1 cm = 0.01m (1/100 meter)
- 1 dm = 0.1m (1/10 meter)
- 1 m = 100 cm = 1000 mm
- 1 km = 1000 m

Conversions

- 1 m = 3.28 ft = 1 m 3 ft 3.37 in
- 1 ft = 0.305 m
- 1 in = 2.54 cm = 25.4 mm

The Mars climate orbiter

On December 11, 1998, NASA launched an **orbiter** designed to study Mars' climate. However, the mission failed when the orbiter was lost in September 1999 as it entered the planet's atmosphere. The failure was caused by a unit conversion error between the orbiter's onboard computer and ground systems, resulting in a miscalculated trajectory. Although no human lives were at risk, the incident resulted in a significant financial loss for NASA (*Mars Climate Orbiter* - NASA Science 2017).

This example highlights the importance of understanding units and their conversions. Including units in calculations and measurements is essential, as a number without a unit does not provide sufficient or meaningful information.

Drawing scale

Depending on the actual size of the represented object, it is often necessary to reduce or enlarge its size on a drawing. For example, large structures such as bridges or buildings cannot be drawn at full scale (actual size) and must be reduced to fit the sheet.

Conversely, very small objects—like a computer chip—need to be enlarged in drawings to visualize and describe their details and features. The scale of a drawing is the reduction or enlargement of the size of a drawn object relative to its actual size.

There are different ways to specify the scale of a drawing. It can be specified as a ratio, such as 1:2, 1:3, or 1:5, where the first term of the ratio refers to the number of units on the drawing, while the second term of the ratio references the actual units. For example, a scale of 1:2 means that one unit on the drawing represents two actual units. If the drawing units are inches, in this example, 1 inch on the drawing represents 2 inches in reality. Therefore, the object is drawn at half its actual size or half scale. Similarly, a ratio of 1:3 indicates that the object is drawn three times smaller, where one unit on the drawing represents three actual units.

Scales can be specified in various formats, including ratios, decimals, or fractions. For example, a half scale can be written as a ratio (1:2), a decimal (0.5), or a fraction ($\frac{1}{2}$). All of these formats represent the same scale, where the drawing is half the size of the actual object.

✓ Example 1.4.1

On the title block of a technical drawing sheet, a scale of 4:1 is specified. What does it mean?

Solution

This example illustrates an enlargement scale. As explained above, the first term of the ratio indicates the number of units on the drawing, while the second term of the ratio represents the actual units of the represented object. A 4:1 scale means that four units on the drawing represent one actual unit. If the units are inches, 4 inches on the drawing represent 1 inch in reality, meaning the object is drawn four times larger than its actual size..

Scaled Rulers

Scaled rulers are tools used to draw an object to scale or to measure the actual dimensions of objects represented in scaled drawings. This section explains how to use an engineer's scale, an architect's scale, and a metric scale.

Engineer's scale (U.S. customary units)

The engineer's scale is also known as the civil engineer's scale because it was used to draw and measure large structures. It is a decimal scale that uses one inch as its base unit. Each side of the ruler is marked by a number ranging from 10 to 60. These numbers are called divisions and indicate in how many equal parts an inch is divided into on that side. The side marked with the 10 division is also referred to as the full scale, because the distance between zero and one equals one actual inch. This inch is divided into 10 equal parts by small dashes. This side is used for scales such as $1'' = 1''$, $1'' = 10''$, and $1'' = 1'$. When using the side marked 20, the distance between zero and two equals one actual inch, divided into 20 equal parts. This side is used for scales such as $1'' = 2''$, $1'' = 20''$, and $1'' = 2'$. Similarly, the side marked 30 divides one inch into 30 equal parts and is used for scales such as $1'' = 3''$, $1'' = 30''$, and $1'' = 3'$. The same logic is applied to divisions 40, 50, and 60.

Below is a table listing the six divisions, their corresponding ratios, and examples of scales for which they are used.

Engineer's scale divisions

Division	Ratio	Scales		
10 (1 inch is divided into 10 equal parts)	1:1	$1'' = 1''$	$1'' = 1'$	$1'' = 10'$
20 (1 inch is divided into 20 equal parts)	1:2	$1'' = 2''$	$1'' = 2'$	$1'' = 20'$
30 (1 inch is divided into 30 equal parts)	1:3	$1'' = 3''$	$1'' = 3'$	$1'' = 30'$
40 (1 inch is divided into 40 equal parts)	1:4	$1'' = 4''$	$1'' = 4'$	$1'' = 40'$
50 (1 inch is divided into 50 equal parts)	1:5	$1'' = 5''$	$1'' = 5'$	$1'' = 50'$
60 (1 inch is divided into 60 equal parts)	1:6	$1'' = 6''$	$1'' = 6'$	$1'' = 60'$

Table 1.4.1 Engineer's scale divisions and corresponding ratios

✓ Example 1.4.2

The line between points A and B is drawn at a $1''=50'$ scale (see image below). Using the engineer's scale, can you determine the actual distance?

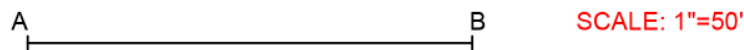


Figure 1.4.1: Distance A-B at a $1'' = 50'$ scale.

Solution

1. Determine which side of the ruler to use for measuring the distance. In this example, the correct side of the ruler is the side marked by the division 50. On this side of the ruler, one actual inch is divided into 50 equal parts. Therefore, the distance between zero and five on the ruler represents one inch—the small dashes between zero and five divide that inch into 50 equal segments.

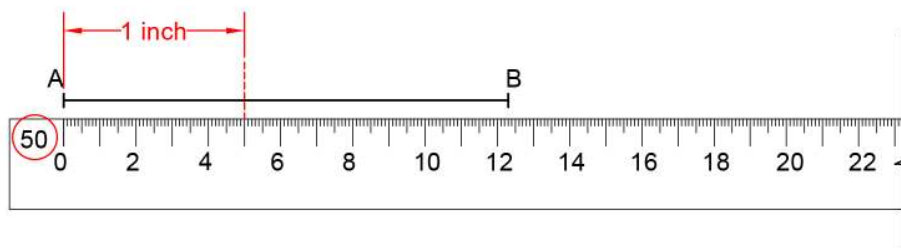


Figure 1.4.2: One actual inch on the engineer's scale, shown on the side marked with the division 50.

2. Once the correct side of the ruler is identified, you can read measurements. Since the scale is $1'' = 50'$, the distance from zero to five in the drawing represents 50 feet in reality. Continuing along the scale, the distance from zero to 12 represents 120 feet.

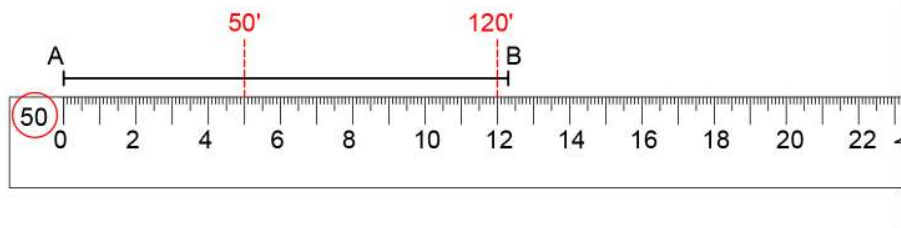


Figure 1.4.3: Distances of 50' and 120' at the $1'' = 50'$ scale, shown on the side of the engineer's scale marked with the division 50.

3. Since the measured line extends beyond 12, it is necessary to count the divisions (dashes) after the number 12 to determine the whole dimension. In this example, there are three dashes after 12, so the total length is 123 feet at a scale of $1'' = 50'$.

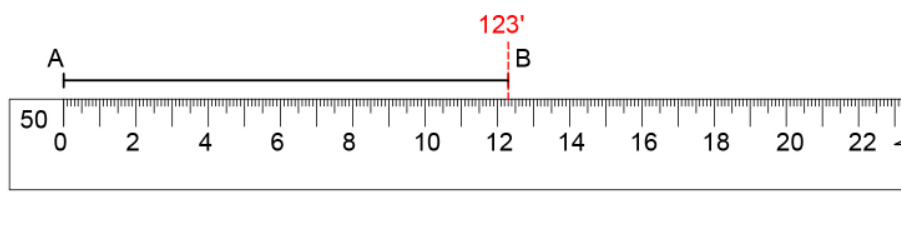


Figure 1.4.4: Distance of 123' at the $1'' = 50'$ scale, shown on the side of the engineer's scale marked with the division 50.

Note: If the drawing scale were $1'' = 5'$, the measured length would need to be divided by 10. In that case, the total length of line A-B would be 12.3 feet.

Please note the importance of including units in your solution. For example, if the drawing scale were $1'' = 5'$, the length would be 12.3 inches, which is very different from 12.3 feet.

Try solving this exercise again using the scales $1'' = 500'$, $1'' = 500''$, and $1' = 5'$.

Architect's scale (U.S. customary units)

The sides of an architect's scale are marked with numbers or fractions that indicate different drawing scales. A typical 6-sided triangular scale includes two scales on five of its edges, allowing it to be read from either direction—left to right or right to left. One edge is marked with a single number, 16, which represents full scale ($1'' = 1''$). The number 16 refers to the division of one inch into sixteenths.

On the other five edges, the numbers or fractions represent the number of inches on the drawing that correspond to one foot in actual size. For example, the edge marked $1/2$ means that $1/2$ inch on the drawing equals 1 foot in reality, or $1/2'' = 1'$. On each of these five edges, the distance representing one foot is subdivided into smaller increments just to the left of the zero mark. Common scale combinations on the ruler include: $1/2$ and 1, $1/8$ and $1/4$, $1\frac{1}{2}$ and 3, $3/8$ and $3/4$, and $3/32$ and $3/16$.

✓ Example 1.4.3

The line between points A and B is drawn at a $1/8'' = 1'$ scale (see image below). Using the architect's scale, can you determine the actual distance?



Figure 1.4.5: Distance A-B at a scale of $1/8'' = 1'$.

Solution

1. Determine which side of the ruler to use for measuring the distance. In this example, the correct side of the ruler is the side marked by the fraction $1/8$ and the measurement can be read from left to right.

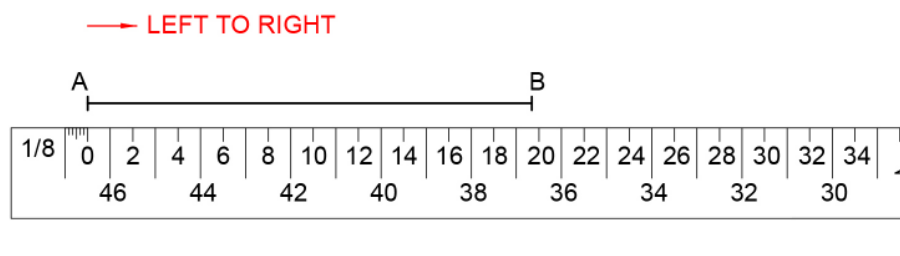


Figure 1.4.6: Distance A-B aligned with the architect's scale on the side marked $1/8$.

2. Align point A with zero on the architect's scale and read the closest dimension at point B. In this example, the measurement is 19 feet.

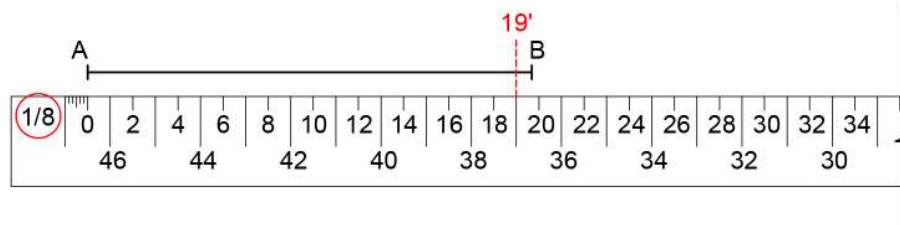


Figure 1.4.7: Distance of 19 feet aligned at a scale of $\frac{1}{8}'' = 1'$ shown on line A-B.

3. Slide the ruler to align point B with 19 on the architect's scale, then read the number of inches by counting the dashes to the left of zero. In this example, the total measurement is 19'-8".

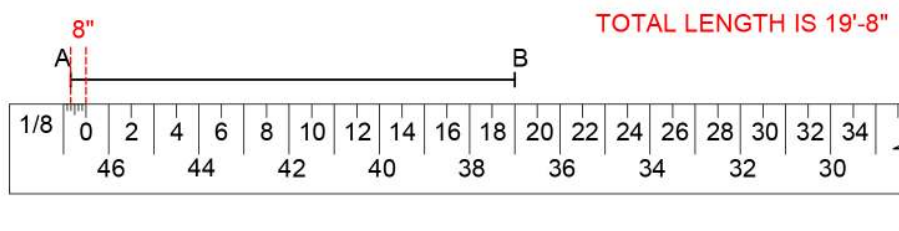


Figure 1.4.8: Divisions to the left of the zero mark.

Note: When reading this side of the ruler from the other direction (right to left), it is possible to measure a distance at a $\frac{1}{4}'' = 1'$ scale.

Metric scale (SI units)

The metric scale uses the meter as its main unit of measurement. On a 6-sided triangular scale, each edge is marked with a ratio (e.g., 1:100), and the distance between 0 and 1 on each side of the ruler represents 1 meter at the indicated scale. For example, the edge marked 1:100 means that 1 millimeter on the drawing represents 100 millimeters in real life. Therefore, 10 millimeters on the drawing equal 1,000 millimeters (or 1 meter) in reality. This edge is also referred to as the full scale because the distance between 0 and 1 on the scale represents 1 actual centimeter as well as 1 meter at the scale 1:100. In fact, 1 centimeter equals to 1 meter at a 1:100 scale, given that 1 centimeter is 1 hundredth of a meter.

There are different metric scales. Common scales include 1:100, 1:50, 1:40, 1:20, 1:33 1/3, 1:80, 1:200, 1:250, 1:300, 1:500, 1:400.

If the scale on the drawing differs from the scale on the ruler by a power of 10, the value of 1 on the ruler should be multiplied or divided by 10, 100, 1000, etc., depending on the drawing scale. For example, if the drawing is at a 1:1000 scale, it is possible to use the 1:100 side of the ruler and multiply all measurements by 10. Conversely, if the drawing is at a 1:10 scale, the 1:100 side of the ruler can still be used, but each measurement should be divided by 10.

✓ Example 1.4.4

The line between points A and B is drawn at a 1:50 scale (see image below). Using the metric scale, can you determine the actual distance?



Figure 1.4.9: Distance A-B at a 1:50 scale.

Solution

1. Determine which side of the ruler to use for measuring the distance. In this example, the correct side is marked with the ratio 1:50. This side of the metric scale can be used for measurements at scales such as 1:5, 1:50, or 1:500.

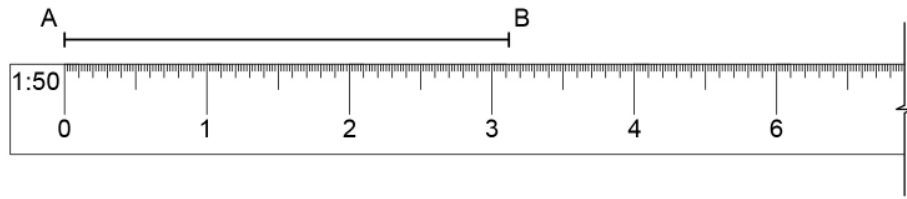


Figure 1.4.10: Distance A-B at a 1:50 scale.

On the metric scale, the distance between 0 and 1 on each side of the ruler represents one meter at the scale indicated. In this example, the drawing scale matches the scale marked on the ruler. Therefore, the distance between zero and one on the drawing represents one actual meter

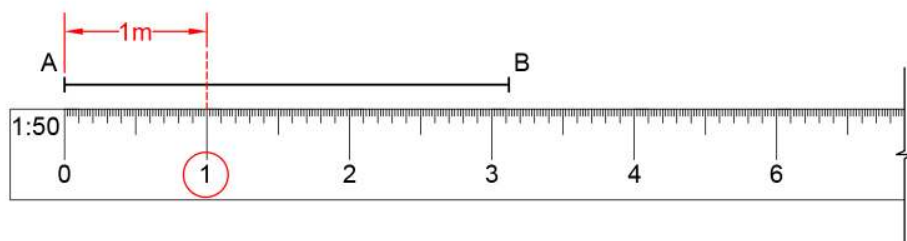


Figure 1.4.11: One meter at a scale of 1:50.

2. Determine the total distance. The small increments between the numbers represent centimeters and help measure the length accurately. In this example, the length of line A-B at a 1:50 scale is 3.12 meters, or 3 meters and 12 centimeters.

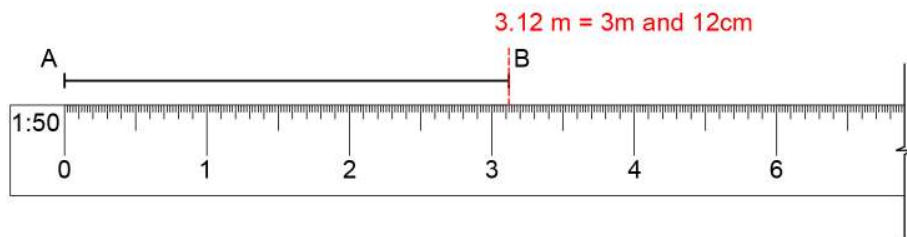


Figure 1.4.12: Total length of line A-B at a 1:50 scale.

Note: If the drawing scale were 1:500, the measurements would need to be multiplied by 10. In that case, the distance between 0 and 1 on the ruler represents 10 meters, making the total length of line A-B equal to 31.2 meters, or 31 meters and 20 centimeters.

Try solving this exercise again using the scales 1:5 and 1:5,000.

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1.5: Geometric elements

Learning Objectives

By the end of this section, learners will be able to

1. Define and describe basic geometric elements.
2. Identify basic geometric elements, such as points, lines, angles, circles, and polygons.

This section introduces fundamental geometric elements and definitions of terms that engineers should be familiar with.

Points

A point has no width, height, or depth. It can be depicted as the intersection of two lines (a), a small dash crossing a line (b), or a cross (c).

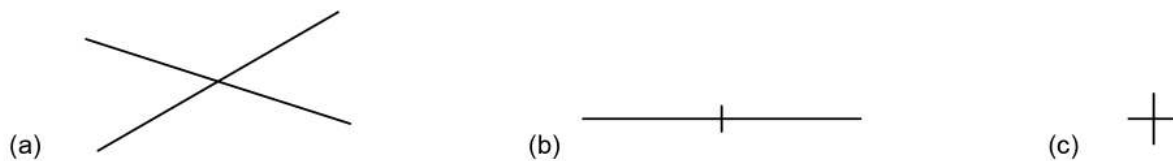


Figure 1.5.1: Three ways to describe a point graphically.

Lines

Euclid defines a line as "that which has length without breadth." Figure 1.5.2 shows different types of straight lines. A straight line is the shortest distance between two points. Figure 1.5.2(a) shows a line of indefinite length, while Figure 1.5.2(b) illustrates a line with a definite length, identified by its endpoints. Other important terms include perpendicular lines, which form a right angle (90 degrees), as shown in Figure 1.5.2(c). Lines can also be parallel (Figure 1.5.2(d)), horizontal (Figure 1.5.2(f)), or vertical (Figure 1.5.2(g)).

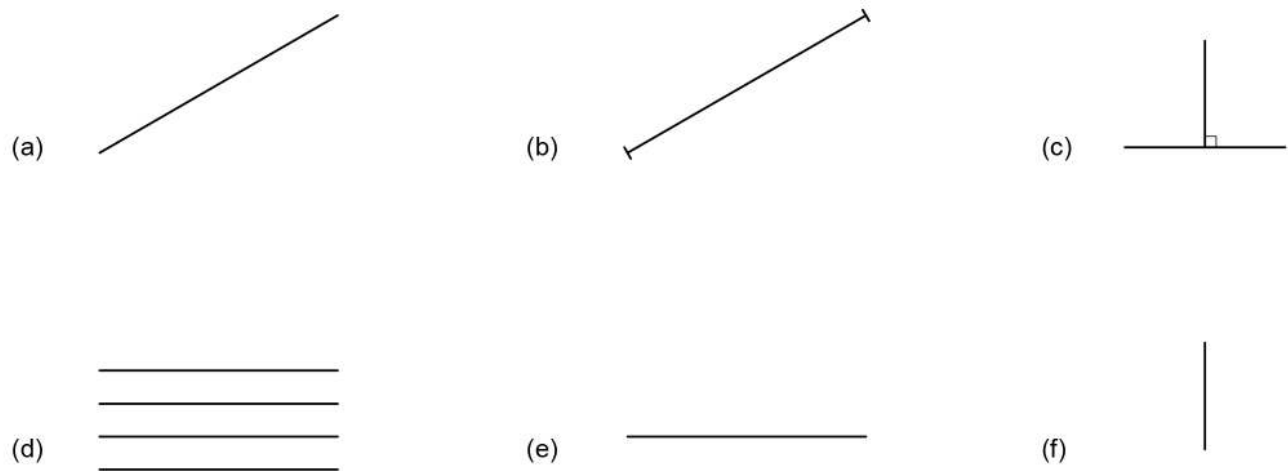


Figure 1.5.2: Six types of lines: (a) line of indefinite length, (b) line with a definite length, (c) perpendicular line, (d) parallel lines, (e) horizontal line, and (f) vertical line.

Angles

An angle is formed at the intersection of two lines. There are 360 degrees in a full circle and 180 degrees in a half-circle. A 90-degree angle is called a right angle, and two lines that meet at a right angle are known as perpendicular or orthogonal lines. Angles

smaller than 90 degrees are called acute angles, while angles greater than 90 degrees are called obtuse angles. Finally, complementary angles are two angles whose measures add up to 90 degrees.

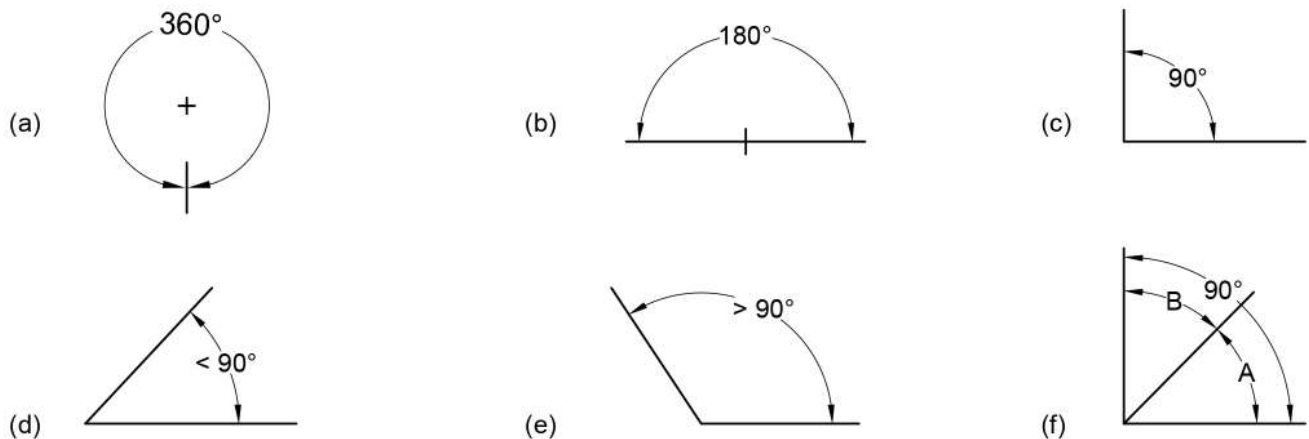


Figure 1.5.3: Six types of angles: (a) 360-degree angle, (b) 180-degree angle, (c) 90-degree angle, (d) acute angle, (e) obtuse angle, (f) complementary angles.

Quadrilaterals

Quadrilaterals are geometric elements with four sides. Figure 1.5.4 illustrates different types of quadrilaterals.

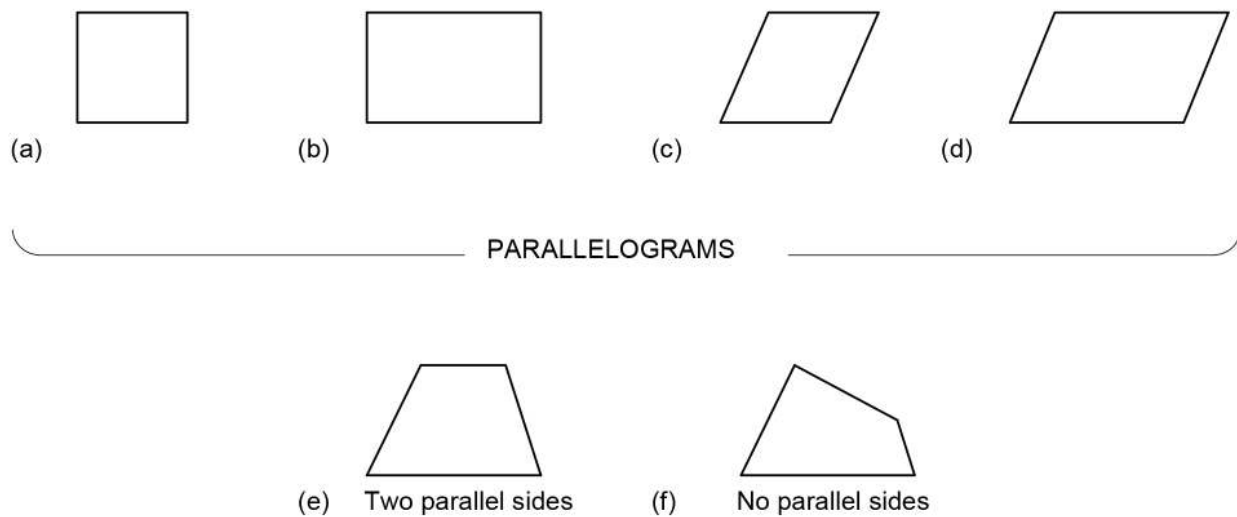


Figure 1.5.4: Quadrilaterals: (a) square, (b) rectangle, (c) rhombus, (d) rhomboid, (e) trapezoid, (f) trapezium.

Regular polygons

Figure 1.5.5 illustrates different types of regular polygons. Polygons are geometric shapes bounded by straight lines. When all sides and angles of a polygon are equal, and the shape can be inscribed in or circumscribed around a circle, it is called a regular polygon. A triangle has three sides, a square has four, a pentagon has five, a hexagon has six, a heptagon has seven, and an octagon has eight. Additional polygons include the nonagon (nine sides), the decagon (ten sides), and the dodecagon (twelve sides).

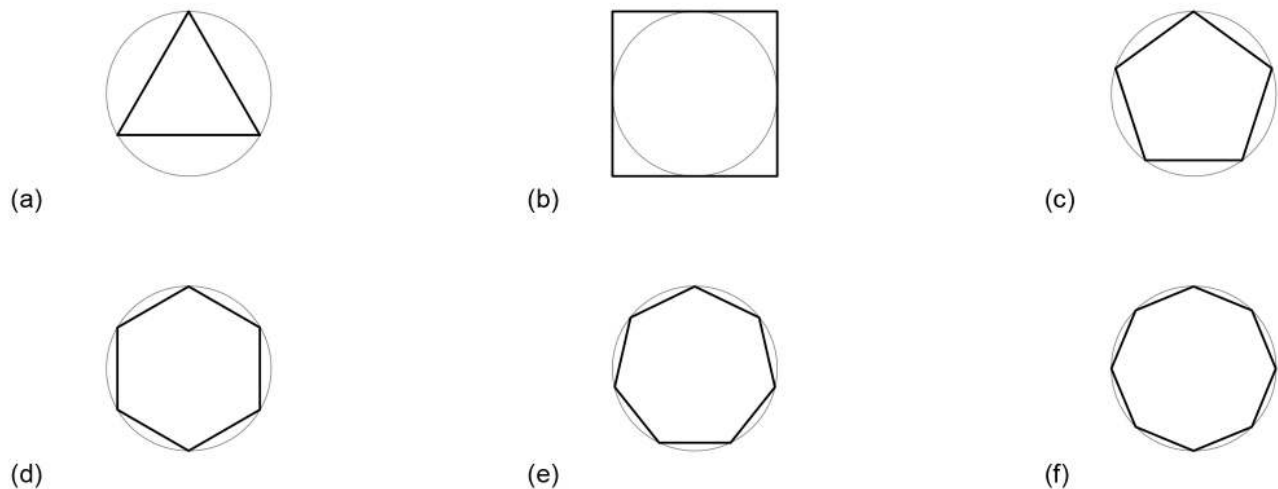


Figure 1.5.5: Regular polygons: (a) triangle, (b) square, (c) pentagon, (d) hexagon, (e) heptagon, (f) octagon.

The circle

A circle is a closed curved line in which all points are the same distance from a central point, indicated with a cross in Figure 1.5.6(a). The circumference is the length of the circle's perimeter and can be calculated by multiplying the diameter by π (≈ 3.1416). Figure 1.5.6(c) introduces the concept of a tangent line—a line that touches the circumference at only one point. A line that passes through a circle, intersecting it in two points, is called a secant. Figure 1.5.6(d) illustrates two concentric circles—circles with different diameters that share the same center point. In contrast, Figure 1.5.6(e) shows two eccentric circles with different centers.

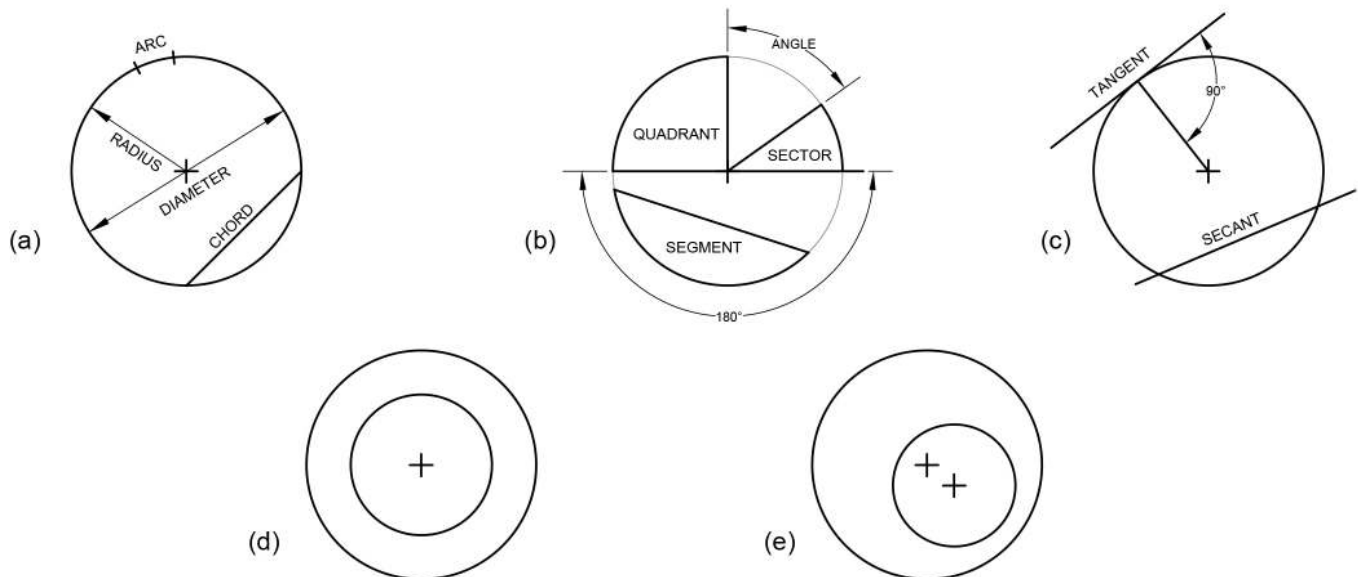


Figure 1.5.6: The circle.

The following section focuses on geometric constructions and tangencies. It draws on concepts introduced in this section, including the definition and specification of points, parallel and perpendicular lines, tangent lines, and concentric circles.

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1.6: Geometric constructions and tangencies

Learning Objectives

By the end of this section, learners will be able to

1. Construct a line bisecting another line, an arc, or an angle using the drawing tools.
2. Define a line tangent to an arc or circle.
3. Construct a line tangent to a circle at a point P.
4. Use the drawing tools to draw an arc or circle tangent to two lines forming an acute, obtuse, or right angle.
5. Draw an arc or circle tangent to two existing circles.

This section focuses on geometric constructions and references definitions introduced in [section 1.5](#). It includes a variety of exercises that can be completed using a compass, a straightedge or triangles, and a pencil.

Bisect a line or arc

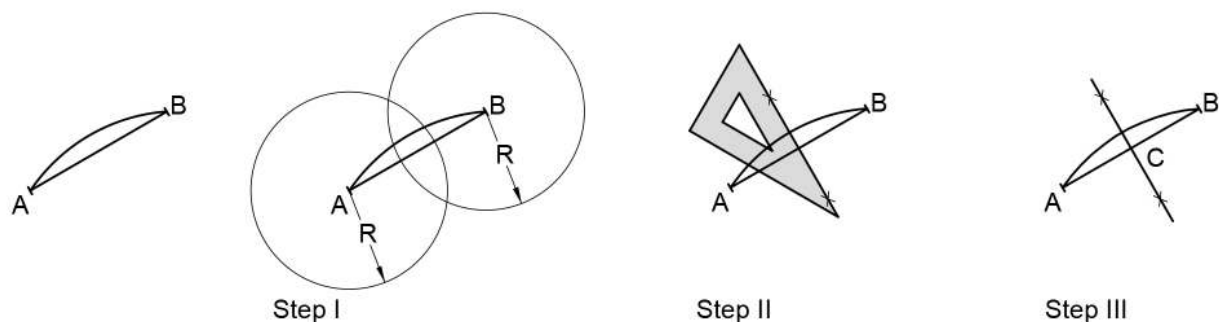


Figure 1.6.1: Line bisecting a given line (A-B) or arc.

Draw a line bisecting a given line (A-B) or arc:

1. Using a compass, draw two circles (or arcs) with centers at points A and B and a radius greater than half the length of segment A-B.
2. Identify the two points where the arcs intersect—one above and one below the given line or arc.
3. Use a triangle or straightedge to draw a line connecting the two intersection points. This line is the bisector and will intersect line A-B at its midpoint, point C.

Bisect an angle

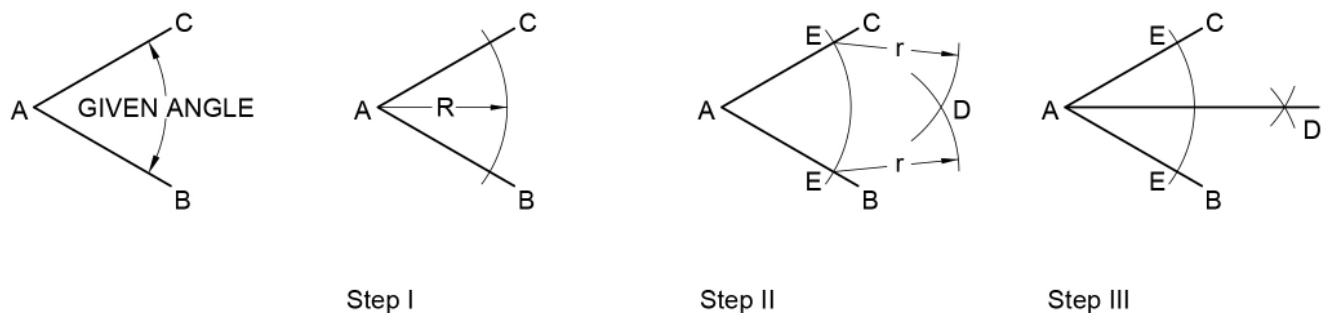


Figure 1.6.2: Line bisecting an angle.

Draw a line bisecting a given angle (A):

1. Using a compass, draw an arc with a random radius R and identify two points (E) on lines A-B and A-C.
2. Draw two circles or arcs with centers at points E and a radius (r) greater than half the distance between the two points E.

3. Use a triangle or straightedge to draw a line connecting the intersection point of the arcs. This line is the bisector of angle A.

Draw a line tangent to a circle or arc at point P

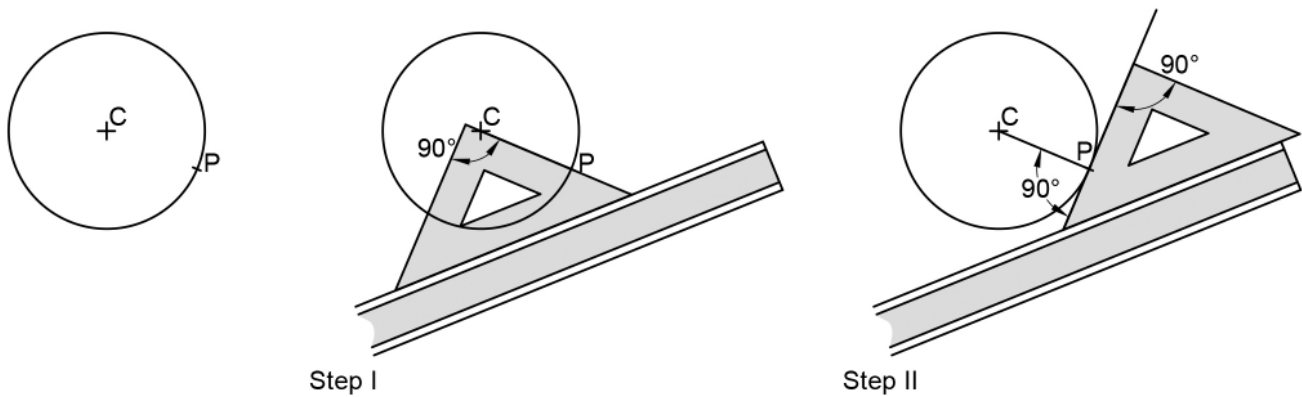


Figure 1.6.3: Line tangent to a circle at point P.

Draw a line tangent to a circle at point P:

A line tangent to a circle is perpendicular to the line connecting the point of tangency and the circle's center point. therefore, to resolve the exercise,

1. Draw a line connecting the center point C and the point of tangency P. Align a triangle with the right angle along the line C-P.
2. slide the triangle and use the perpendicular edge to draw a perpendicular line through the point of tangency P.

Draw a circle or arc tangent to two lines

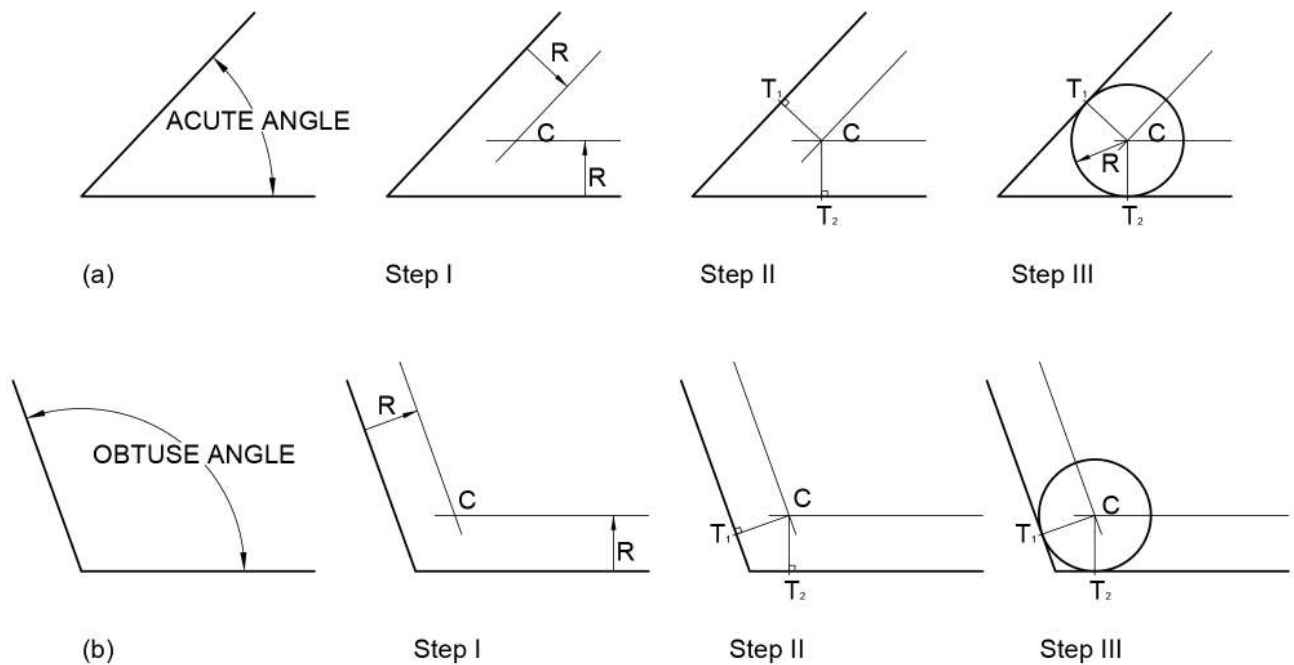


Figure 1.6.4: Arc tangent to two lines.

Draw a circle or arc with a given radius R that is tangent to two lines meeting at an acute (a) or obtuse (b) angle:

1. The first step involves finding the center point C. Since the radius is given, C is a point that is located at a distance equal to R from both lines. To find C, draw two lines parallel to the given lines and at a distance equal to the radius R. The intersection point of these two parallel lines is the center point C.
2. Draw two lines through C and perpendicular to the given lines 1 and 2 to find the points of tangency T_1 and T_2 . (See previous exercise on how to draw a line tangent to a circle at a given point P)
3. Using a compass set to radius R, draw the circle or arc at C touching the two given lines at the points of tangency T_1 and T_2 .

Draw an arc tangent to two lines forming a right angle

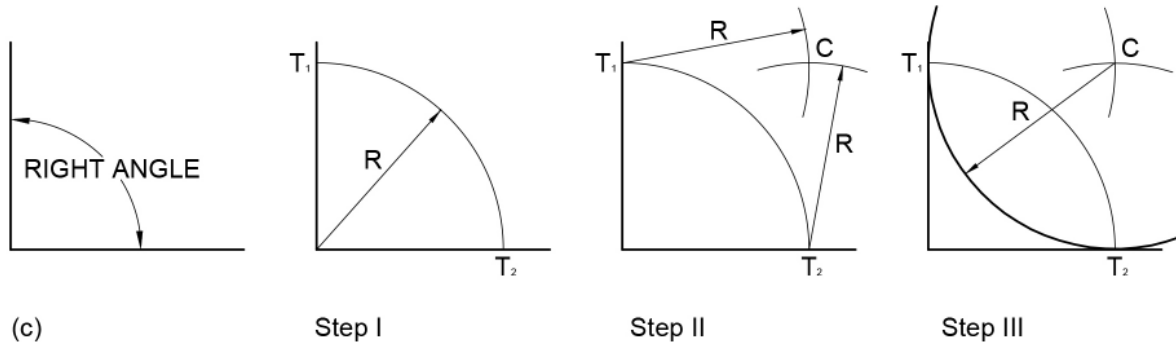


Figure 1.6.5: Arc tangent to two line at a right angle.

Draw an arc with a given radius R tangent to two lines that meet at a right angle:

1. A Similar approach to the previous exercise can be used to resolve this exercise. However, there is also a more straightforward method that involves using the compass only. Draw an arc with the center point at the intersection of the two lines and with a radius R to find T_1 and T_2 .
2. Next, draw two arcs with centers at T_1 and T_2 , using the same radius R. The intersection of these arcs is the center point C of the desired arc.
3. Finally, using a compass set to radius R, draw an arc centered at point C. This arc will be tangent to both lines at points T_1 and T_2 .

Draw an arc tangent to a circle and a line

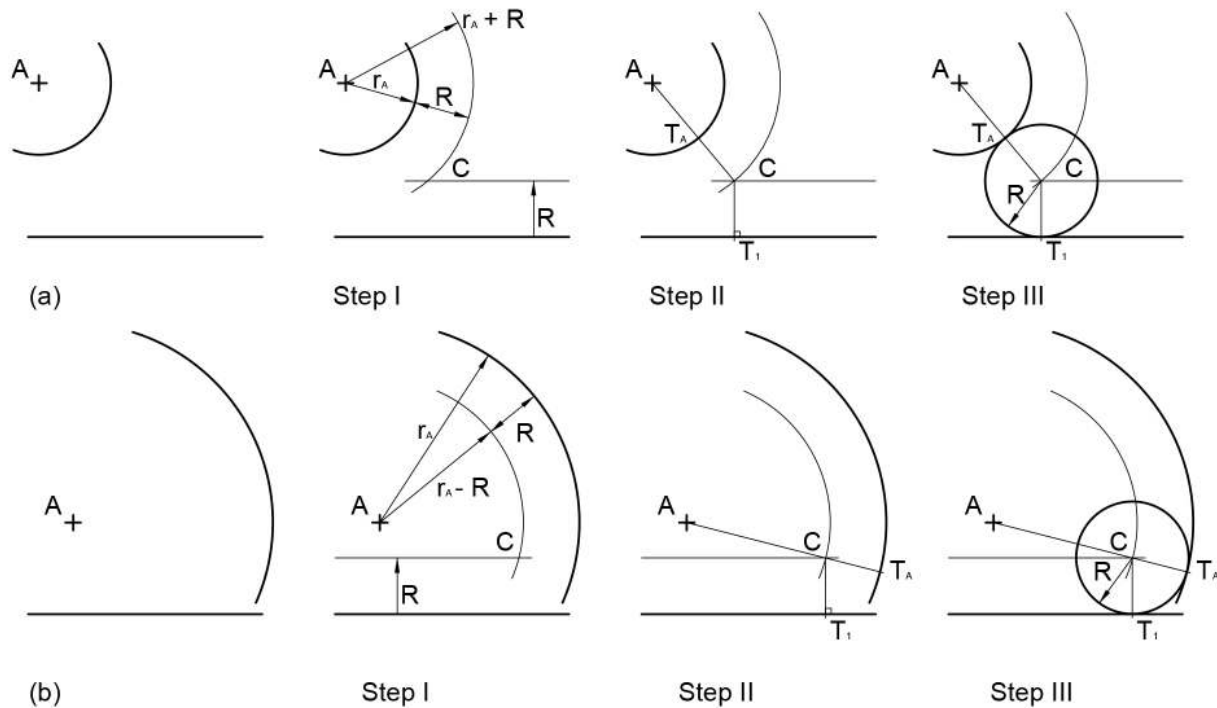


Figure 1.6.6: Arc tangent to a line and a circle.

Draw an arc with a given radius R tangent to a line and a circle or arc:

1. The first step involves finding the center point C . First, draw a line parallel to the given line, offset by a distance R . Then, using a compass, draw a concentric circle with center point A and a radius equal to either $r_A + R$ (a) or $r_A - R$ (b), depending on whether the desired arc lies outside or inside the circle. The intersection of the concentric circle and the parallel line is the center point C .
2. Draw a line connecting C to the center of circle A to find the point of tangency on the circle, T_A . Then draw a line perpendicular to the given line and through C to find the point of tangency on the line, T_1 .
3. Using a compass set to radius R , draw the arc centered at point C . This arc will be tangent to both the given line and the circle at points T_1 and T_A .

Draw an arc tangent to two circles

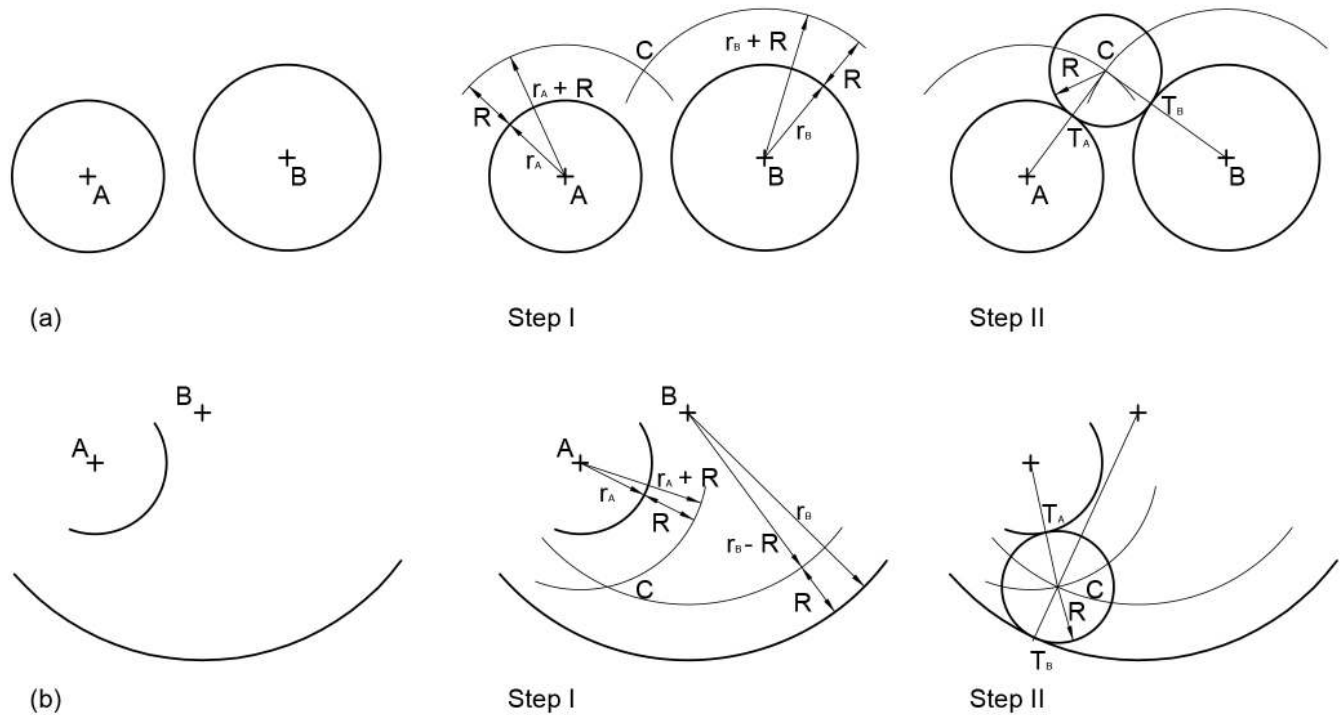


Figure 1.6.7: Arc tangent to two circles.

Draw a circle or arc with a given radius R tangent to two circles or arcs:

1. Begin by finding the center point C of the desired arc or circle. Draw two concentric circles: one centered on circle A with radius $r_A + R$, and one centered on circle B with radius $r_B + R$ if the desired arc lies outside both circles (case a). If the arc lies between the two circles (case b), use radius $r_B - R$ for the second concentric circle. The point where these two concentric circles intersect is the center point C .
2. Draw lines connecting point C to the centers of circles A and B . The points of tangency (T_A and T_B) are located where these lines intersect the original circles or arcs.
3. Using a compass set to radius R , draw the arc or circle centered at point C . This arc will be tangent to both circles at points T_A and T_B .

Draw an arc with a given radius R tangent to two circles, (a) enclosing both circles, and (b) enclosing only circle B (b)

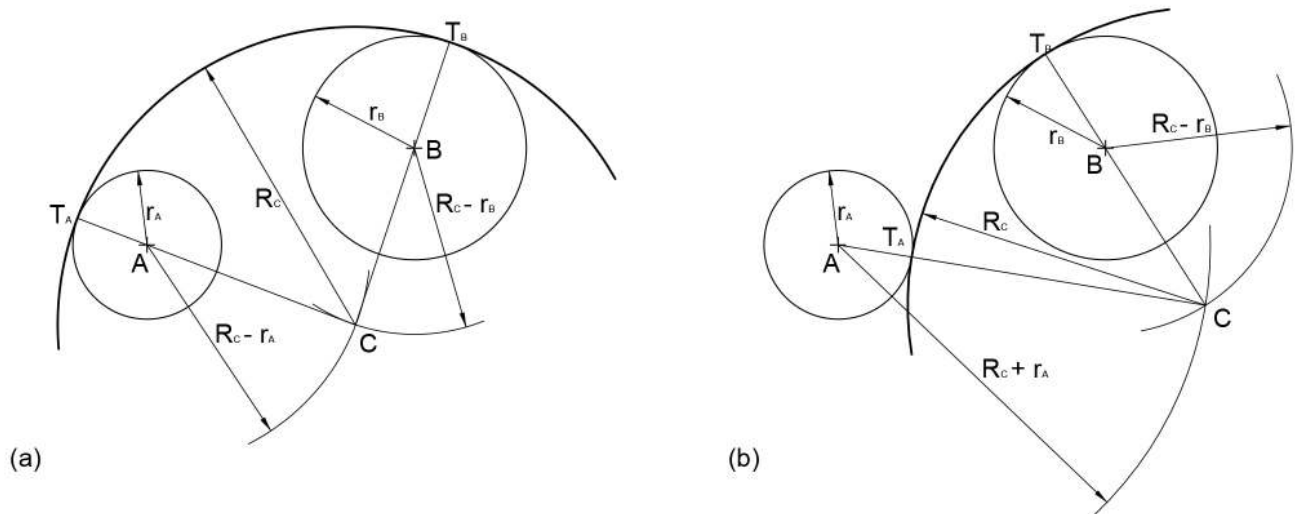


Figure 1.6.8: Arc tangent to two circles, (a) enclosing both circles, and (b) enclosing only circle B.

(a) Draw an arc with a given radius R_c tangent to two circles and containing both.

1. Draw two concentric circles centered at A and B with radii equal to $R_c - r_A$ and $R_c - r_B$, respectively. The center point C of the desired arc is located at the intersection of these two concentric circles.
2. Draw lines connecting point C to the centers of circles A and B. Extend each line to the circumference of the original circles to identify the points of tangency, T_A and T_B .
3. Using a compass set to radius R_c , draw the arc centered at point C. This arc will be tangent to both circles at points T_A and T_B and will contain both circles.

(b) Draw an arc with a given radius R_c tangent to two circles and containing only circle B.

1. Draw two concentric circles centered at A and B with radii equal to $R_c + r_A$ and $R_c - r_B$, respectively. The center point C of the desired arc is at the intersection of these two concentric circles.
2. Draw lines connecting point C to the centers of circles A and B to identify the points of tangency, T_A and T_B .
3. Using a compass set to radius R_c , draw the arc centered at point C. This arc will be tangent to both circles at points T_A and T_B and will contain only circle B.

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1.7: Exercises

This section presents exercises that apply the knowledge covered in Module A. Exercise 1 focuses on line types; exercise 2 addresses the engineer's and the metric scales; exercise 3 focuses on the architect's scale, and exercises 4 and 5 explore geometric constructions and tangencies.

Exercise 1: Line Types

Follow the instructions in the left and right columns:

- Left column: Using your drawing tools, draw the line type indicated, using the correct line thickness (thin or thick line) and style (solid or dashed line).
- Right column: in 2-3 sentences, explain the purpose and meaning of each line type.

USING YOUR DRAWING TOOLS, DRAW EACH OF THE FOLLOWING LINE TYPES LISTED BELOW. PAY CLOSE ATTENTION TO: (1) LINE THICKNESS (E.G. THICK OR THIN LINE AS APPROPRIATE) (2) LINE STYLE (SOLID, DASHED, ETC.)	BRIEFLY EXPLAIN (1-3 SENTENCES) THE PURPOSE OF EACH LINE TYPE AND HOW IT IS USED IN TECHNICAL OR ENGINEERING DRAWING.
Visible Line  	Visible Line:
Hidden Line  	Hidden Line:
Center Line  	Center Line:
Section Line  	Section Line:
Cutting-plane Line  	Cutting-plane Line:
Shirt-break Line  	Shirt-break Line
Long-break Line  	Long-break Line:
Dimension Line (including extension lines)  	Dimension Line (including extension lines):
NAME:	

Figure 1.7.1: Exercise 1: Line types

Exercise 2: Engineer's and metric scale

Follow the instructions in the exercise and measure distances imagining the drawing is created at different scales.

DRAW A STRAIGHT LINE AND MEASURE THE DISTANCE BETWEEN EACH POINT FROM THE BOTTOM RIGHT CORNER OF EACH SQUARE MARKING THE LOCATION OF EACH OBJECT.
(DRAW THROUGH THE TREES)

METRIC SCALE

FIND THE DISTANCE BETWEEN PERSON 1 AND FLAG G USING THE SCALE 1:20 _____

FIND THE DISTANCE BETWEEN PERSON 4 AND FLAG D USING THE SCALE 1:100 _____

FIND THE DISTANCE BETWEEN PERSON 3 AND FLAG C USING THE SCALE 1:25 _____

ENGINEERING SCALE

FIND THE DISTANCE BETWEEN PERSON 2 AND FLAG E USING THE SCALE 1"=50" _____

FIND THE DISTANCE BETWEEN PERSON 3 AND FLAG A USING THE SCALE 1"=4' _____

FIND THE DISTANCE BETWEEN PERSON 1 AND FLAG F USING THE SCALE 1"=60" _____

NAME: _____

Figure 1.7.2: Exercise 2: The engineer's and metric scales

Exercise 3: Architect's scale

Measure the walls of the provided floor plan at a scale $1/8" = 1'$ using the architect's scale.

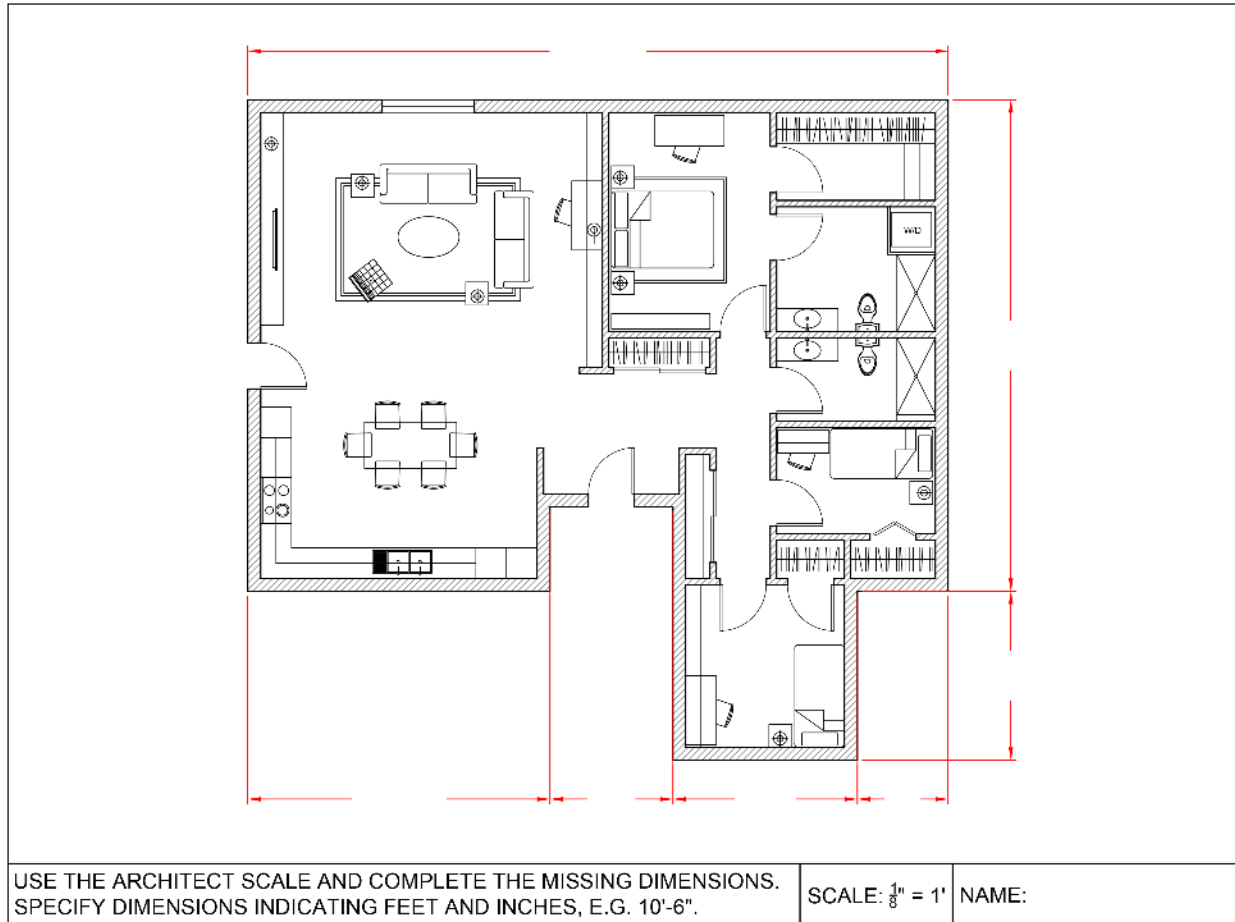


Figure 1.7.3: Exercise 3: The architect's scale

Exercise 4: Geometric constructions and tangencies

Follow instructions and resolve exercises 1-6 using the drawing tools: triangles, T-square, and a compass.

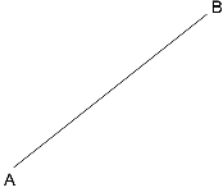
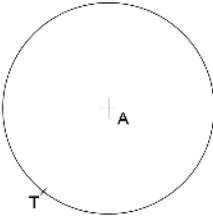
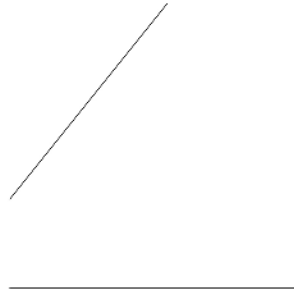
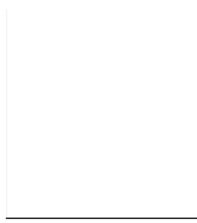
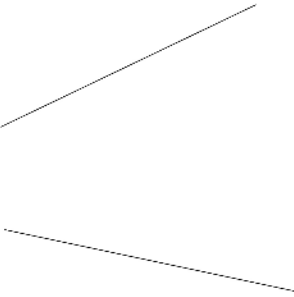
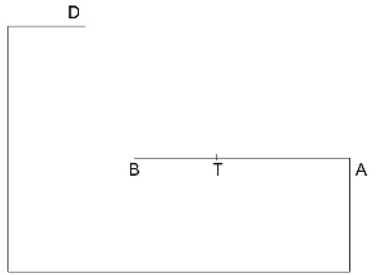
		
BISECT LINE A-B (USE COMPASS)	DRAW LINE TANGENT TO CIRCLE A AT POINT T (SHOW CONSTRUCTION LINES)	DRAW ARC TANGENT TO GIVEN LINES, $R=0.5"$ (SHOW CONSTRUCTION LINES AND POINTS OF TANGENCY)
		
DRAW ARC TANGENT TO GIVEN LINES, $R=1.2"$ (SHOW CONSTRUCTION LINES AND POINTS OF TANGENCY)	DRAW ARC TANGENT TO GIVEN LINES, $R=1"$ (SHOW CONSTRUCTION LINES AND POINTS OF TANGENCY)	DRAW ARC TANGENT TO LINE A-B AT T AND THROUGH POINT D (SHOW CONSTRUCTION LINES AND POINTS OF TANGENCY)
GEOMETRIC CONSTRUCTIONS & TANGENCIES	DATE:	NAME:

Figure 1.7.4: Exercise 4: Geometric Constructions and Tangencies

Exercise 5: Geometric constructions and tangencies

Follow instructions and resolve exercises 1-6 using drawing tools: triangles, T-square, and a compass.

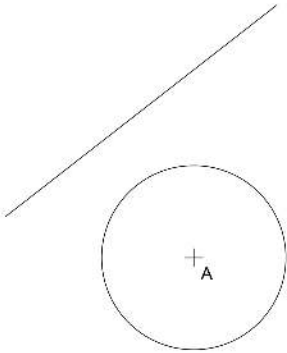
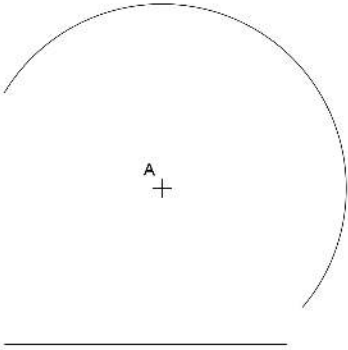
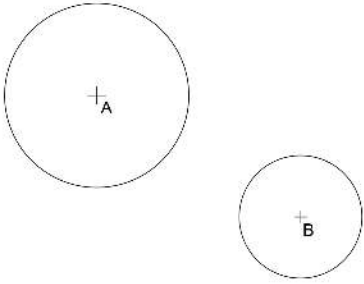
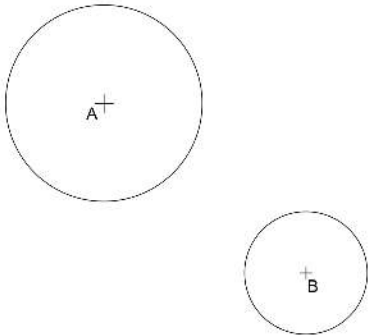
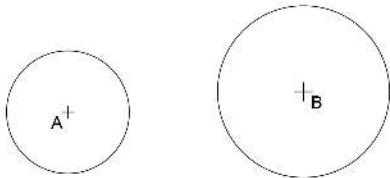
		
DRAW ARC TANGENT TO GIVEN LINE AND CIRCLE A, $R=0.5"$ (SHOW CONSTRUCTION LINES AND POINTS OF TANGENCY)	DRAW ARC TANGENT TO GIVEN LINE AND CIRCLE A, $R=1"$ (SHOW CONSTRUCTION LINES AND POINTS OF TANGENCY)	DRAW ARC TANGENT TO CIRCLES A AND B, $R=0.8"$ (SHOW CONSTRUCTION LINES AND POINTS OF TANGENCY)
		
DRAW ARC TANGENT TO CIRCLES A AND ENCLOSING ONLY CIRCLE A, $R=2"$ (SHOW CONSTRUCTION LINES AND POINTS OF TANGENCY)		DRAW ARC TANGENT TO CIRCLES A AND ENCLOSING BOTH CIRCLES, $R=2"$ (SHOW CONSTRUCTION LINES AND POINTS OF TANGENCY)
GEOMETRIC CONSTRUCTIONS & TANGENCIES		NAME: _____ DATE: _____

Figure 1.7.5: Exercise 5: Tangencies

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CHAPTER OVERVIEW

2: Module B - Orthographic projections

- [2.1: System of projections](#)
- [2.2: Orthographic projections](#)
- [2.3: Mutiview drawings](#)
- [2.4: Hidden edges in orthographic projections](#)
- [2.5: Curved edges and surfaces in orthographic projections](#)
- [2.6: Normal, inclined, and oblique surfaces](#)
- [2.7: Exercises](#)

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2.1: System of projections

Learning Objectives

By the end of this section, learners will be able to

1. Define the concepts of perspective and parallel projections.
2. Classify different types of projections.

Understanding projections

Projections can be classified into two main categories: **Perspective** and **Parallel projections**.

Definition:

Perspective projections mimic how our eyes perceive the world and provide a realistic representation of what we see. In perspective drawings, projectors converge at the vanishing point on the horizon line. This results in distant objects appearing smaller than objects closer to the viewer. The station point represents the viewer's eyes. There are different types of perspective projections, including 1-point perspective, 2-point perspective, and 3-point perspective.

In **parallel projections**, the projectors run parallel to each other and do not converge in the vanishing point. Parallel projections are used in technical drawings to accurately describe an object's details, features, and dimensions.

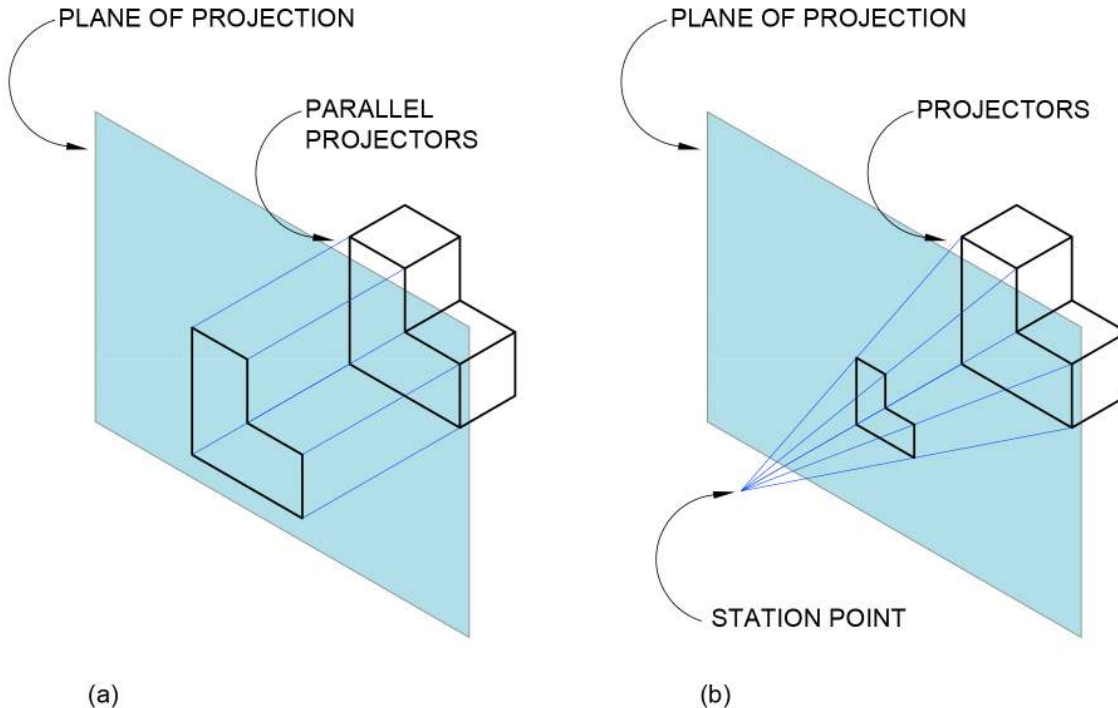


Figure 2.1.1: Parallel (a) and perspective (b) projection.

Classification of Projections

The diagram below illustrates the different types of projections and their classification.

The lectures in Modules B and C focus on parallel projections, as illustrated in the diagram below. Orthographic projection is a type of parallel projection in which the projectors are perpendicular (orthogonal) to the projection plane. This category includes multiview and axonometric drawings. Oblique projection also falls under parallel projections, but unlike orthographic projection, the projectors are set at an angle other than 90 degrees to the projection plane. Cabinet and cavalier projections are types of oblique projection and will be discussed in [Module C, Section 3.4](#).

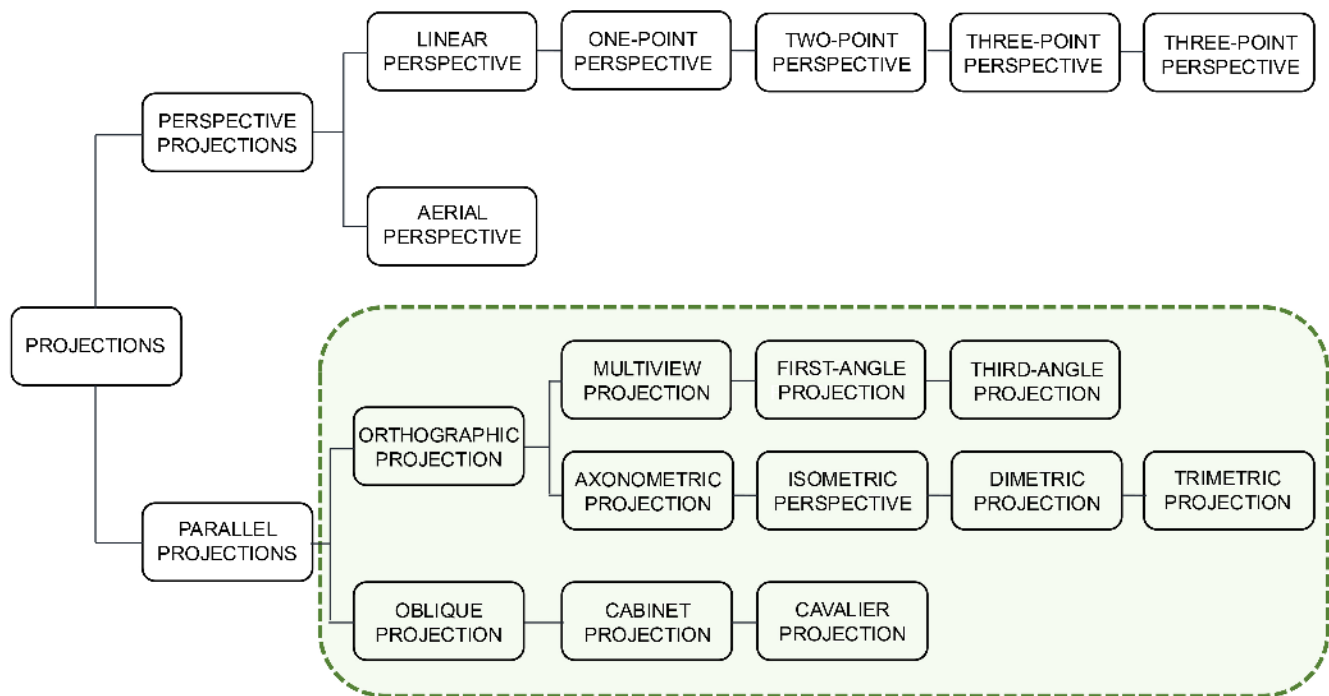


Figure 2.1.2: Types and classification of projections.

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2.2: Orthographic projections

Learning Objectives

By the end of this section, learners will be able to

1. Define surfaces, edges, and vertices.
2. Describe width, depth, and height as the three principal dimensions.
3. Identify and describe the six standard orthographic views and corresponding planes of projection.
4. Explain how the first-angle and third-angle projection methods differ in terms of object placement and arrangement of views.

Surfaces, edges, and vertices

Learning the basic elements of a solid and the terms used to describe them is essential to understand orthographic projections. A solid consists of surfaces, edges, and vertices.

Surfaces - figure 2.2.1(a) - are the outer faces that enclose a solid. They can be planar (flat) or curved. If a flat surface is parallel to one of the standard planes of projection, it is called a normal surface. If it is not parallel to a standard plane of projection, it is either an inclined surface or an oblique surface. [Section 2.6](#) describes how to identify, represent, and interpret normal, inclined, and oblique surfaces.

Edges, shown in red in Figure 2.2.1(b), are formed where two surfaces meet. Depending on the shape of these surfaces, edges can be either straight or curved.

Finally, a **vertex** is a point where three or more surfaces intersect. Figure 2.2.1(c) illustrates a surface with six vertices.

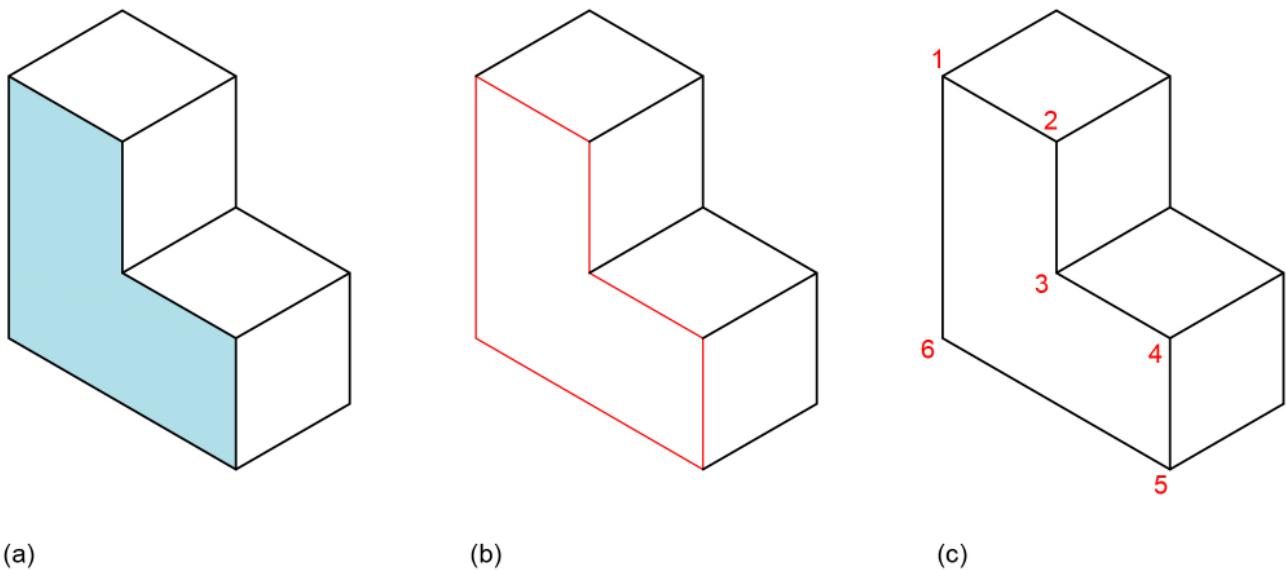


Figure 2.2.1: Primary elements of a solid: Surfaces (a), edges (b), and vertices (c).

A solid's three principal dimensions are width, depth, and height, as shown in Figure 2.2.2.

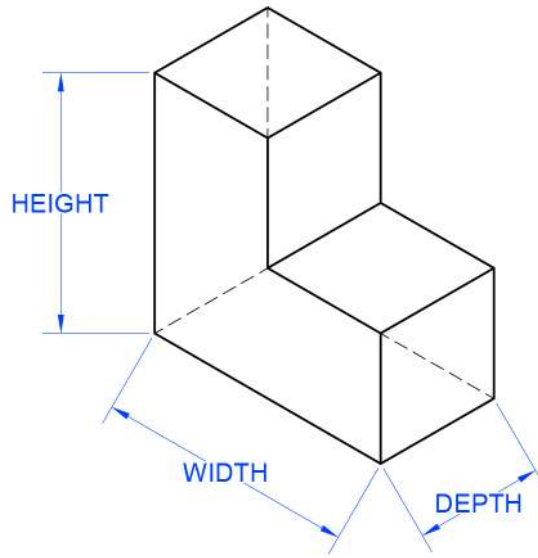


Figure 2.2.2: The three principal dimensions: width, depth, and height.

Orthographic Projections

A type of parallel projection, **orthographic projection** is a projection method in which all projectors are parallel to each other and orthogonal (at a 90-degree angle) to the plane of projection.

A view or projection is a two-dimensional representation of a three-dimensional object. There are six principal (or standard) views: top, bottom, front, rear, left-, and right-side views. Each view provides information about two of the object's three dimensions. Depending on the projection method—either the third-angle or first-angle projection method—these six views are arranged on the drawing sheet in a specific order relative to one another.

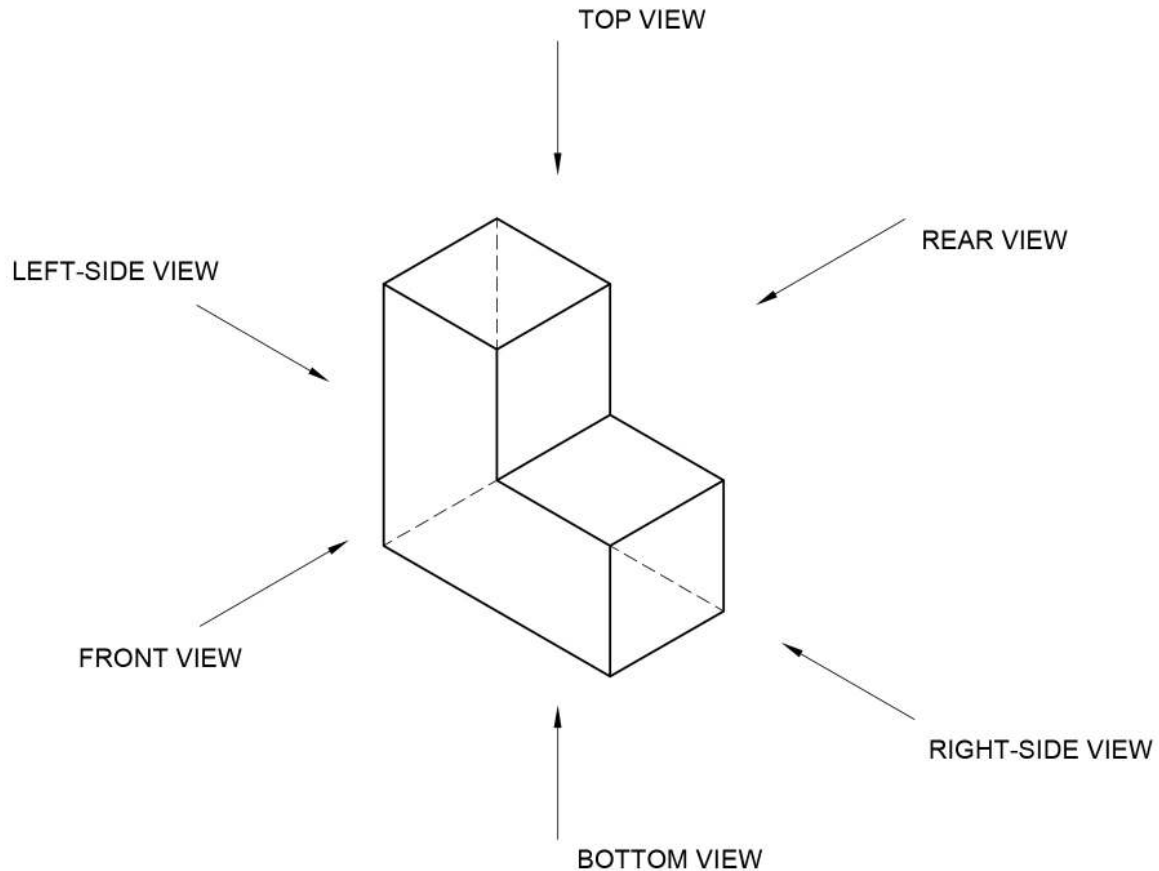


Figure 2.2.3: The six standard views.

First- and third-angle projection methods

There are two primary methods for orthographic projection: first-angle and third-angle projection. In the United States, the third-angle method is used, following the ASME Y14.3-2003 standard. Europe, Asia, and most of the world use the first-angle method.

Note

ASME stands for American Society of Mechanical Engineers. The American National Standards Institute (ANSI) is the organization that administers and oversees the development of standards by other organizations, such as ASME.

To understand the difference between these two systems, imagine a vertical plane intersecting a horizontal plane at a right angle, as shown in Figure 2.2.4. The intersection of these two planes forms four distinct regions, called quadrants. Figure 2.2.5 illustrates the four quadrants highlighting the first and third quadrants, which are used in the respective projection methods.

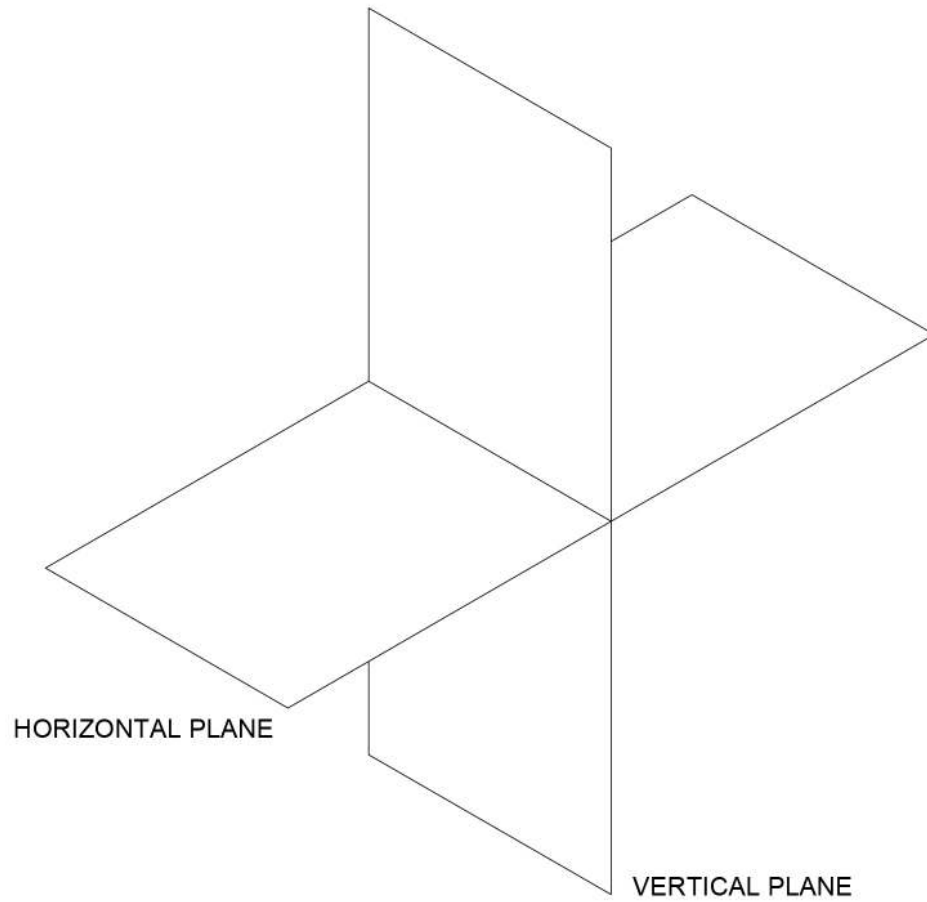


Figure 2.2.4: Horizontal and vertical planes intersecting.

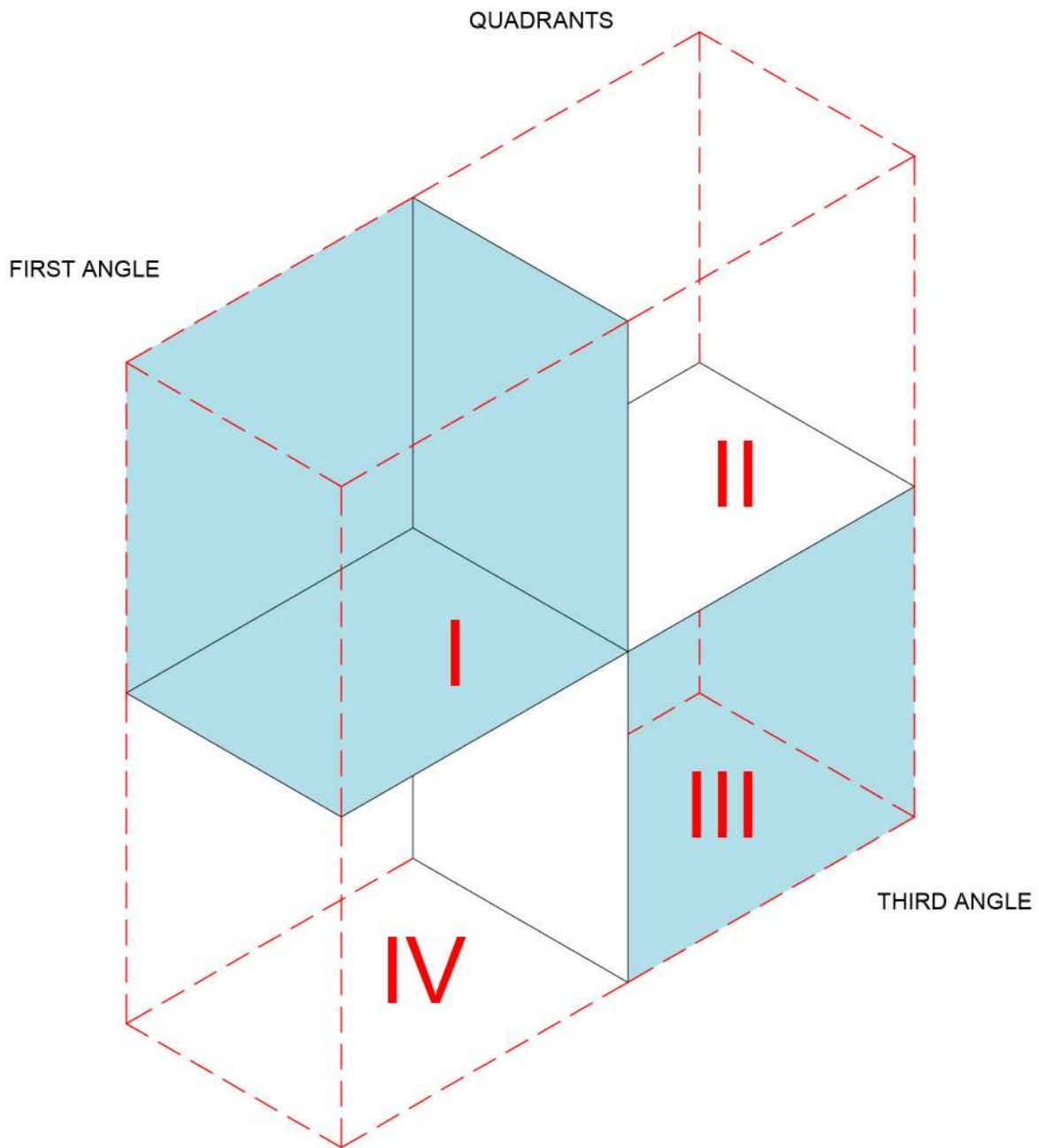


Figure 2.2.5: The four quadrants.

First-angle method

The figure below illustrates the first-angle projection method using the L-shaped object from the previous section, which is placed in the first quadrant (Figure 2.2.6).

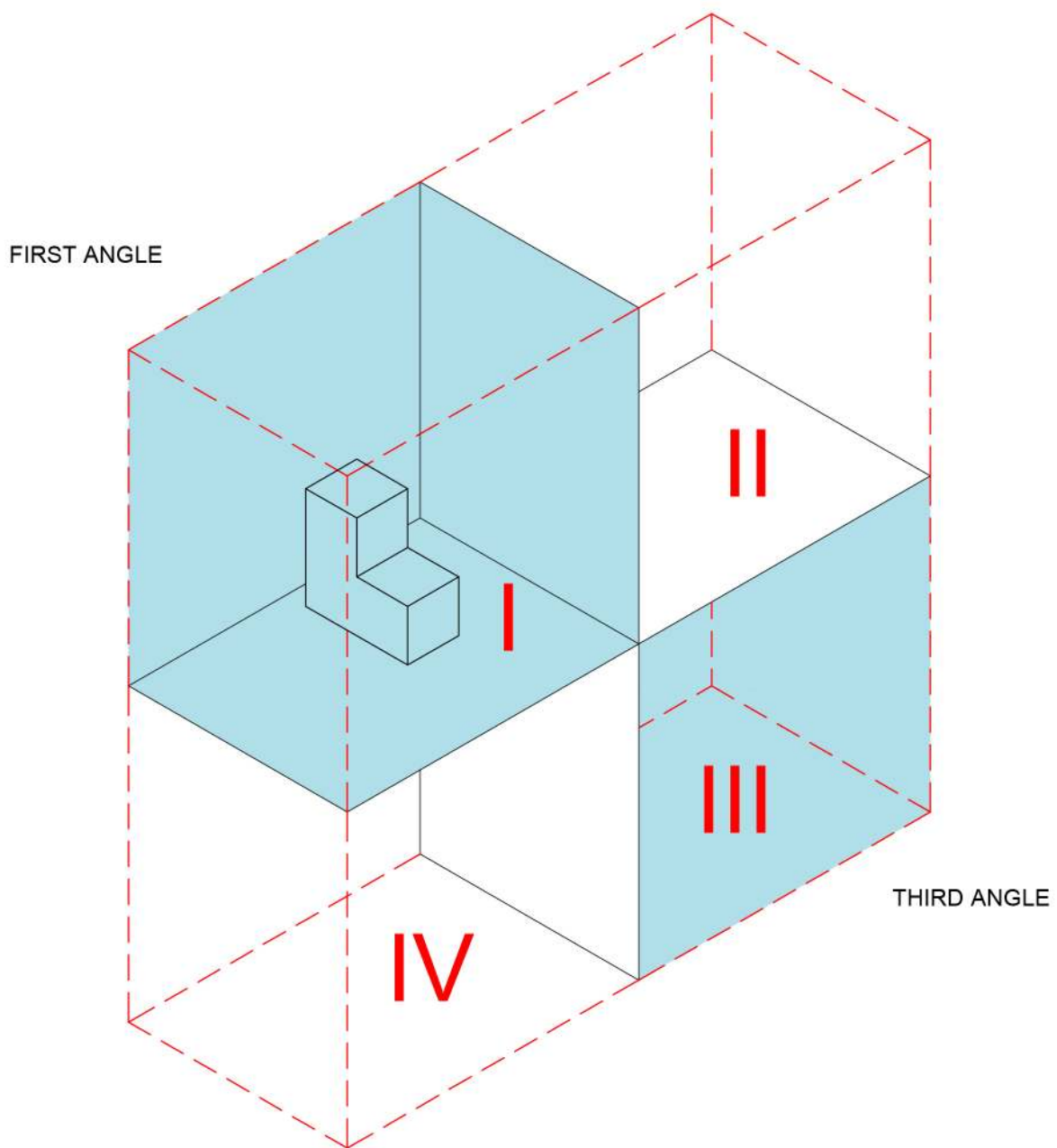


Figure 2.2.6: Object placed in the first quadrant.

In this method, the object is positioned above the horizontal plane and in front of the vertical plane, between the observer and the projection planes. Figure 2.2.7 provides a closer view of this quadrant. Three arrows indicate the observer's lines of sight used to project the front, top, and right-side views.

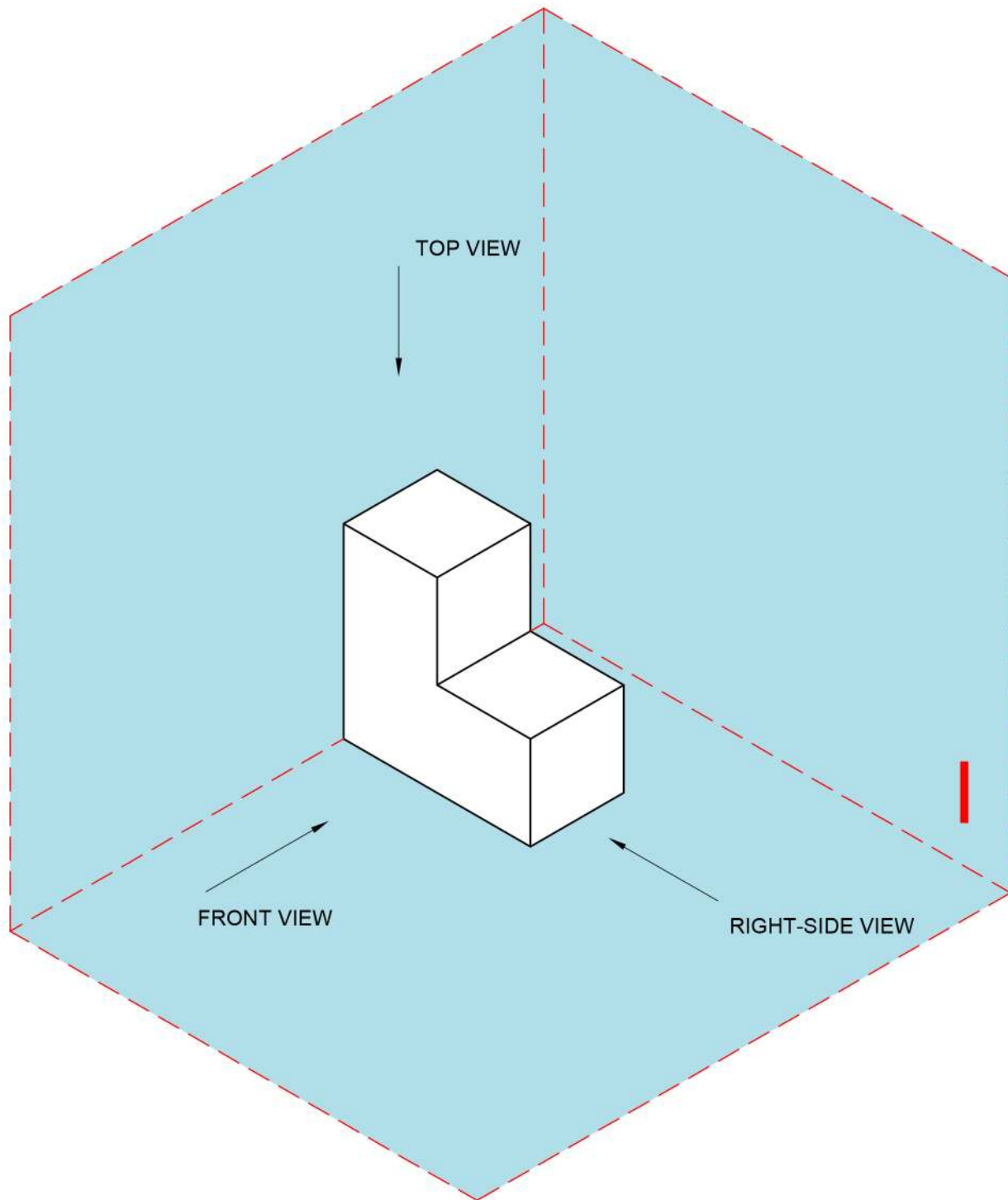


Figure 2.2.7: First quadrant and lines of sight.

Following the direction of the line of sight, the front view is projected onto the vertical plane across the object, as shown in Figure 2.2.8. The top view is projected onto the horizontal plane below the object, and the right-side view is projected onto a vertical plane placed to the left of the object.

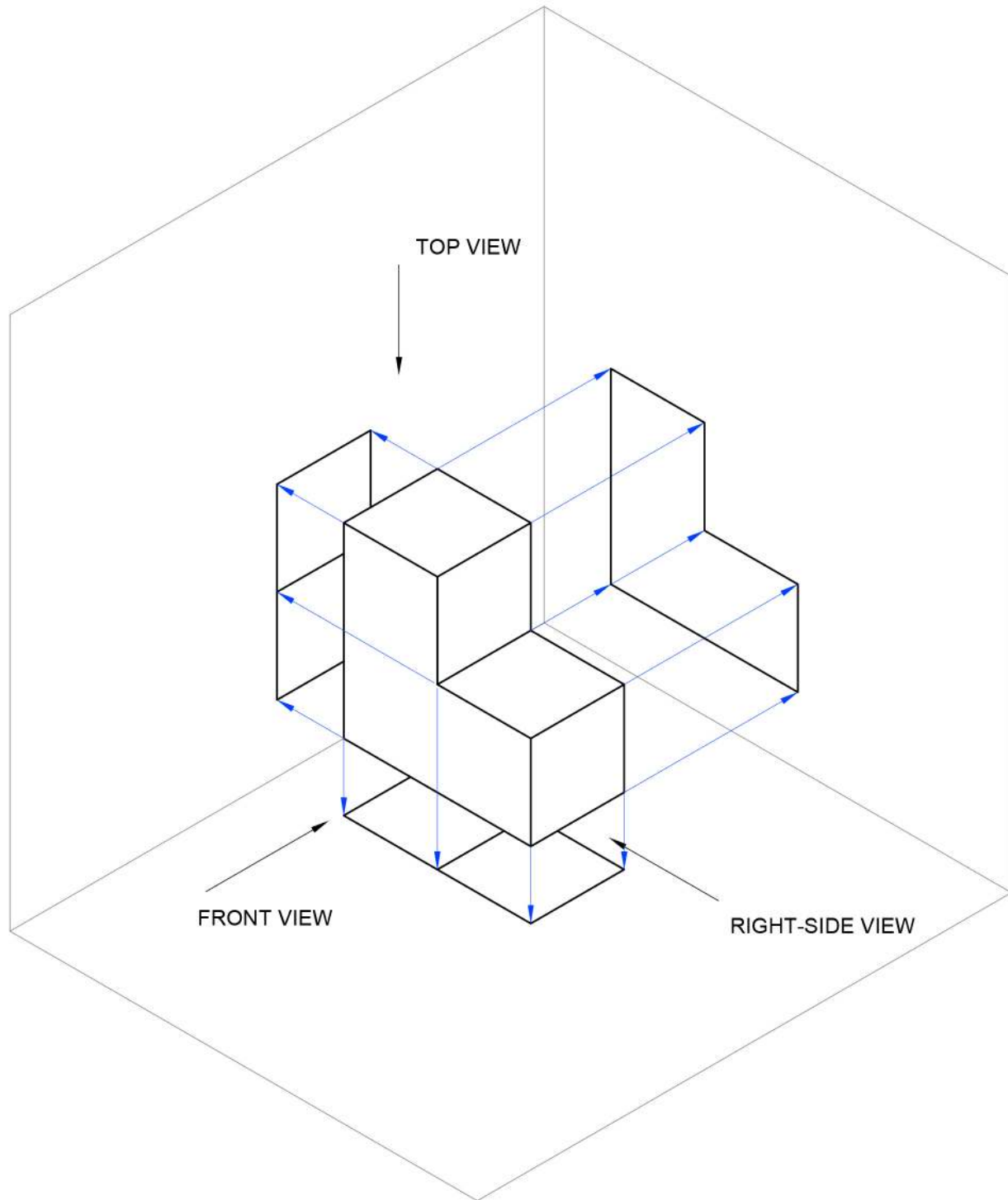


Figure 2.2.8: Projection of top, front, and right-side views in the first-angle method.

By unfolding the planes, we obtain the arrangement of the three views in the first-angle projection.

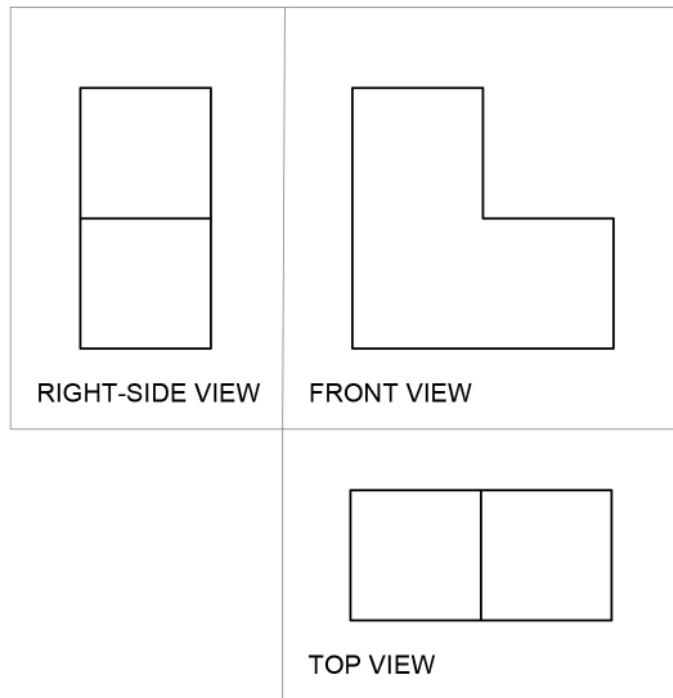


Figure 2.2.9: First angle projection arrangement of views.

Third-angle projection method

Similarly, the same L-shaped object can be placed in the third quadrant to illustrate the third-angle projection method. In this method, the object is positioned below the horizontal plane and behind the vertical plane, as shown in Figure 2.2.10.

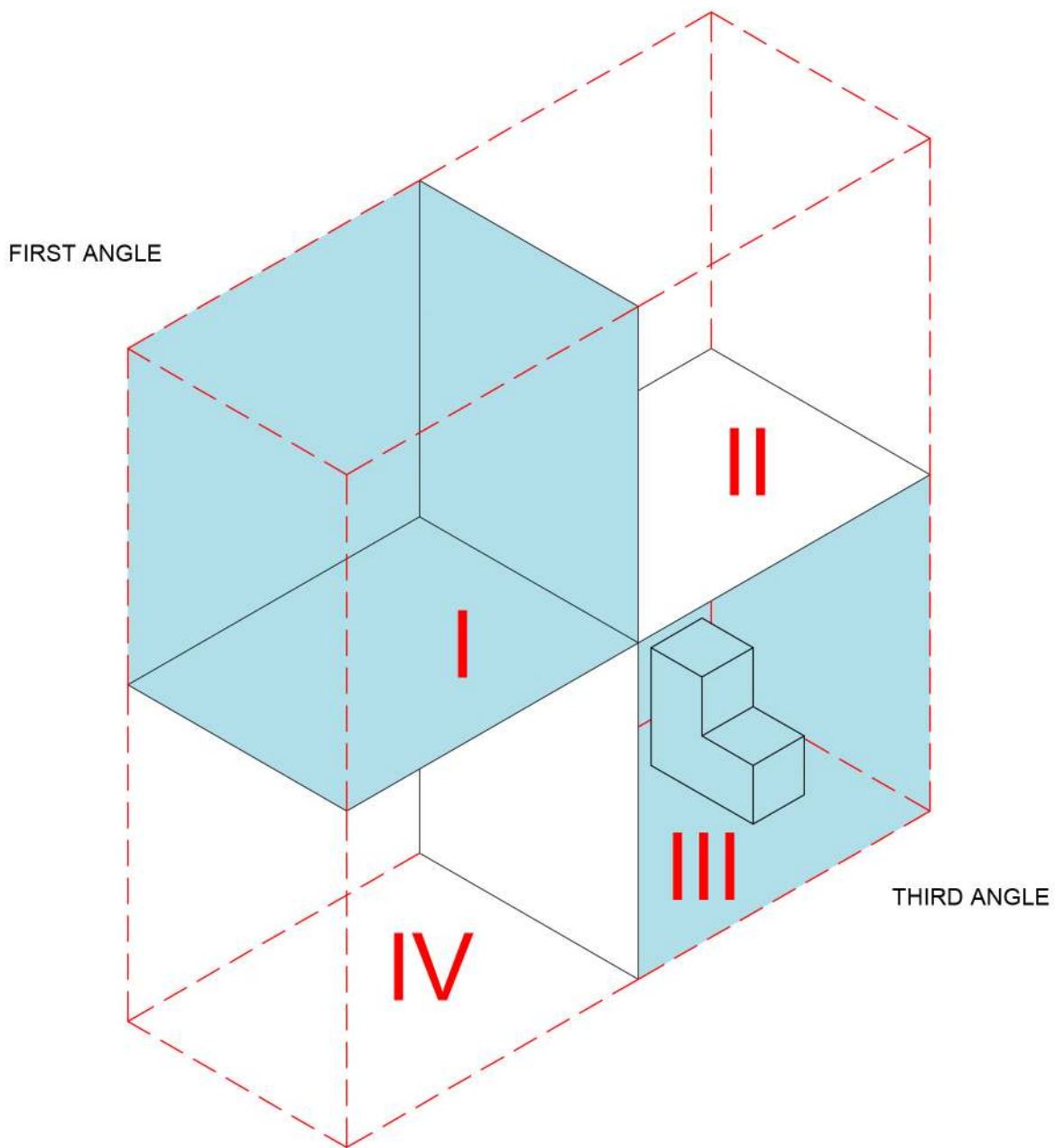


Figure 2.2.10: Object in the third quadrant.

Figure 2.2.11 provides a closer view of this quadrant. In this case, the observer is “outside, looking in,” with the planes of projection located between the observer and the object. Three arrows represent the lines of sight used to project the front, top, and right-side views. The front view is obtained by looking directly at the front of the object, the top view is projected onto the plane above the object, and the right-side view is projected onto the plane to its right (Figure 2.2.12).

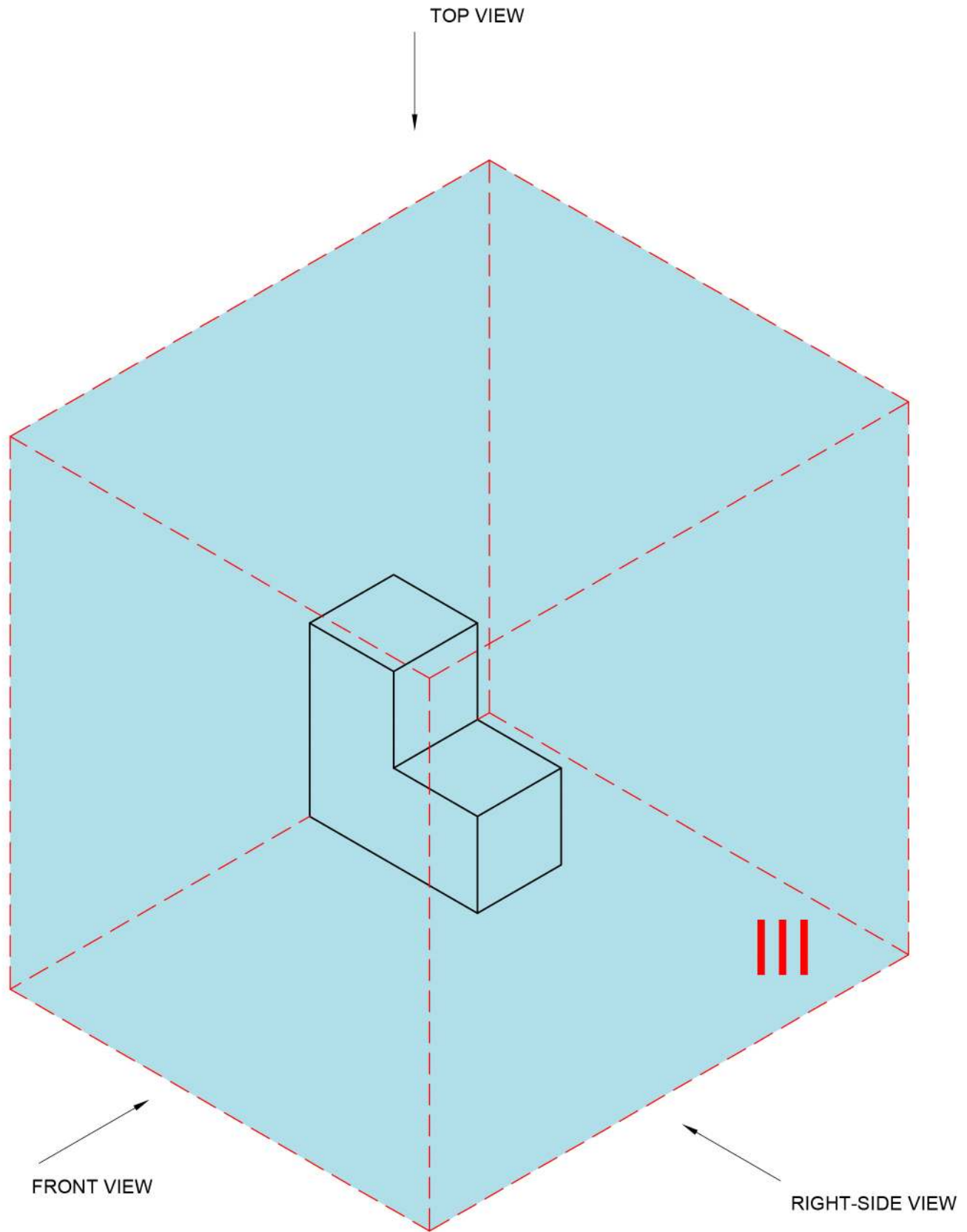


Figure 2.2.11: Third quadrant and lines of sight.

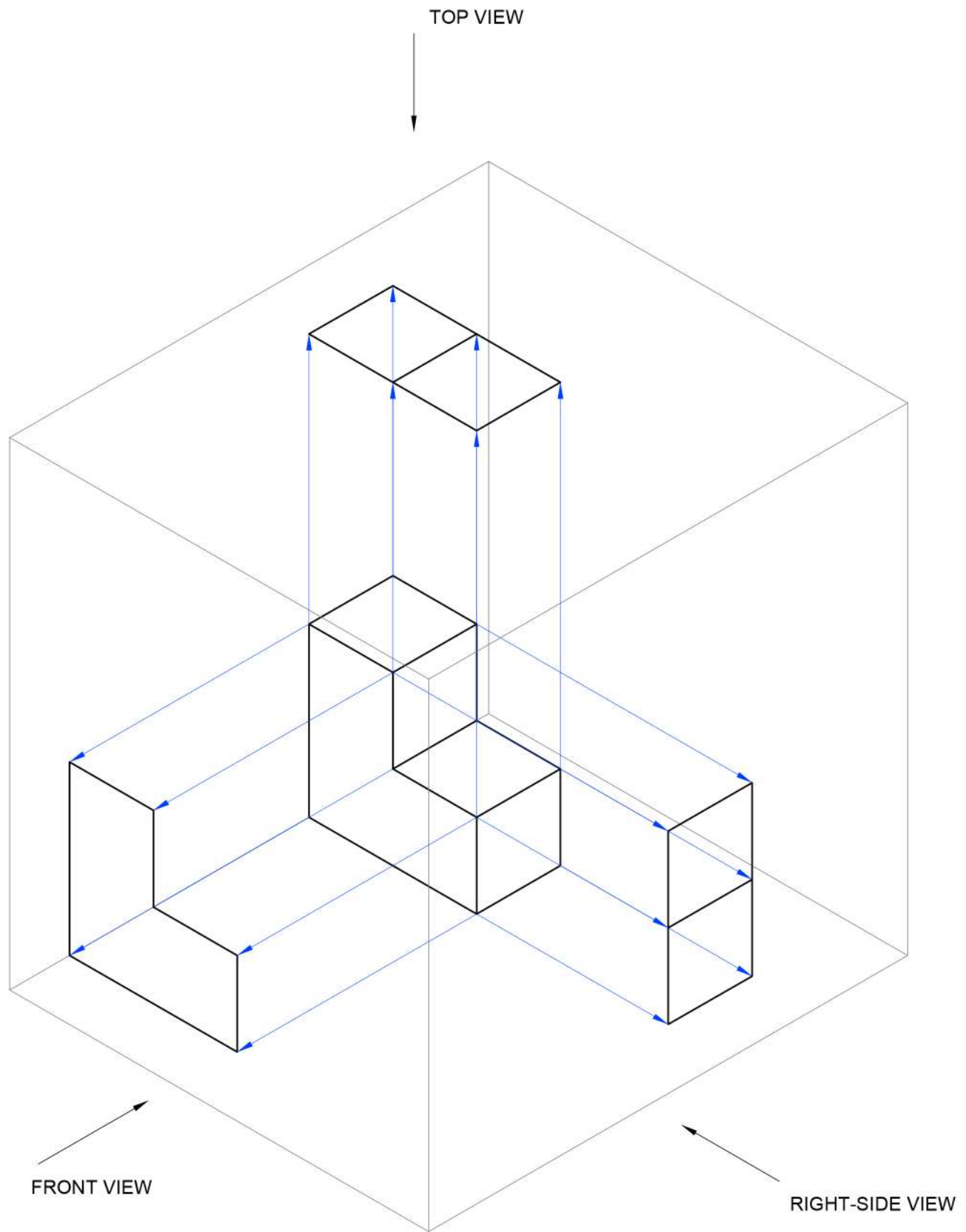


Figure 2.2.12: Projection of top, front, and right-side views in the third-angle method.

By unfolding the box, the standard arrangement of views in the third-angle projection is obtained (Figure 2.2.13).

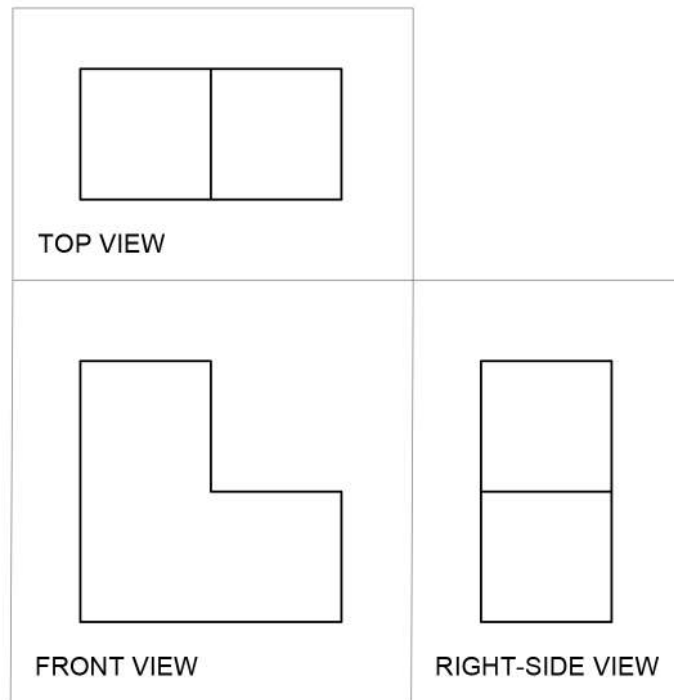


Figure 2.2.13: Third-angle projection arrangement of views

Ultimately, the difference between first- and third-angle projection lies in the different arrangement of views. To avoid mistakes in the interpretation, international projection symbols are used to distinguish between the two projection methods.

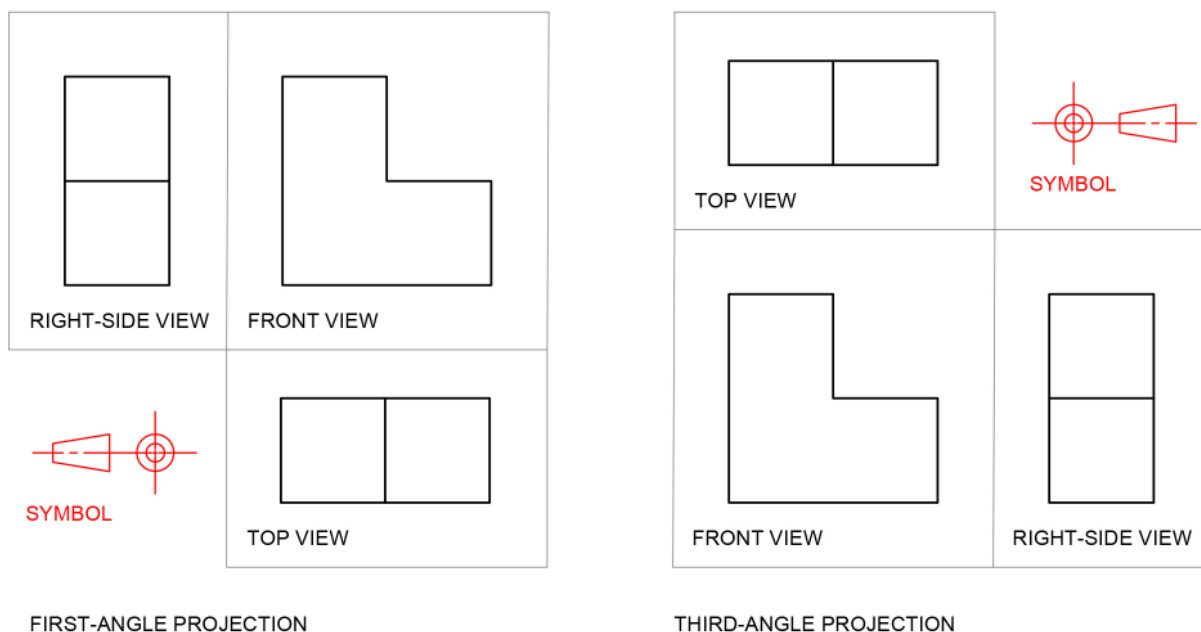


Figure 2.2.14: International projection symbols in first-and third-angle projection.

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2.3: Mutiview drawings

Learning Objectives

By the end of this section, learners will be able to

1. Understand orthographic views and projections.
2. Explain the standard arrangement of views in multiview drawings and how the views relate to one another.
3. Interpret and create multiview drawings of a solid object.

The glass box method

The glass box method helps develop a better understanding and visualization of third-angle projection and multiview drawings. The example below shows an object enclosed in an imaginary glass box. Each face of the glass box represents one of the six standard planes of projections and views: top, bottom, front, rear, left, and right-side views.

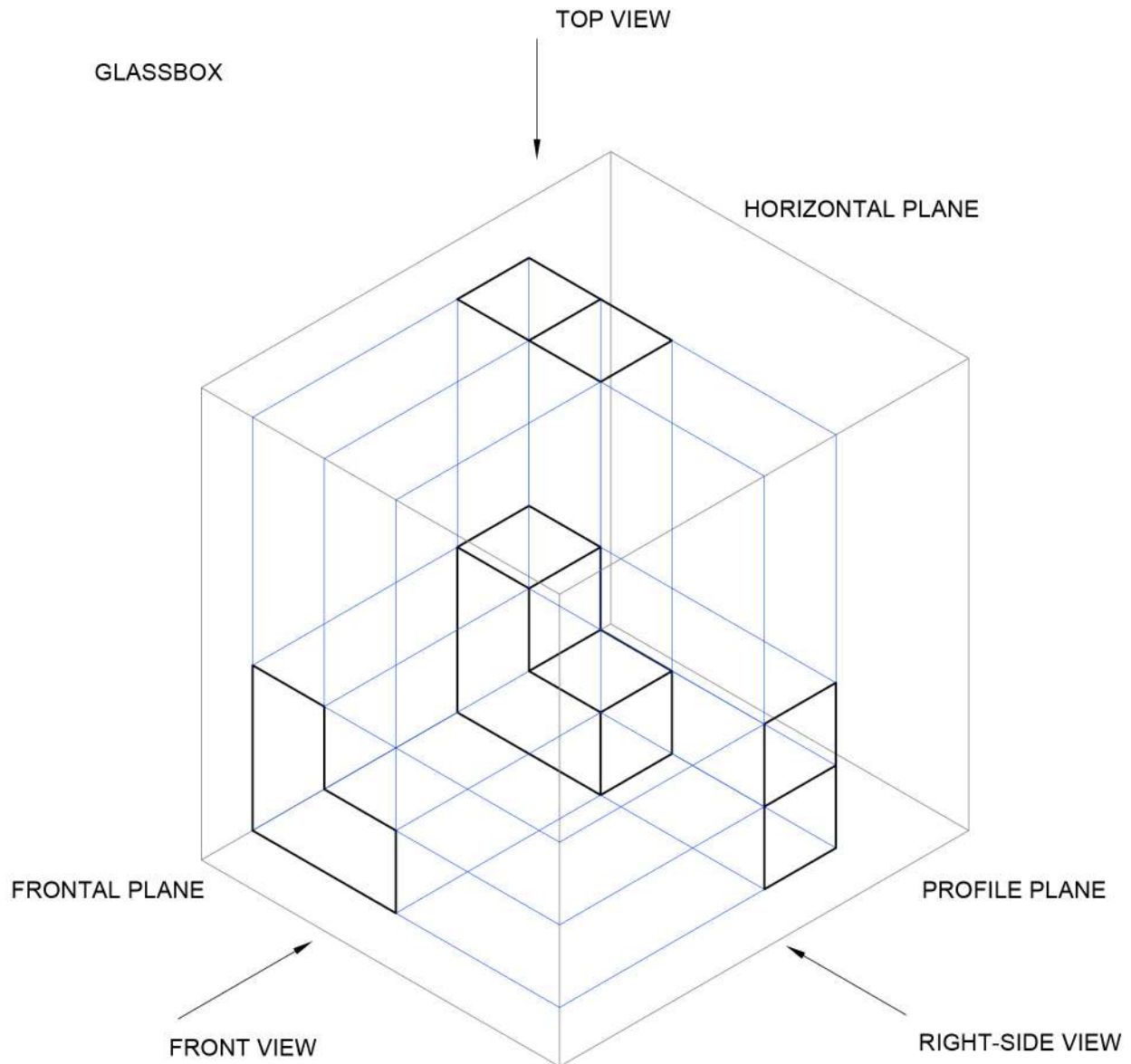


Figure 2.3.1: Imaginary glass box.

To create a top view of this object, its vertices are projected onto the top plane using projectors perpendicular to the plane of projection, as shown in Figure 2.3.1. Following the same process, the front view is projected onto the frontal plane using projectors perpendicular to that plane, the right-side view is projected on the profile plane, and so on for all six views.

Each orthographic view provides information about two of the three dimensions: width, depth, and height. Therefore, more than one view is necessary to interpret orthographic projections correctly. A system of views is called a multiview projection.

The standard arrangement of views

The standard views are organized on a sheet following a specific order in accordance with the American National Standard. The standard arrangement of view is obtained by unfolding the glass box, as shown in Figure 2.3.2. It is important to maintain the correct order and placement in order to interpret the drawing correctly.

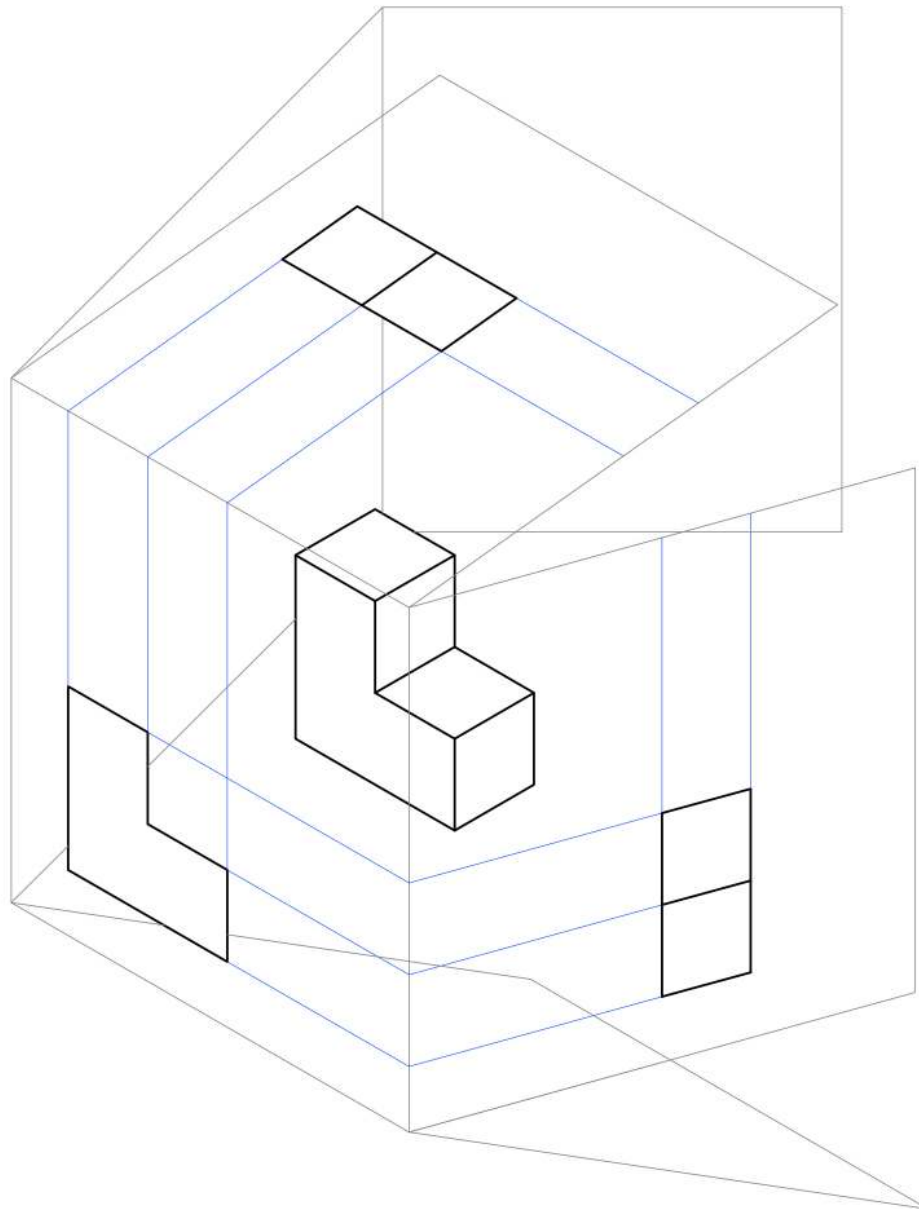


Figure 2.3.2: Glass box unfolding.

The figure below shows the unfolded glass box (Figure 2.3.3). The top, front, and bottom views are aligned vertically; the width can be transferred between these three views. The rear, left-side, front, and right-side views are aligned horizontally. The height can be transferred between these three views. Lastly, the depth is transferred between the left-side, top, right-side, and bottom views with the use of a miter line, which is a 45-degree line (see Figure 2.3.4).

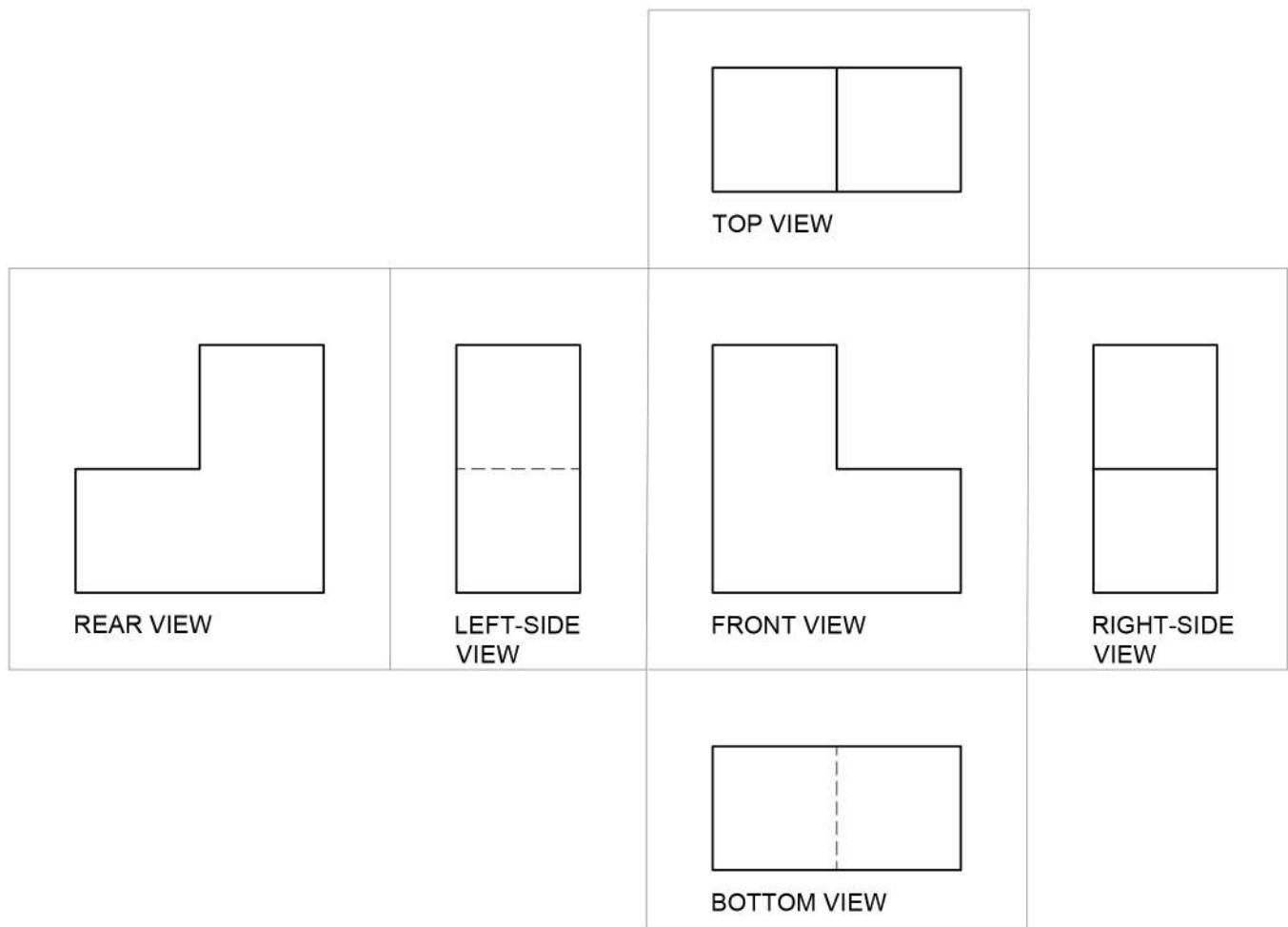


Figure 2.3.3: Standard arrangement of views.

The six views relate to each other through one of the three dimensions, as shown in Figure 2.3.4. Keeping the correct arrangement of the six views is important because it allows for the transfer of dimensions between views. For example, the width can be transferred between the front and top views.

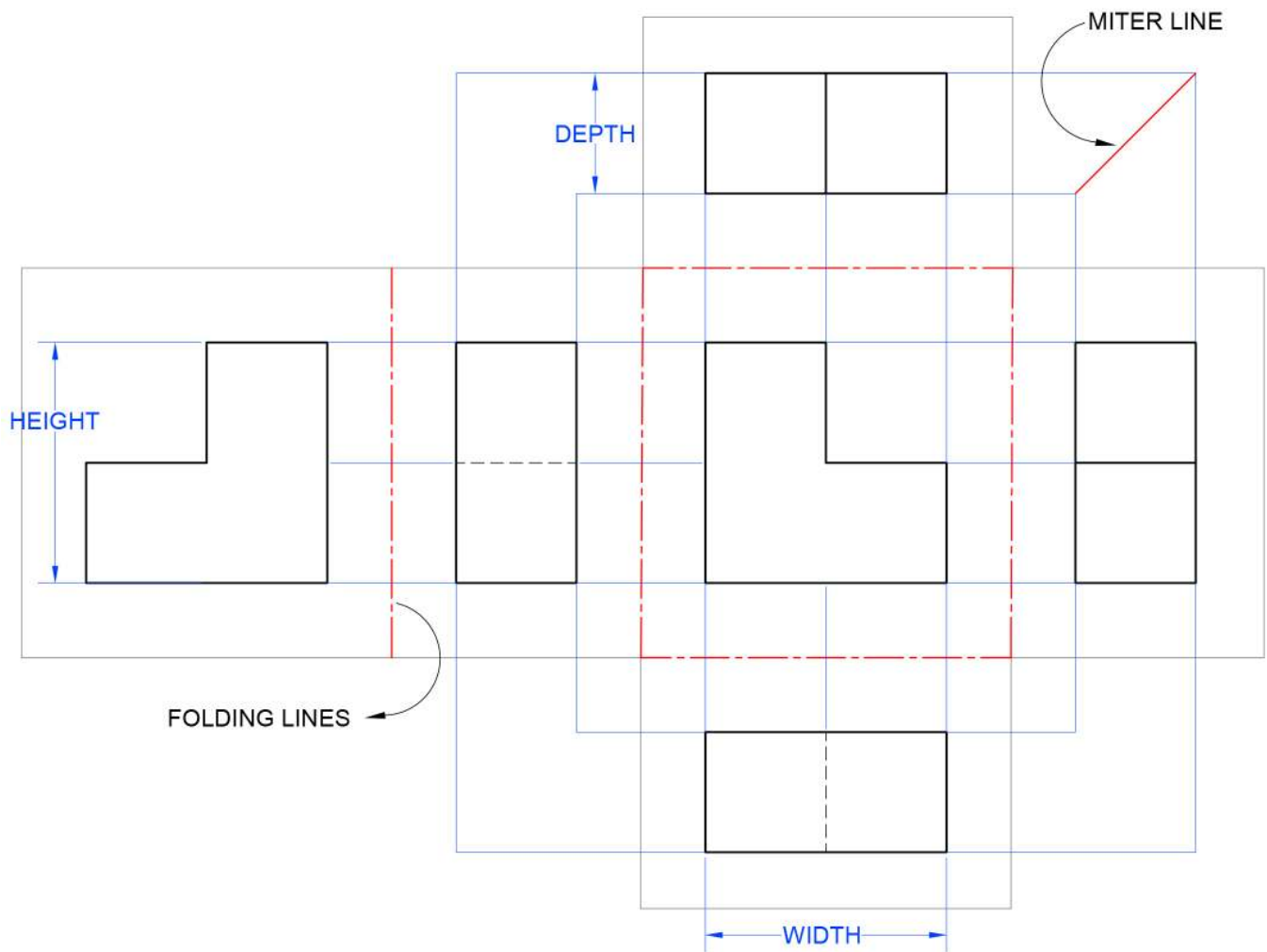


Figure 2.3.4: Dimensions transferred between views.

✓ Example 2.3.1

This example illustrates how to create top, front and right-side views of the object depicted below.

Figure 2.5. shows an isometric view of the object with numbered vertices. This object has a total of 20 vertices.

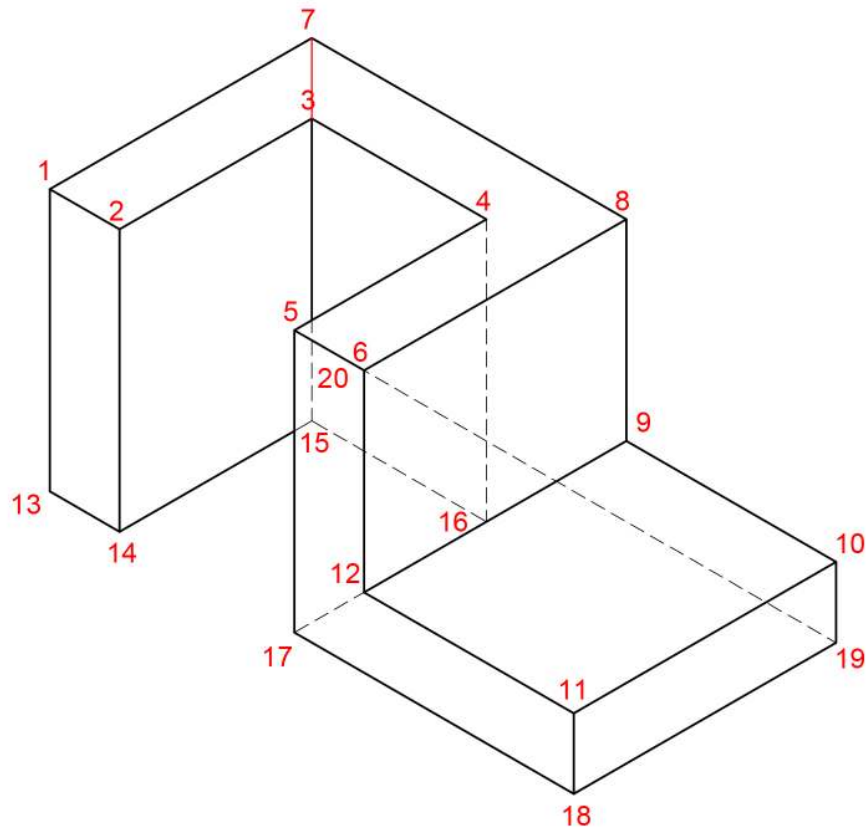


Figure 2.3.5: Isometric view of 3D object

Solution

First, draw the top and front views of the object aligned according to the standard arrangement of views. Guidelines or construction lines can be used to transfer the width between these two views, as shown in Figure 2.3.6. For example, vertices 1 and 7 lie on the same construction line on both views.

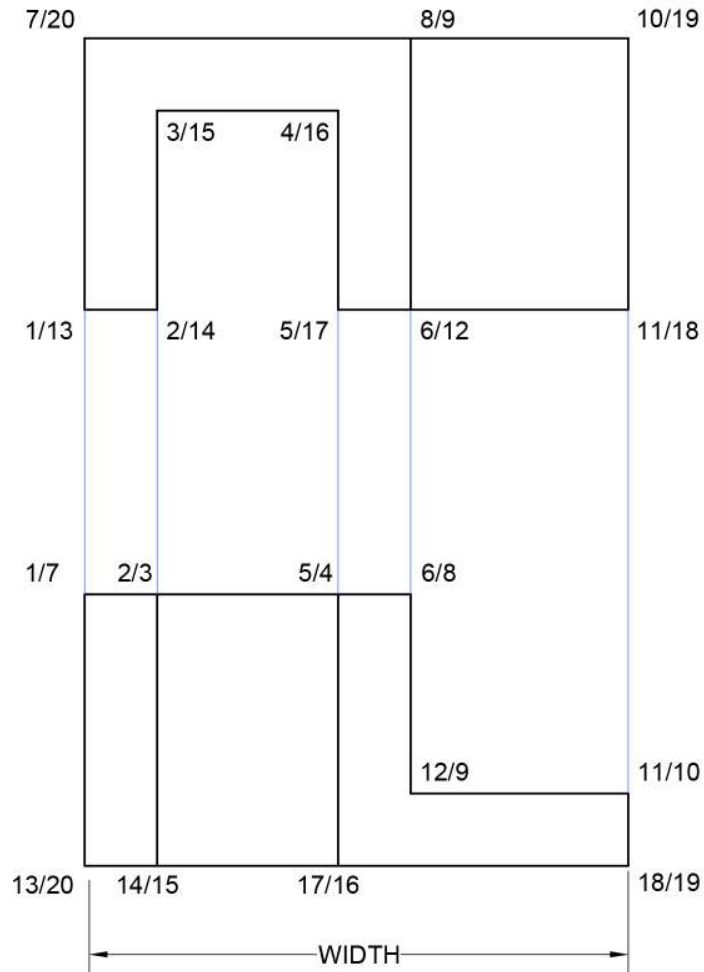


Figure 2.3.6: Transfer of width between views.

The height can be transferred between the front and right-side views using horizontal construction lines.

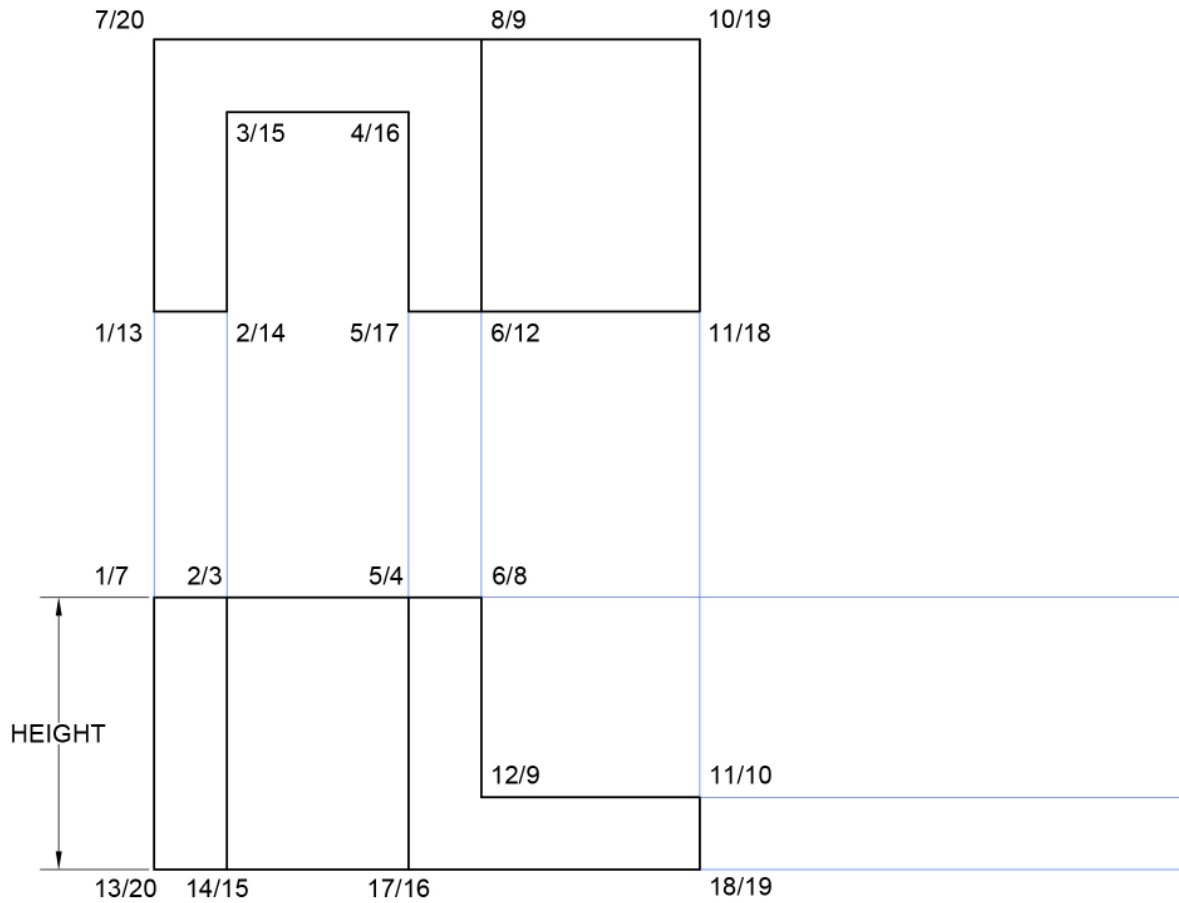


Figure 2.3.7: Transfer of height between front and right-side views.

Finally, the depth can be transferred between top and right-side views using a miter line, as shown in Figure 2.3.8. The miter line is a 45-degree line. A construction line is projected from the top view to the miter line. At the intersection with the miter line, the construction line is transferred downward to the right-side view or vice versa.

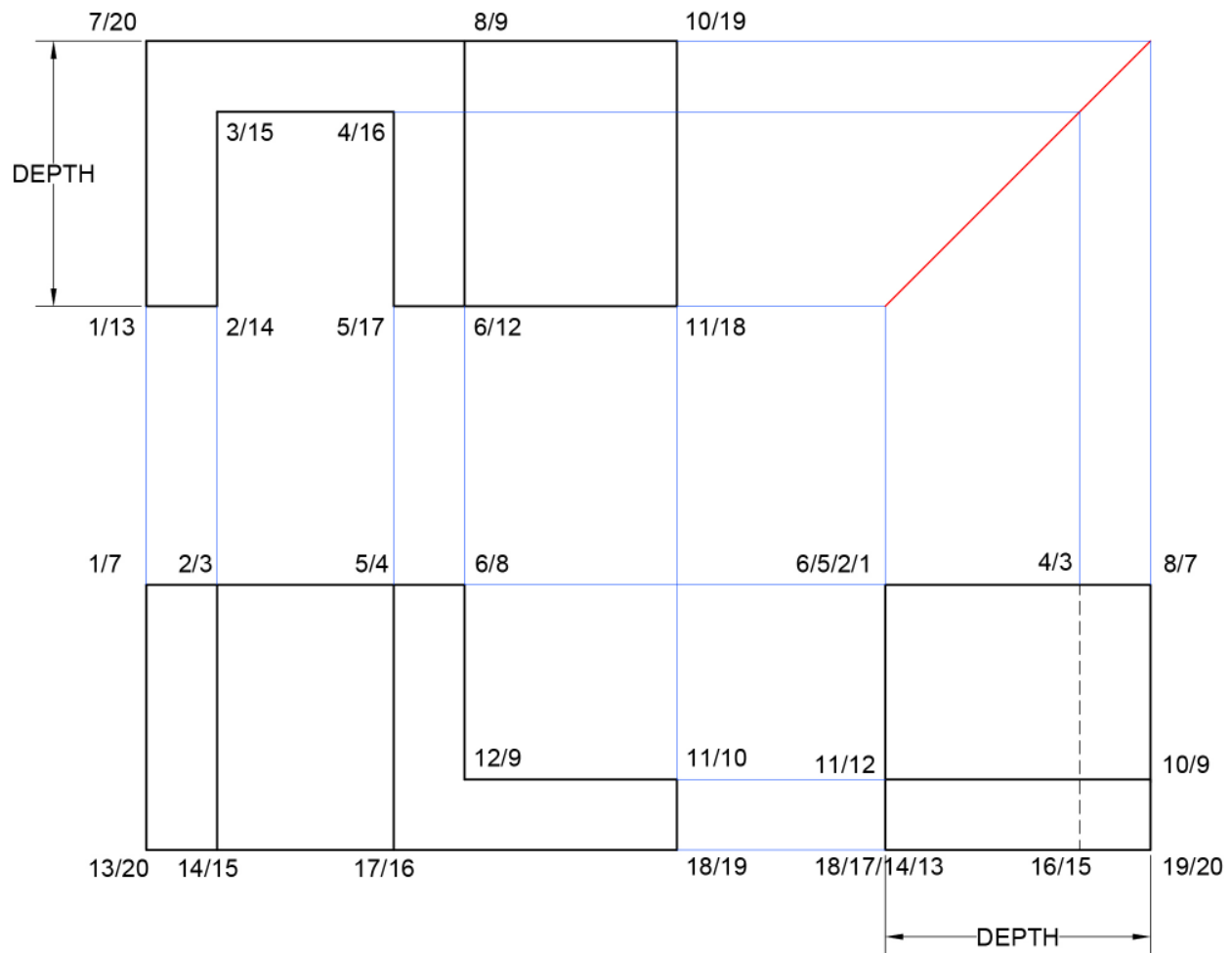


Figure 2.3.8: Transfer of depth between top and right-side views using a miter line.

Video lecture



Photographic projections_Multiview | Edoarda Corradi

Watch on YouTube

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2.4: Hidden edges in orthographic projections

Learning Objectives

By the end of this section, learners will be able to

1. Explain the purpose of hidden lines in multiview drawings.
2. Identify and interpret hidden edges in multiview drawings.

The previous sections introduced orthographic projections and multiview drawings. The L-shaped solid used as an example in those chapters showed only visible edges in the three regular views: the top, front, and right-side views. As explained in [Section 1.2: Line types](#), visible edges are represented by thick, continuous lines.

In contrast, edges that are hidden from view are known as hidden edges, and they are represented using thin, dashed lines. This section introduces hidden edges in multiview drawings.

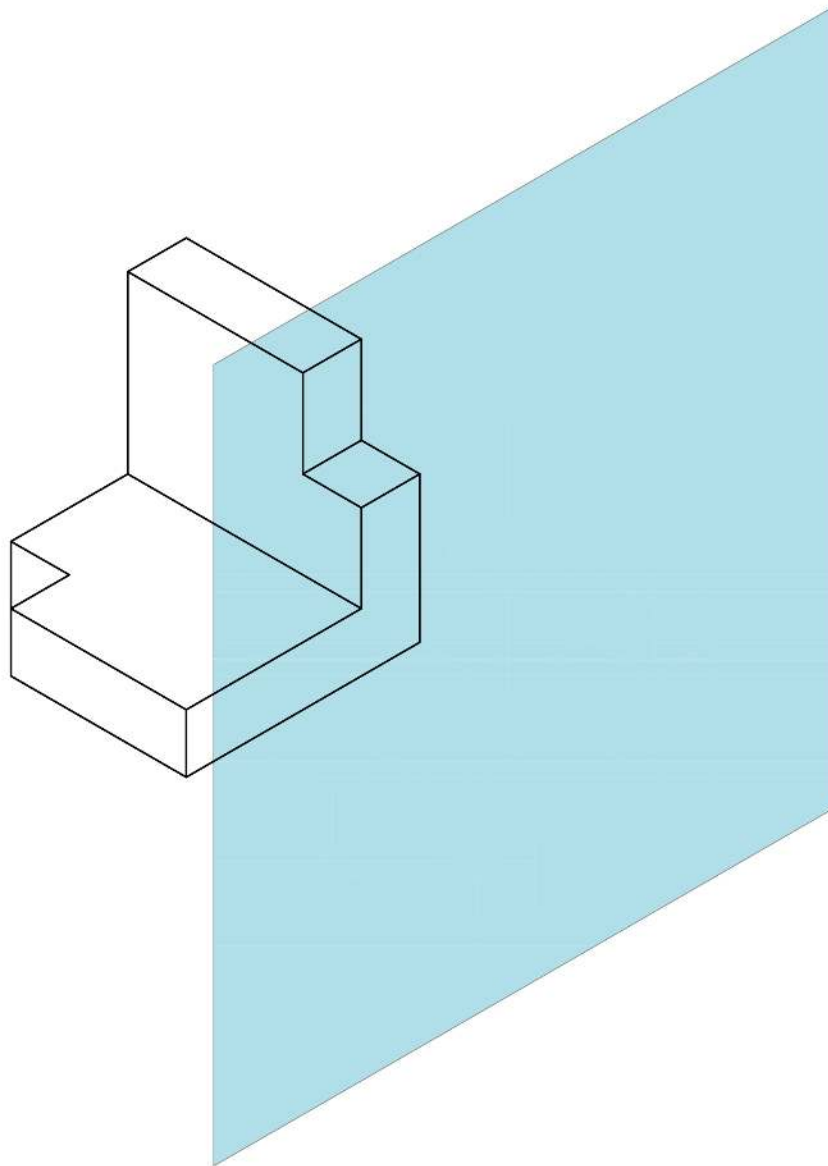


Figure 2.4.1: Object and profile plane.

In Figure 2.4.1, an object is projected onto the profile plane using parallel projectors. When viewed from the right side, only two surfaces are visible. They are labeled as Surface 1 and Surface 2 in Figure 2.4.2.

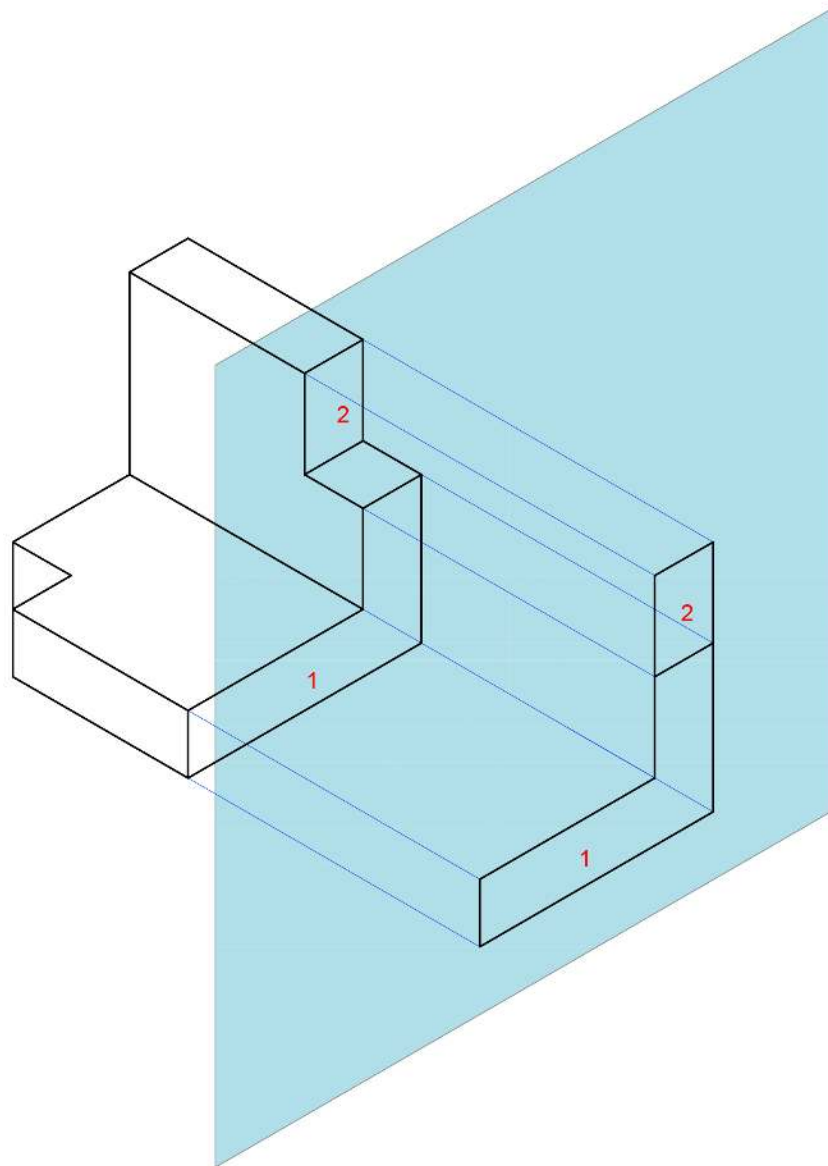


Figure 2.4.2: Two visible surfaces projected on the profile plane.

The right-side view shown in Figure 2.4.2 is incomplete: there is a third square surface located behind Surface 1, which is not visible from that viewpoint. To complete the view, the vertical edge on the right side of Surface 3 must be represented as a hidden line (see Figure 2.4.3). The other three edges of this surface lie directly behind visible edges of Surface 1, so only the vertical edge will appear as a hidden line. In the left-side view of this object, that same vertical edge would appear as a visible line, separating Surface 3 from the L-shaped surface that encloses the object on the left side.

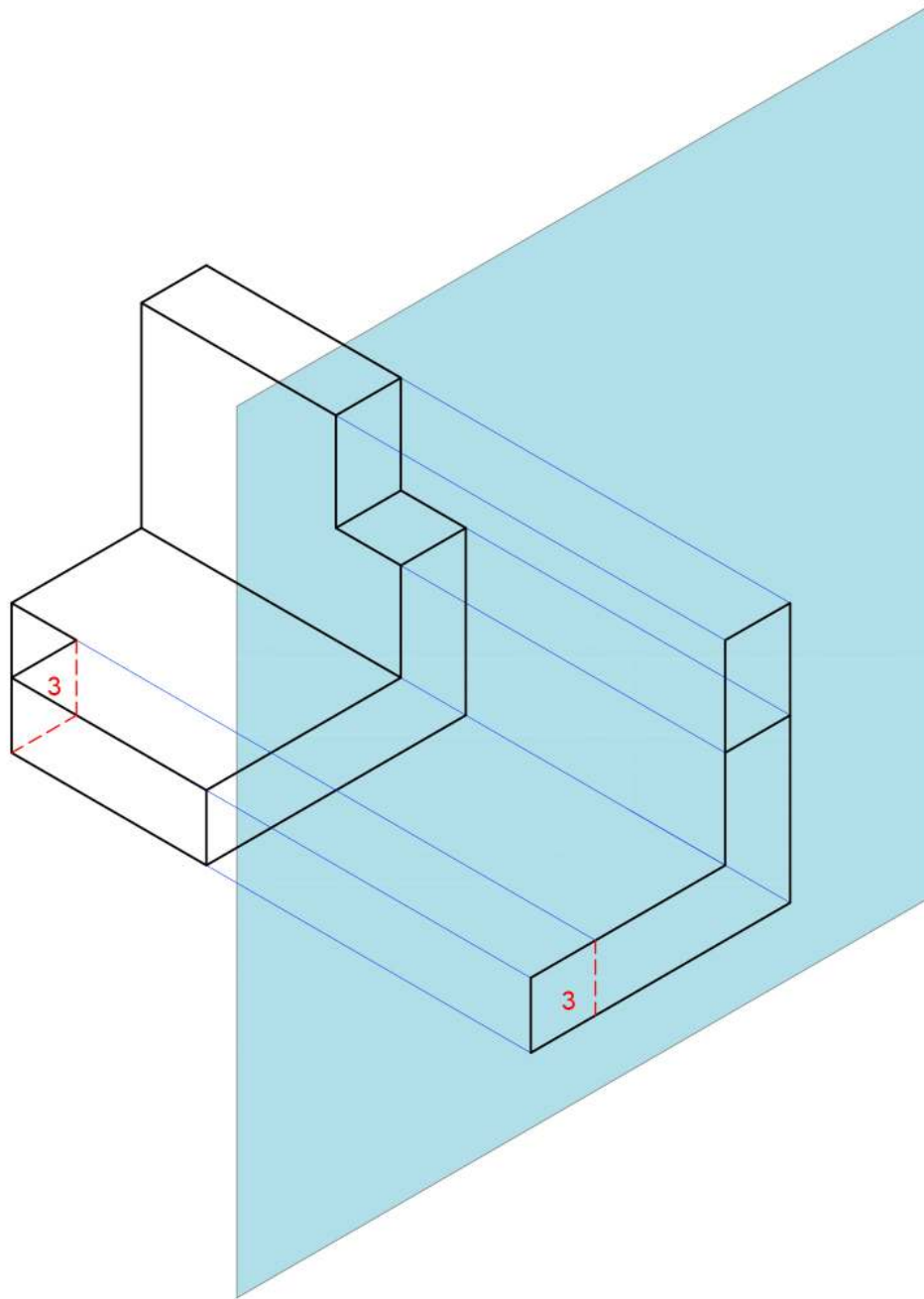


Figure 2.4.3: Surface 3 in right-side and left-side views.

If the object is modified by adding a circular hole through its lower portion, the edges of the hole must also be shown using hidden lines in the appropriate views (see Figure 2.4.4). In this example, the hole would appear as a hidden line in the front and right-side views. Since the hole is circular, its central axis is represented by a center line.

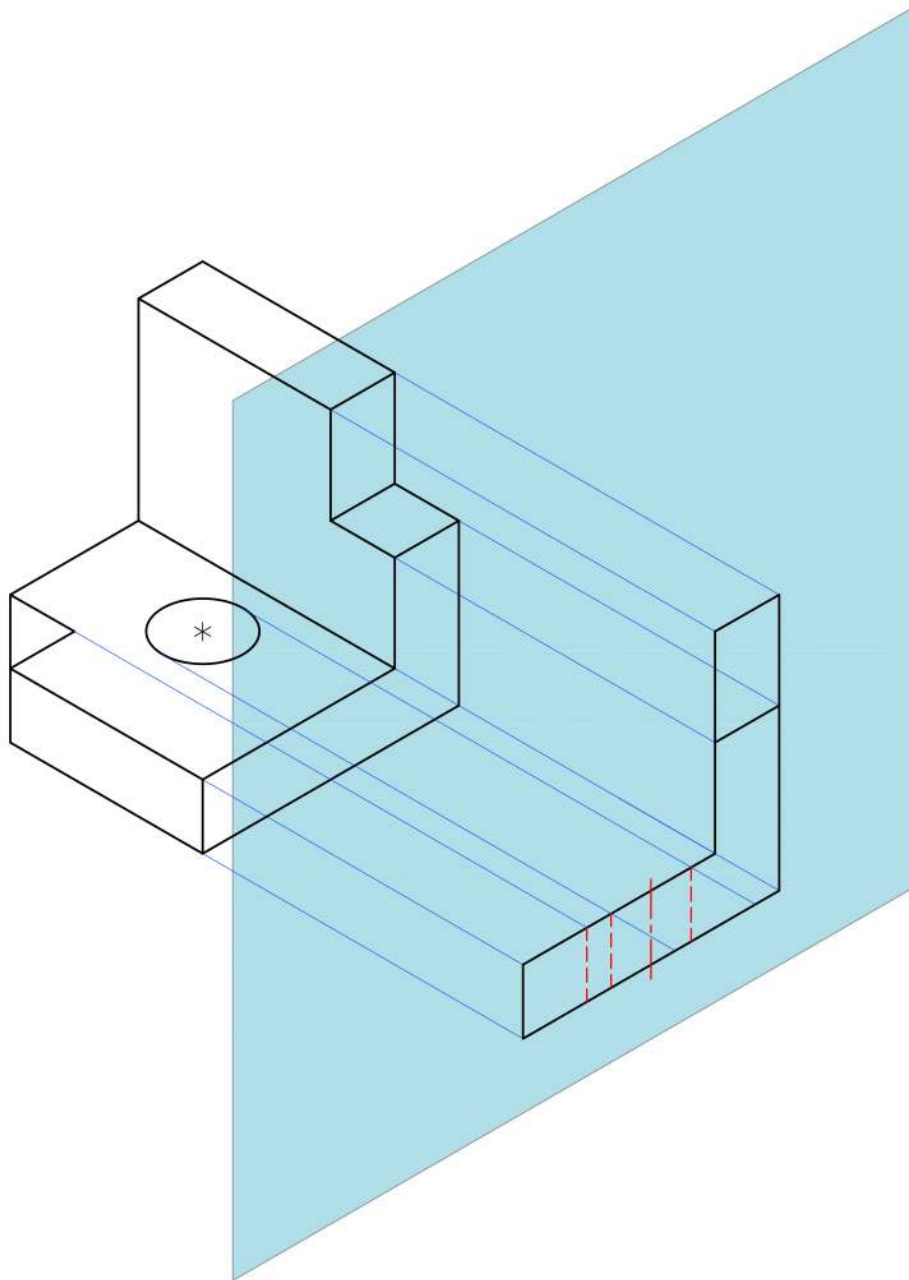


Figure 2.4.4: Circular hole in left-side view.

Note

Unlike center lines, hidden lines should not extend beyond the object's visible edges. Hidden lines represent actual edges of features that are not visible in a particular view and therefore must connect to the object's edges. They should not appear to "float" on the drawing sheet.

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2.5: Curved edges and surfaces in orthographic projections

Learning Objectives

By the end of this section, learners will be able to

1. Identify curved surfaces and edges in orthographic projections and multiview drawings.
2. Describe how curved surfaces are represented across different orthographic views.
3. Create multiview drawings of objects that feature curved edges and surfaces.

Curved edges and surfaces in orthographic projections can be challenging to interpret because they appear as straight lines in some views. This section explores why a curved edge may project as a straight line on an orthographic plane.

Consider the example of a cylinder, as shown in the figures below. As with previous examples, the object is imagined to be enclosed within a transparent glass box. Each face of this box represents one of the principal planes of projection. The object is projected onto these planes using parallel projectors perpendicular to the surfaces of the box.

To help describe and visualize this example in three dimensions, a Cartesian coordinate system is included. The x-axis represents the width, the y-axis represents the depth, and the z-axis represents the height. Any point in space can be described by its three coordinates (x,y,z).

As explained in previous book sections, each orthographic plane provides information about two of the three dimensions. For example, the frontal plane represents the width (x-axis) and the height (z-axis), but it does not provide any information about the depth (y-axis).

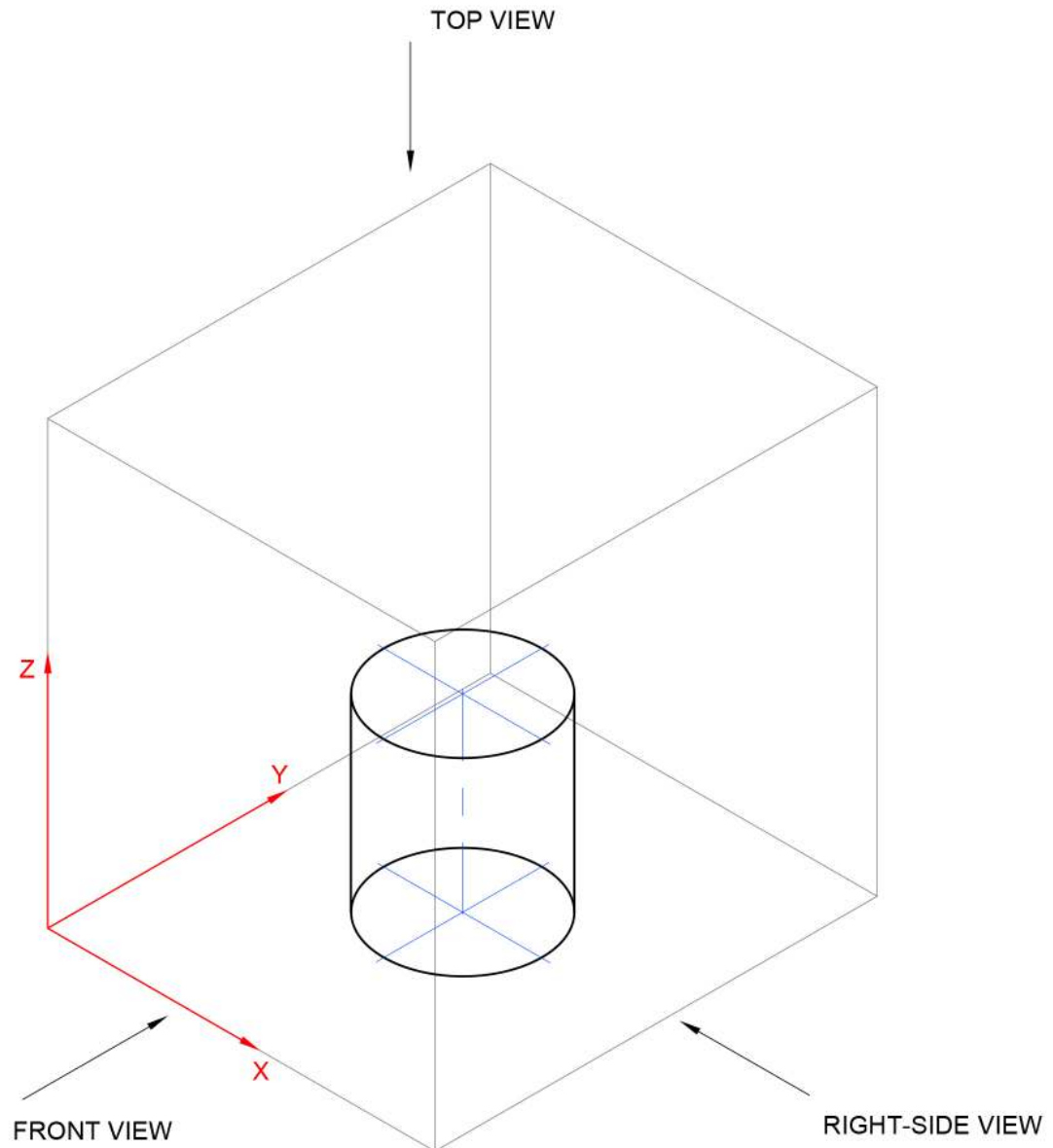


Figure 2.5.1: Cylinder contained in glass box.

The figures below illustrate how the front view of the cylinder is constructed. Four points along the curved top edge are highlighted, and their projections onto the frontal plane are shown. Observing how these points align on the plane helps explain why a curved edge appears as a straight line in an orthographic view.

Let us examine how the front view of a cylinder is constructed.

Four points along the curved top edge of the cylinder are marked in the images below. These points are then projected onto the frontal plane.

Figure 2.5.2 shows points 1 and 2 projected onto the frontal plane. On this plane, point 1 is defined by its width (coordinate x_1) and height (coordinate z_1). Point 2 has a different width (x_2) but shares the same height as point 1, with $z_1 = z_2$.

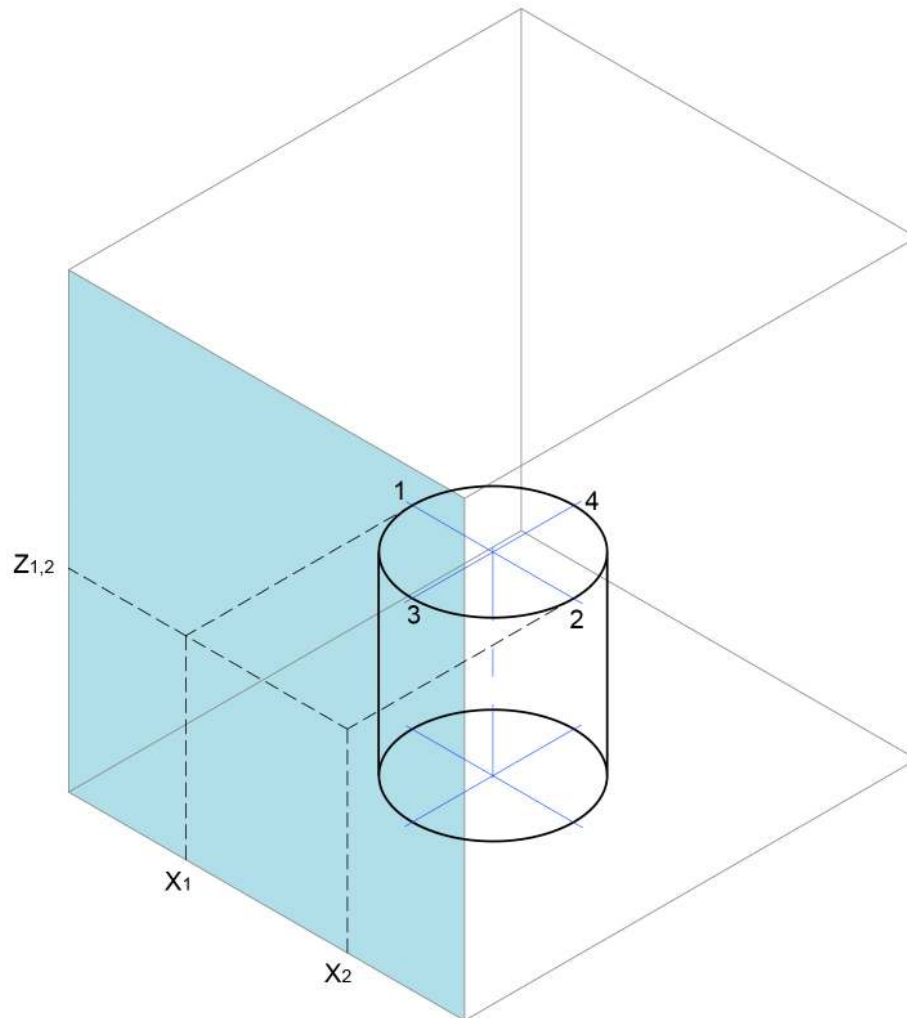


Figure 2.5.2: Projection of points 1 and 2 on the frontal plane.

Similarly, point 3 is projected on the frontal plane, with the width coordinate x_3 located between x_1 and x_2 , and the height coordinate z_3 equal to z_1 and z_2 , as shown in Figure 2.5.3. Point 4 overlaps with point 3 in the front view, with $x_4 = x_3$, and $Z_4 = Z_{3,2,1}$.

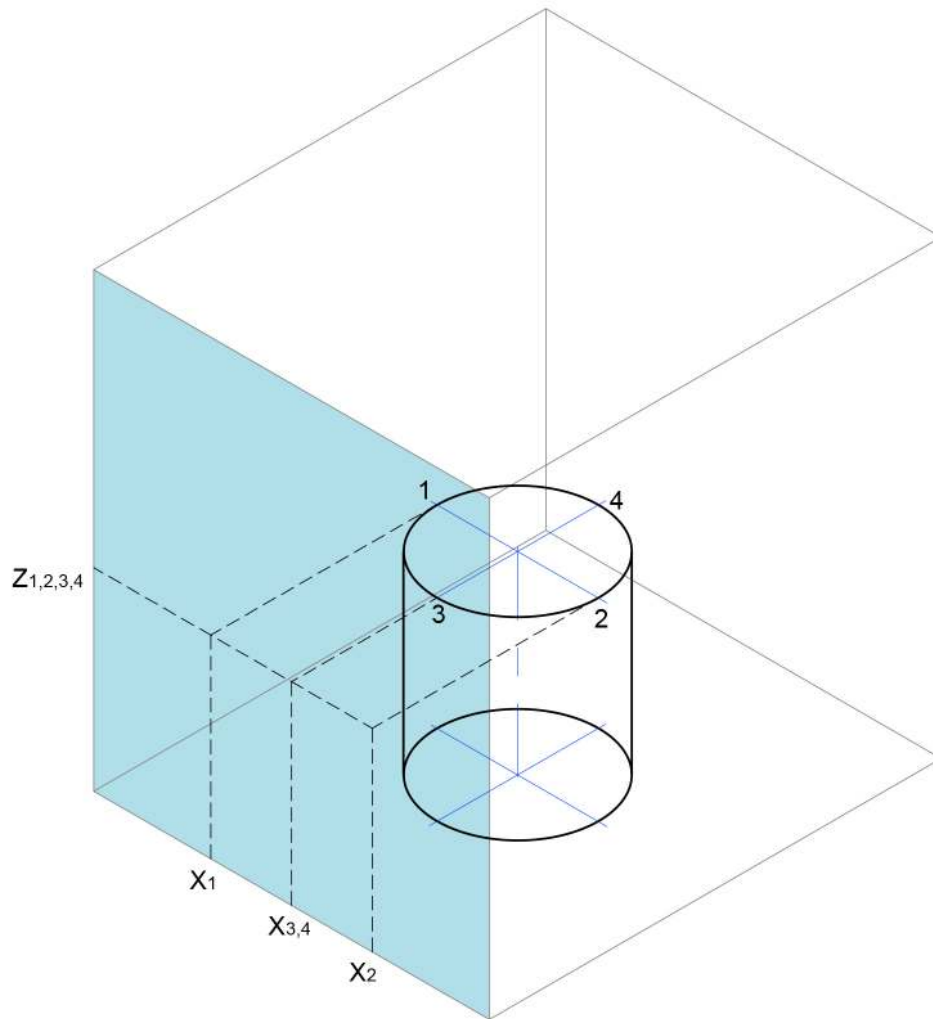


Figure 2.5.3: Projection of point 3 on the frontal plane.

Connecting points 1, 2, and 3 on the frontal plane, we obtain a straight line, since the front view does not capture the depth (y-values) of the original points located in a 3D space, as shown in figure 2.5.4. The curved edge appears straight due to the limitations of the two-dimensional representation.

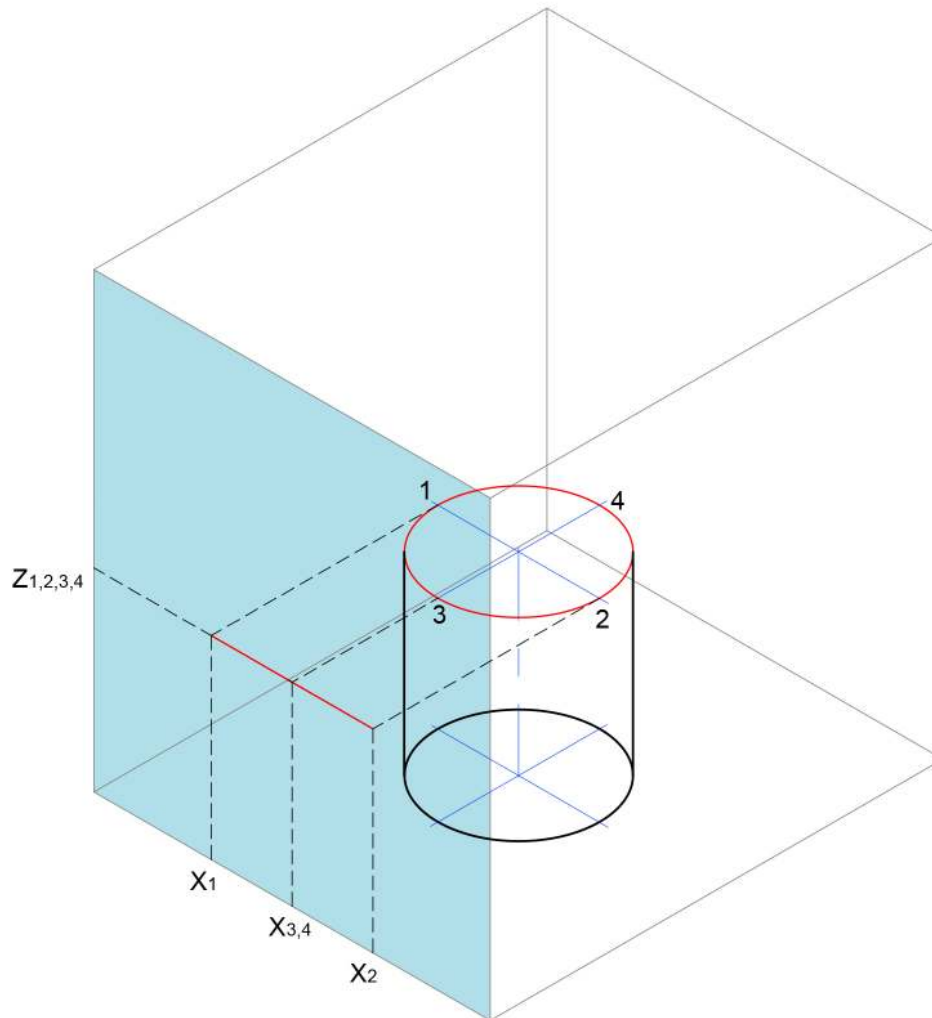


Figure 2.5.4: Projection of curved edge as a straight line on frontal plane.

Figure 2.5.5 shows the projections of the cylinder onto the top, front, and right-side planes. In the top view, which captures width (x) and depth (y), the circular shape of the cylinder becomes visible. In the front view, the cylinder shows as a rectangle, since the view does not provide information about the depth. Similarly, in the right-side view, the cylinder appears as a rectangle, since the width is not represented in the right-side view.

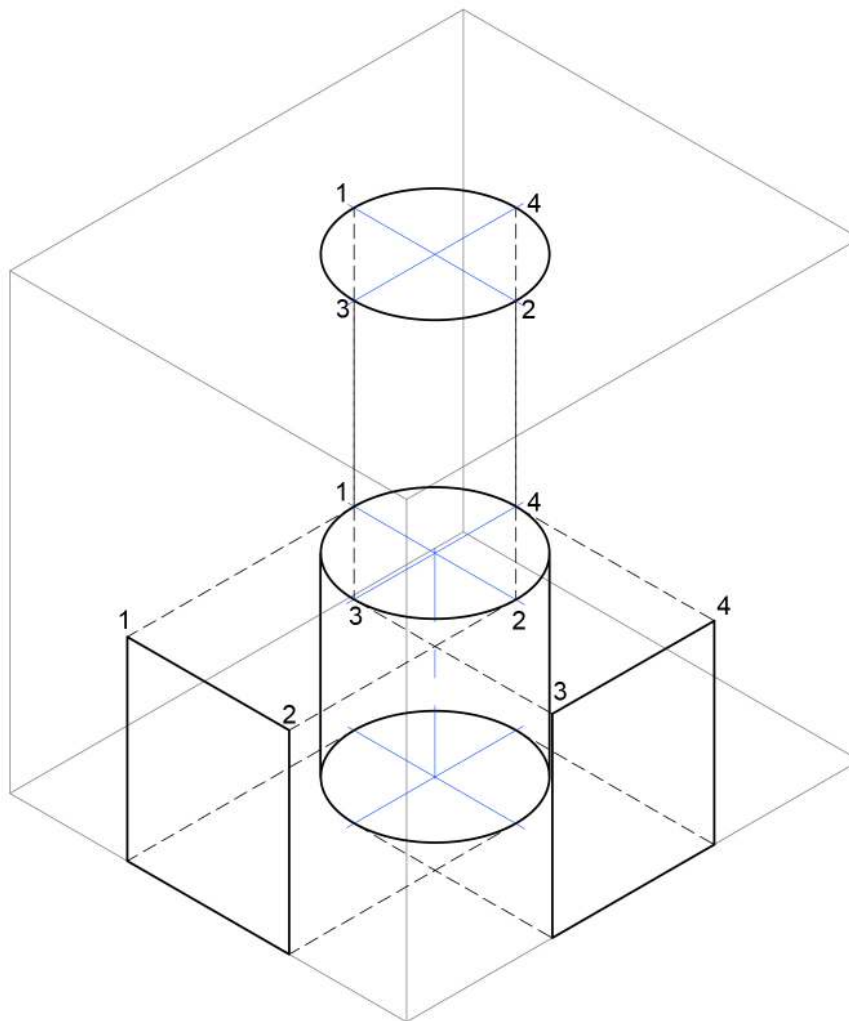


Figure 2.5.5: Top, front, and right-side views of the cylinder.

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2.6: Normal, inclined, and oblique surfaces

Learning Objectives

By the end of this section, learners will be able to

1. Distinguish between normal, inclined, and oblique surfaces in multiview drawings.
2. Identify normal, inclined, and oblique surfaces in orthographic views.
3. Create orthographic projections of normal, inclined, and oblique surfaces.

To correctly interpret orthographic projections, it is important to develop the ability to identify and distinguish normal (Figure 2.6.1a), inclined (Figure 2.6.1b), and oblique surfaces (Figure 2.6.1c). This section describes each surface type and explains how it appears in the standard views. Recognizing shape patterns in orthographic drawings is an important step in developing and strengthening spatial visualization skills.

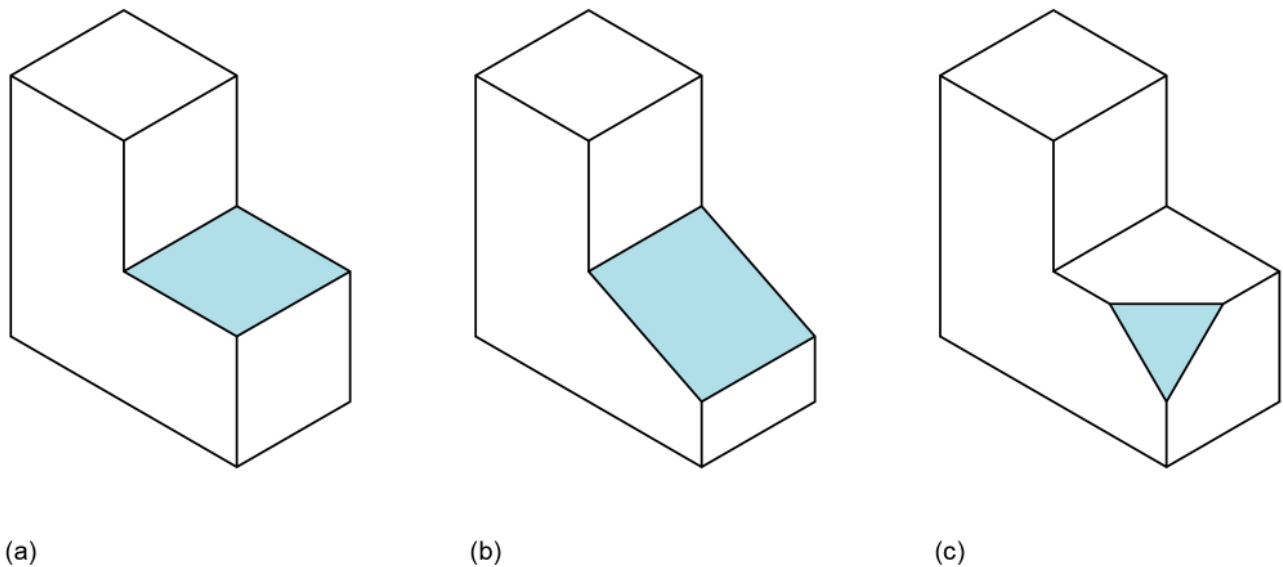


Figure 2.6.1: Normal (a), inclined (b), and oblique (c) surfaces.

Normal surfaces

A normal surface is parallel to one principal plane of projection and perpendicular to the other two. It appears in its true shape and size on the plane it is parallel to, and as an edge on the adjacent planes.

In Figure 2.6.2, the highlighted rectangular surface is parallel to the horizontal plane. In the top view, it appears as a rectangle in true size. In the front view, it appears as a horizontal edge, with vertices 1/2 and 4/3 aligned one behind the other. Similarly, in the right-side view, it will show as a horizontal line with vertices 4/1 and 3/2 aligned one behind the other.

Normal surfaces are generally the easiest to interpret in multiview drawings, because they show actual shape and size in one of the three standard views.

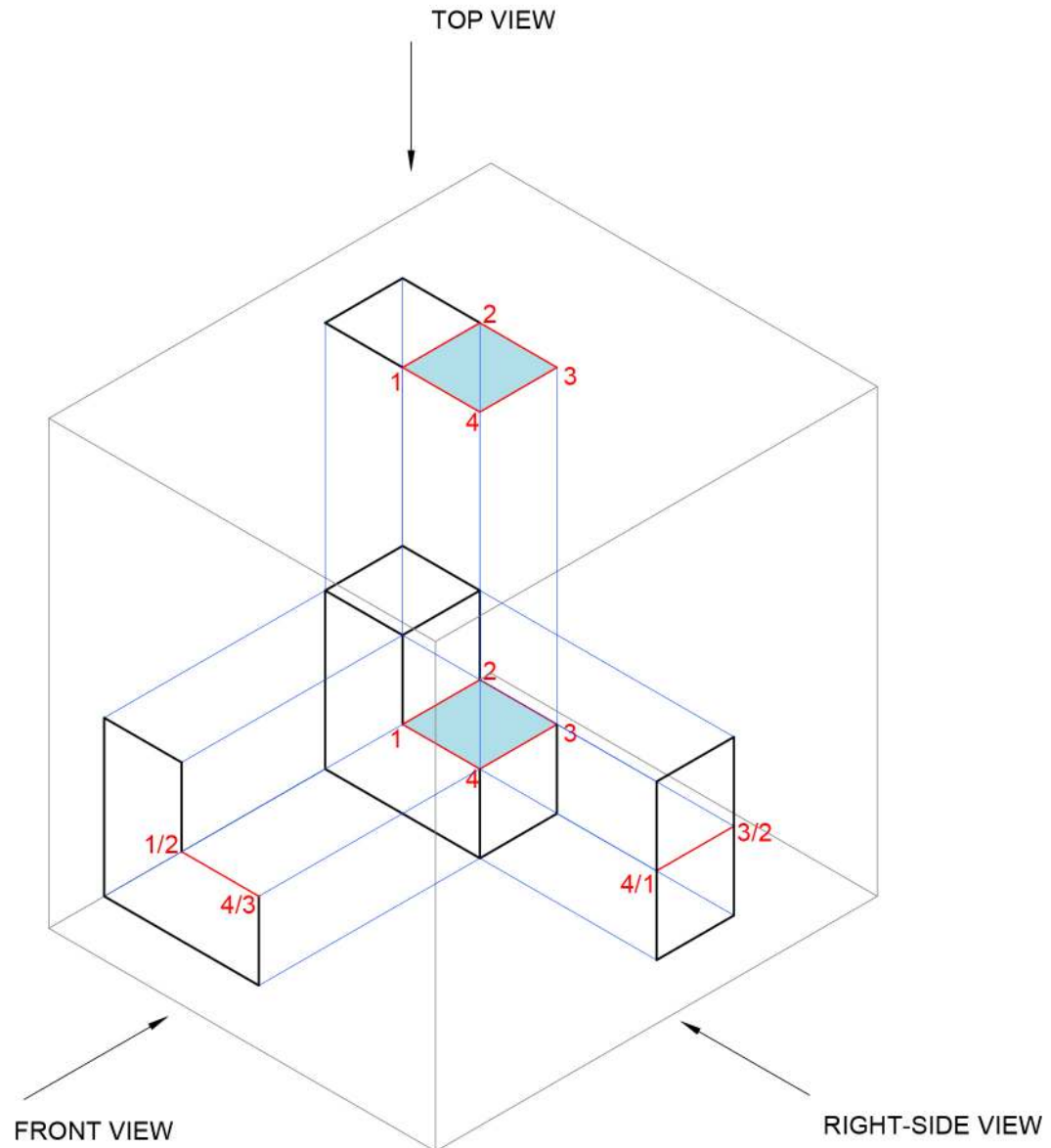


Figure 2.6.2: Projection of a normal surface parallel to the horizontal plane onto the top, front, and right-side views.

Inclined surfaces

An inclined surface is tilted to two of the principal planes and is perpendicular to the third. It appears foreshortened in the views to which it is inclined, and as a true-size edge in the view corresponding to the plane it is perpendicular to.

In Figure 2.6.3, vertices 3 and 4 of the highlighted rectangular surface from Figure 2.6.2 have been moved down along the direction of the z-axis to create an inclined surface. The surface is tipped relative to the horizontal and profile planes and appears foreshortened in the top and right-side views. Because it is perpendicular to the frontal plane, it appears as a true-size edge in the front view, with vertices 1/2 and 4/3 aligned one behind the other.

Note

The top views in Figures 2.6.2 and 2.6.3 are identical because only the height coordinate of vertices 3 and 4 was changed, while the width and depth coordinates remained the same. Since the top view shows width and depth but does not convey height, this change is not reflected in the top view. This example demonstrates why more than one orthographic view is necessary to interpret a three-dimensional object accurately.

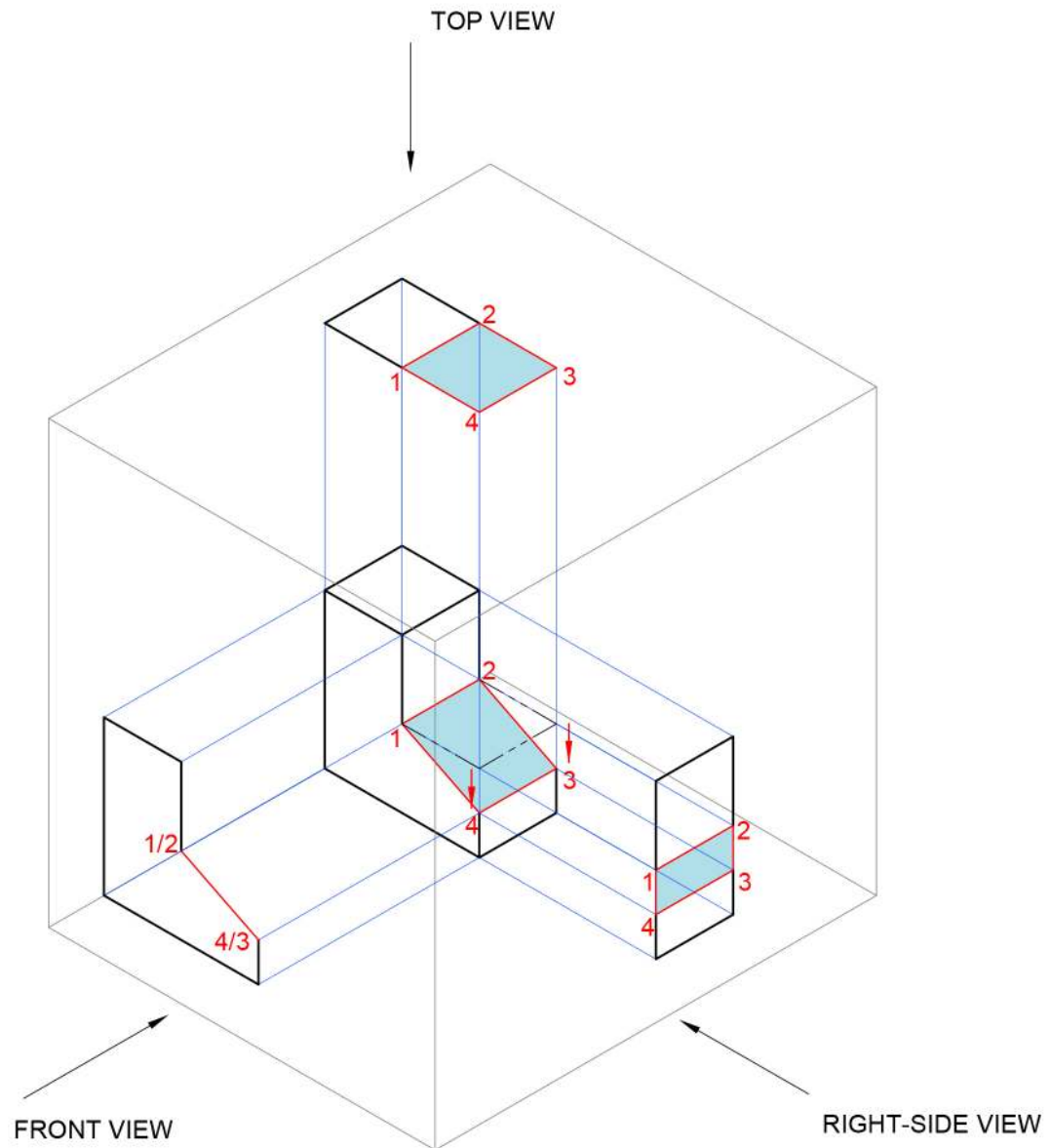


Figure 2.6.3: Projection of an inclined surface perpendicular the frontal plane onto the top, front, and right-side views.

Oblique surfaces

An oblique surface is tilted to all three principal planes. It appears foreshortened in every standard view and never shows its actual size. Oblique surfaces are often the most challenging to interpret.

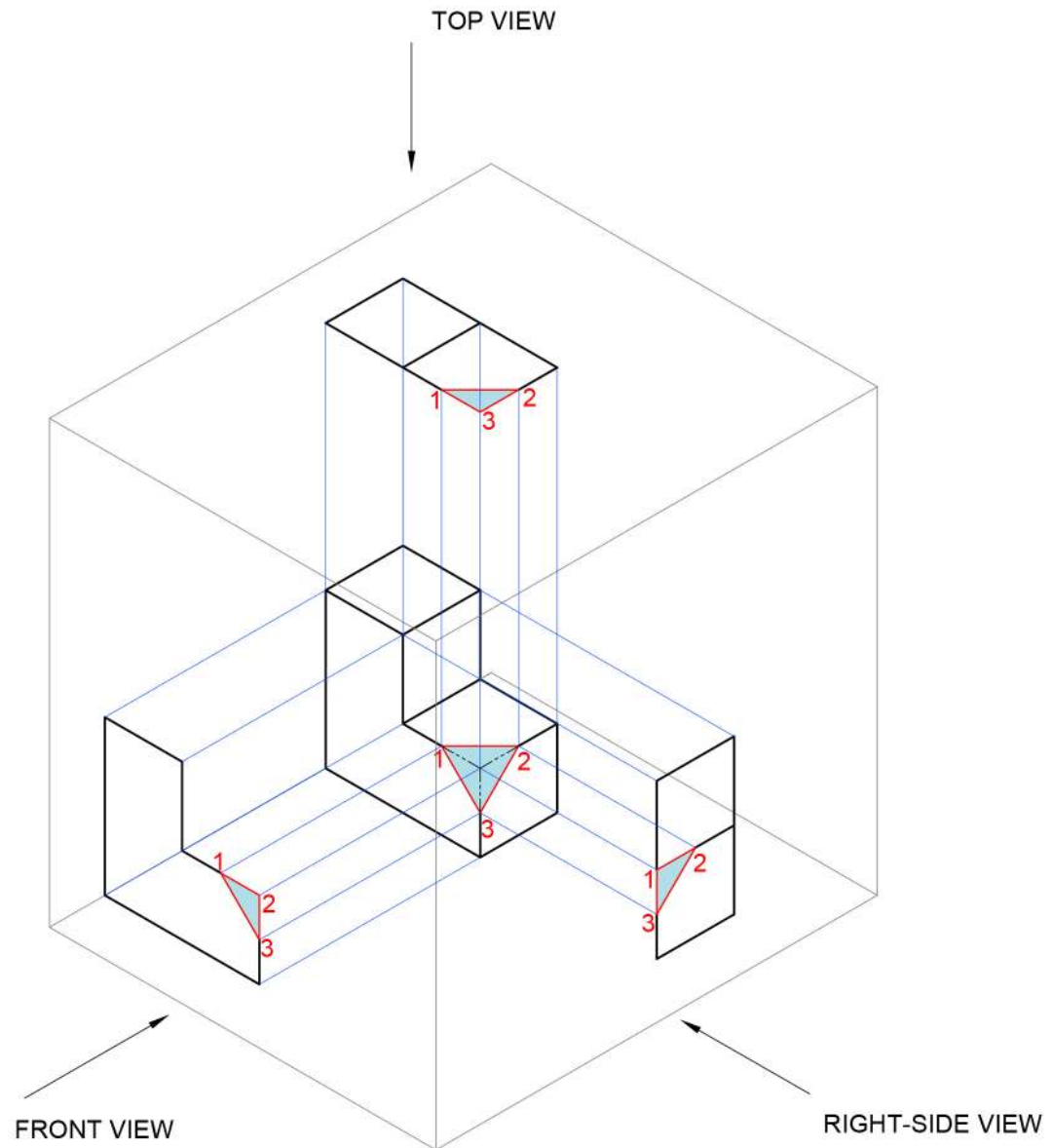
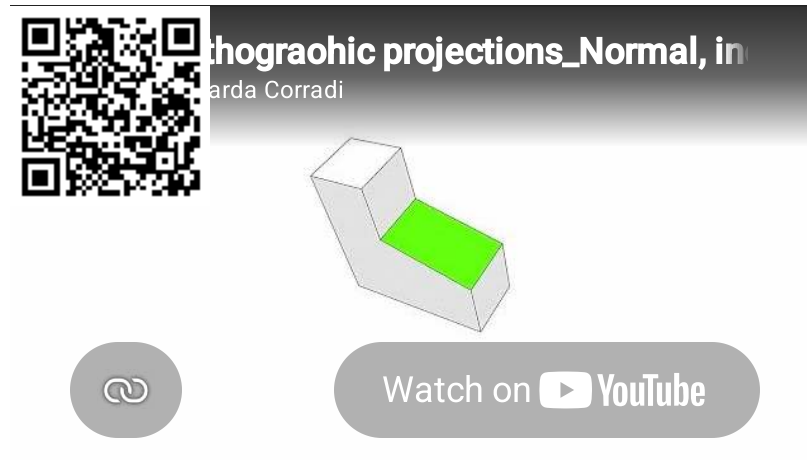


Figure 2.6.4: Projection of an oblique triangular surface onto the top, front, and right-side views.

Note

Even though inclined and oblique surfaces appear foreshortened, all their vertices and overall geometry remain visible in orthographic projections. For example, the surface in Figure 2.6.4 appears as a triangle in all principal views, with all three vertices shown in each view. Recognizing similar shapes and patterns across views is an important skill for correctly interpreting and constructing orthographic drawings.



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2.7: Exercises

This section presents exercises that apply the knowledge covered in Module B. All exercises include two sheets.

1. Exercise 1

- Sheet 1: Provides 3D images of six objects.
- Sheet 2: Create the top, front, and right-side views of the six objects.

2. Exercise 2

- Sheet 1: Provides six multiview drawings of different objects.
- Sheet 2: Using the given top, front, and right-side views, create 3D [isometric sketches](#) of the objects on the provided isometric grid.

3. Exercise 3

- Sheet 1: Provides incomplete multiview drawings of six objects. Some drawings are missing a view entirely, while others contain an incomplete view (e.g., missing visible or hidden edges).
- Task: Complete the missing or incomplete views in sheets 1, and then draw the isometric sketches for Exercises 1–4 in sheet 2.

Exercise 1: From 3D to 2D views

Using Sheet 2, draw top, front and right-side views of objects depicted in sheet 1 (exercises 1-6).

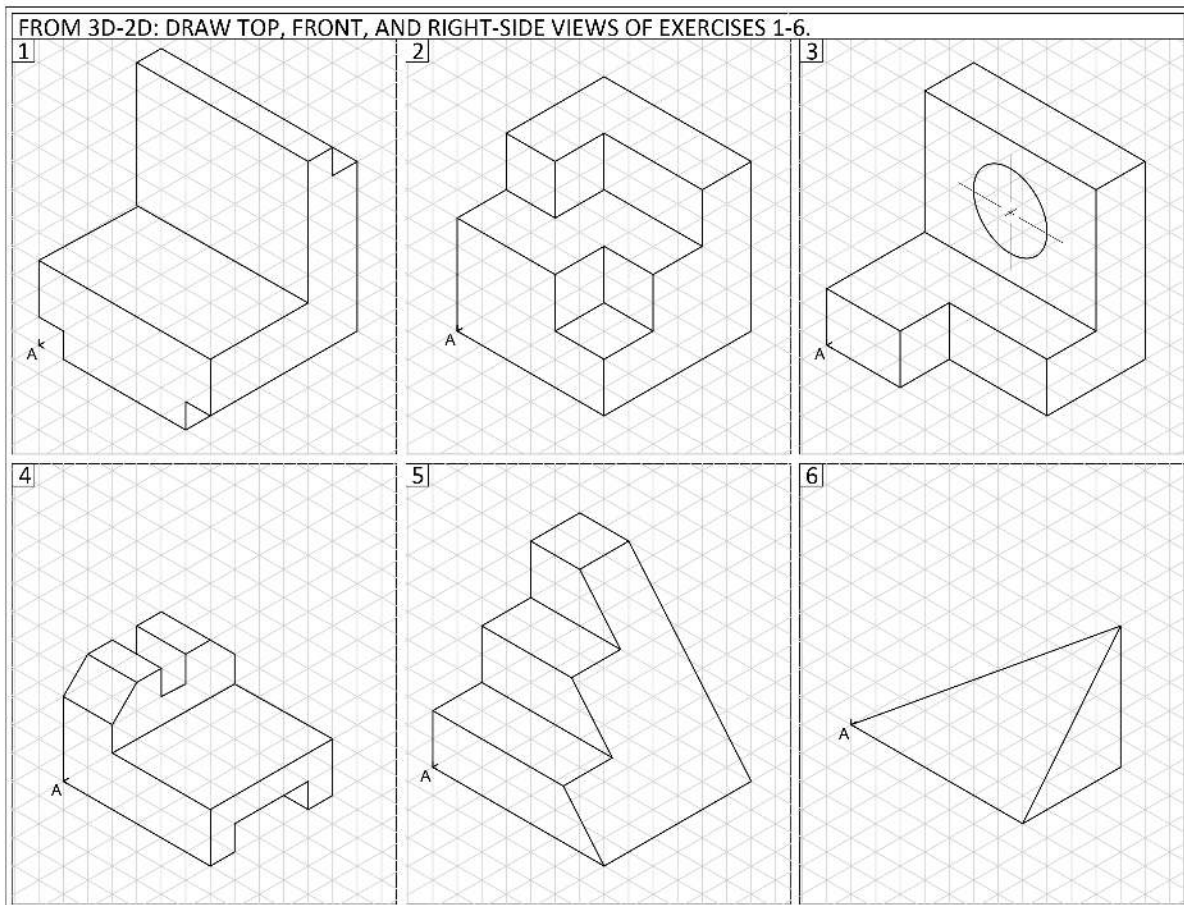


Figure 2.7.1: Exercise 1: Sheet 1_Isometric views of 6 objects

1 <!-- Isometric axes --> A^L A^L A^L	2 <!-- Isometric axes --> A^L A^L A^L	3 <!-- Isometric axes --> A^L A^L A^L
4 <!-- Isometric axes --> A^L A^L A^L	5 <!-- Isometric axes --> A^L A^L A^L	6 <!-- Isometric axes --> A^L A^L A^L
NAME: _____ DATE: _____		

Figure 2.7.2: Exercise 1: Sheet 2

Exercise 2: From 2D views to 3D isometric sketches.

On sheet 2, draw isometric sketches of exercises 1-6 illustrated in sheet 1. Completed top, front and right-side views of each object are provided in sheet 1.

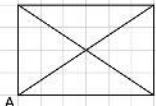
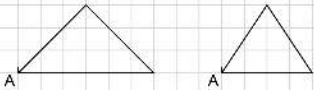
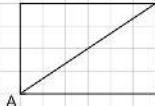
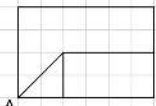
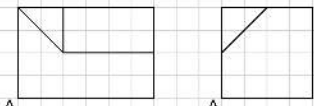
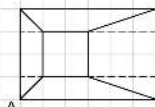
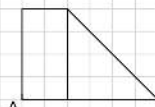
FROM 2D-3D: SKETCH ISOMETRIC DRAWINGS OF EXERCISES 1-6 (VIEWS ARE COMPLETE).		
1  A  A	2  A  A	3  A  A
4  A  A	5  A  A	6  A  A
NAME:		DATE:

Figure 2.7.3: Exercise 2: Sheet 1_Top, front, and right-side views of 6 objects

1 A	2 A^k	3 A^k
4 A^k	5 A^k	6 A^k
NAME:		DATE:

Figure 2.7.4: Exercise 2: Sheet 2

Exercise 3: complete isometric views and draw 3D sketches.

On Sheet 1, complete the views for Exercises 1–6. In each exercise, one of the three orthographic views is either missing (for example, in Exercise 2 the front view is missing) or incomplete (for example, in Exercise 1 the top view is incomplete).

1. Identify which views are missing or incomplete in each exercise and complete them.
2. Using the isometric grid provided on Sheet 2, sketch the isometric drawings for Exercises 1–4.
3. (Optional): Exercises 5 and 6 contain curved surfaces. Learners are encouraged to try sketching their isometric drawings as well for additional practice. Keep in mind that these will be more challenging, since curved surfaces appear as ellipses in isometric drawings.

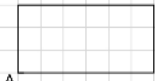
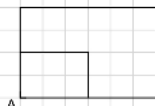
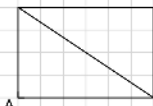
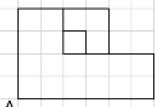
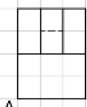
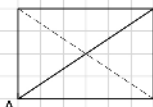
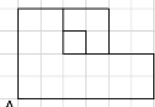
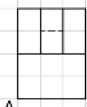
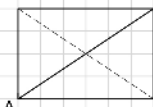
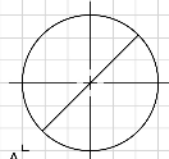
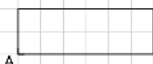
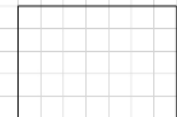
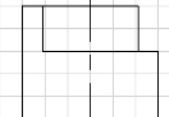
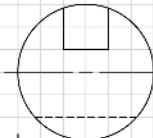
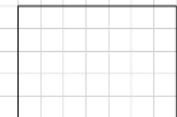
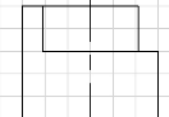
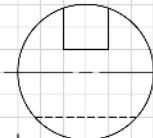
COMPLETE VIEWS (1 VIEW IS INCOMPLETE) OF EXERCISES 1-6. SKETCH ISOMETRIC DRAWINGS OF EXERCISES 1-4.					
1		2		3	
 A		 A		 A	
 A		 A		 A	
 A		 A		 A	
4		5		6	
 A		 A		 A	
 A		 A		 A	
 A		 A		 A	
NAME:		DATE:			

Figure 2.7.5: Exercise 3: Sheet 1_Incomplete orthographic views of 6 objects

1 A^k	2 A^k	3 A^k
4 A^k	5	6
NAME:		DATE:

Figure 2.7.6: Exercise 3: Sheet 2

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CHAPTER OVERVIEW

3: Module C - Auxiliary views, section views, isometric, and oblique projections

[3.1: Auxiliary views](#)

[3.2: Section Views](#)

[3.3: Isometric projections](#)

[3.4: Oblique projections](#)

[3.5: Exercises](#)

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3.1: Auxiliary views

Learning Objectives

By the end of this section, learners will be able to

1. Describe the purpose and application of primary and secondary auxiliary views.
2. Distinguish between depth, width, and height in auxiliary views.
3. Explain the role of the reference plane and demonstrate how to place it effectively to simplify the construction of auxiliary views.
4. Identify and represent hidden edges in auxiliary views.
5. Create a primary auxiliary view of a surface or a complete object.

Auxiliary views are orthographic views that are not standard views (top, front, and side views). They are used to visualize inclined or oblique surfaces in their true shape and size.

A surface appears in its true shape only when it is projected onto a plane that is parallel to it using perpendicular projectors. As discussed in [Module B, section 2.6: Normal, inclined, and oblique surfaces](#), a normal surface appears true shape and size on the plane it is parallel to, while inclined and oblique surfaces appear foreshortened. An auxiliary plane is a plane of projection that is inclined or oblique relative to the standard planes, and it is used to describe inclined or oblique surfaces in their true shape and dimensions.

Figure 3.1.1 illustrates the glass box with one plane replaced by an auxiliary plane.

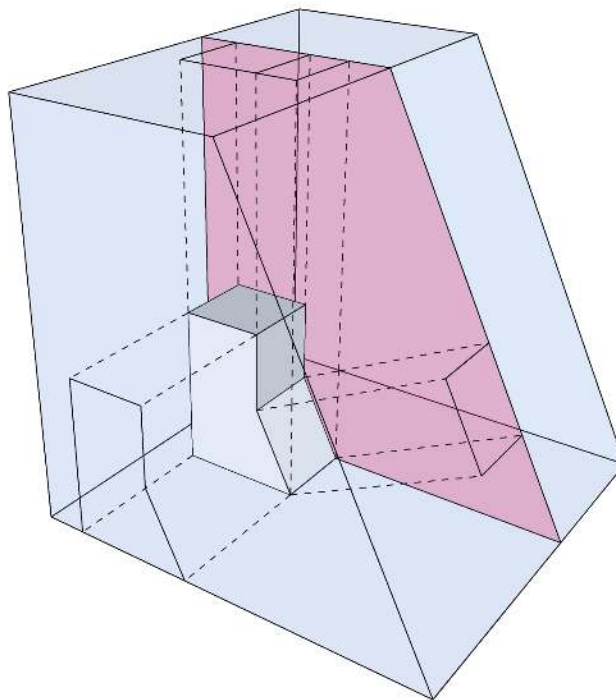


Figure 3.1.1: Auxiliary plane visualized in the glass box.

In a **primary auxiliary view**, the plane of projection is inclined to two standard planes and perpendicular to the third. Primary auxiliary views are projected from the perpendicular standard view and are used to show inclined surfaces in their true shape and dimensions.

Secondary auxiliary views are projected from primary auxiliary views and are used to show oblique surfaces in their true shape and size. Succeeding auxiliary views can be drawn from secondary auxiliary views.

This section focuses on primary auxiliary views.

Depth, width, and height auxiliary views

Auxiliary views are named according to the dimension that is transferred onto the auxiliary plane and shown in the resulting auxiliary view: depth, width, or height. Understanding depth, width, and height auxiliary views is essential for interpreting and creating auxiliary views.

A primary auxiliary plane is an inclined plane of projection; by definition, it is tipped relative to two principal planes and perpendicular to the third standard plane of projection.

- A **depth auxiliary** view is perpendicular to the frontal plane, and the dimension shown on the auxiliary view is the depth. Figure 3.1.2 shows the glass box with a depth auxiliary plane highlighted (in red) perpendicular and hinged to the frontal plane. A depth auxiliary view is projected from the front view, and the unfolded glass box shows how the depth can be transferred from the top view to the auxiliary plane. Although Figure 3.1.2 shows one example of a depth auxiliary plane, an infinite number of planes perpendicular to the front view could be constructed.

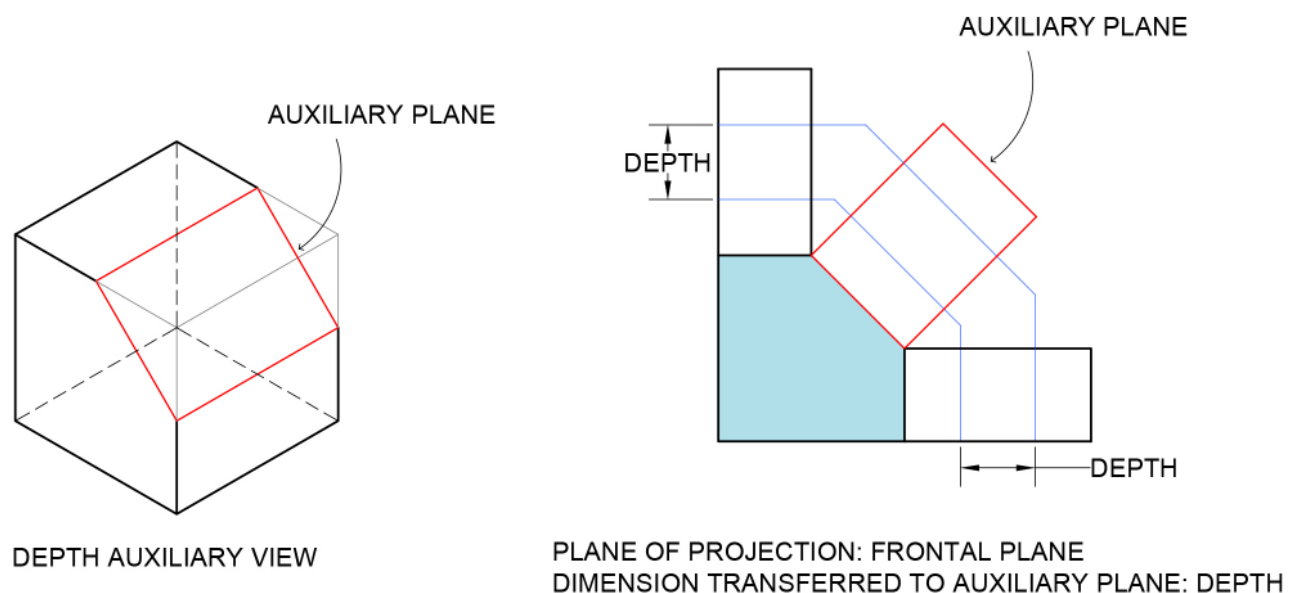
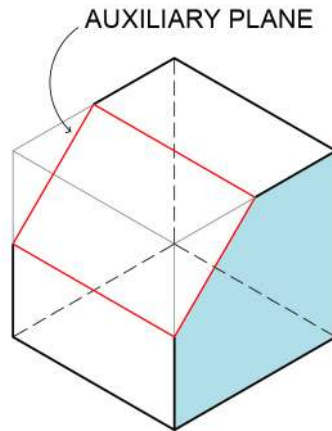
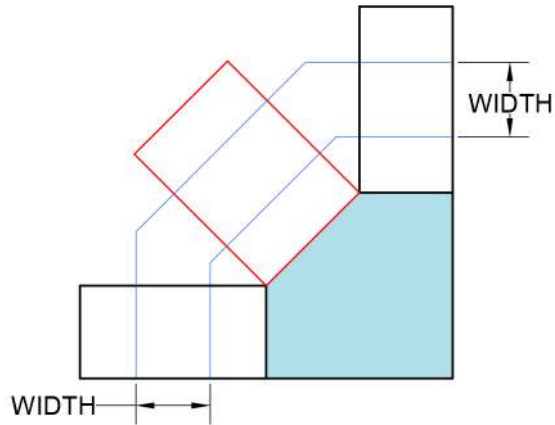


Figure 3.1.2: Depth auxiliary plane.

- A **width auxiliary** view is perpendicular to the profile plane, and the dimension shown on the auxiliary view is the width. Figure 3.1.3 shows the glass box with a width auxiliary plane (in red) perpendicular to and hinged to the profile plane. A depth auxiliary view is projected from the right-side view, and the unfolded glass box shows how the width can be transferred from the front and top views on the auxiliary plane. As with depth, infinitely many width auxiliary planes could be drawn.



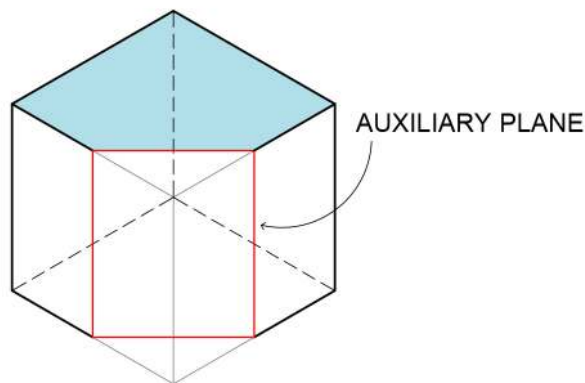
WIDTH AUXILIARY VIEW



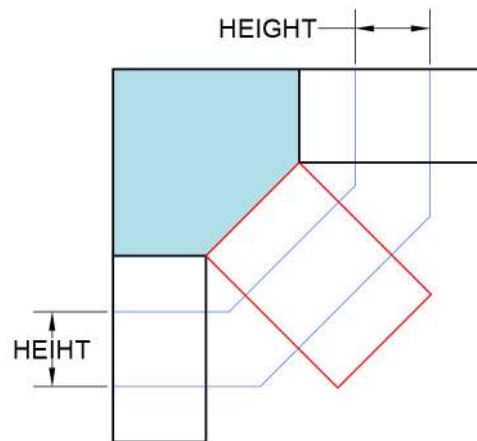
PLANE OF PROJECTION: PROFILE PLANE
DIMENSION TRANSFERRED TO AUXILIARY PLANE: WIDTH

Figure 3.1.3: Width auxiliary plane.

- A **height auxiliary view** is perpendicular to the horizontal plane, and the dimension shown on the auxiliary view is the height. Figure 3.1.4 shows the glass box with a height auxiliary plane (in red) perpendicular to and hinged to the horizontal plane. A height auxiliary view is projected from the top view. The unfolded glass box shows how the height can be transferred from the front view to the auxiliary plane. Similar to the depth and width auxiliary views, there are an infinite number of auxiliary planes perpendicular to the top view.



HEIGHT AUXILIARY VIEW



PLANE OF PROJECTION: HORIZONTAL PLANE
DIMENSION TRANSFERRED TO AUXILIARY PLANE: HEIGHT

Figure 3.1.4: Height auxiliary plane.

The reference plane

Another important concept in creating auxiliary views is the reference plane. The reference plane is always parallel to the plane of projection and perpendicular to the auxiliary plane. It is positioned so that it either touches or passes through the object.

The reference plane is used to transfer the depth, width, or height onto the auxiliary plane. The advantage of using a reference plane is that it reduces the number of measurements needed, since some vertices lie directly on the reference plane.

- In a **depth auxiliary view**, the reference plane is parallel to the frontal plane. It can be located at any position in space along the depth direction (the y-coordinate in the figure below). It appears as a horizontal edge in the top view and as an edge perpendicular to the line of sight in the auxiliary view.

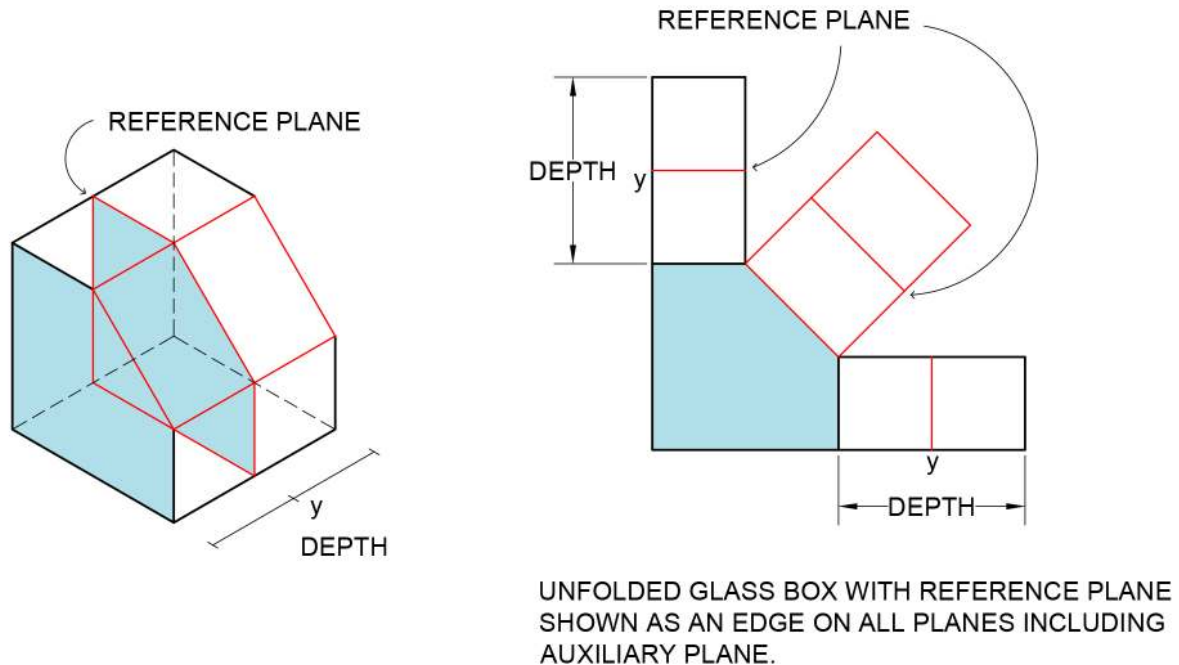
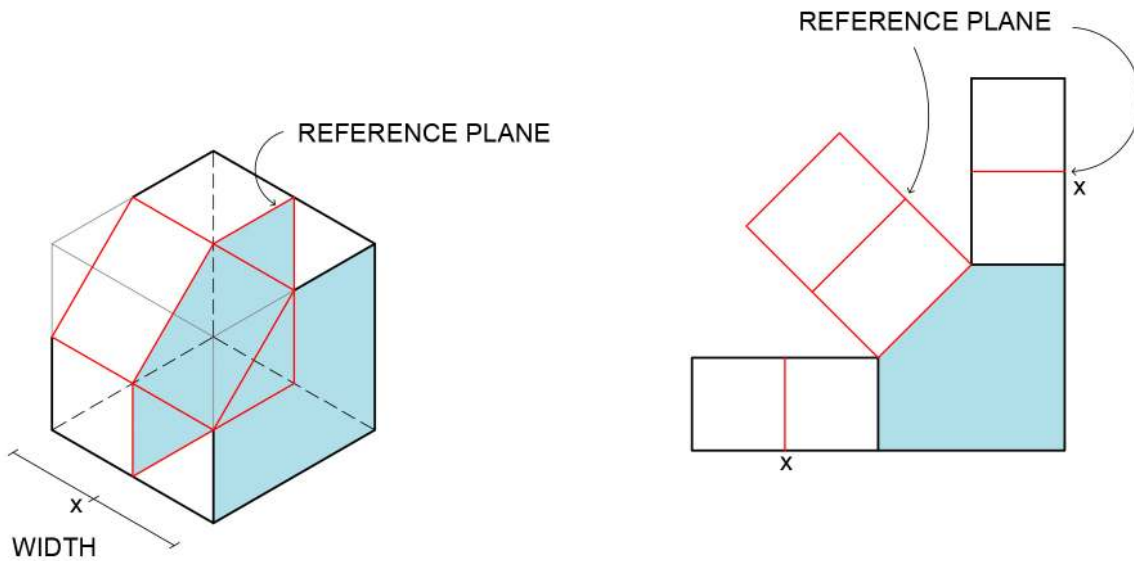


Figure 3.1.5: Reference plane shown in a depth auxiliary view.

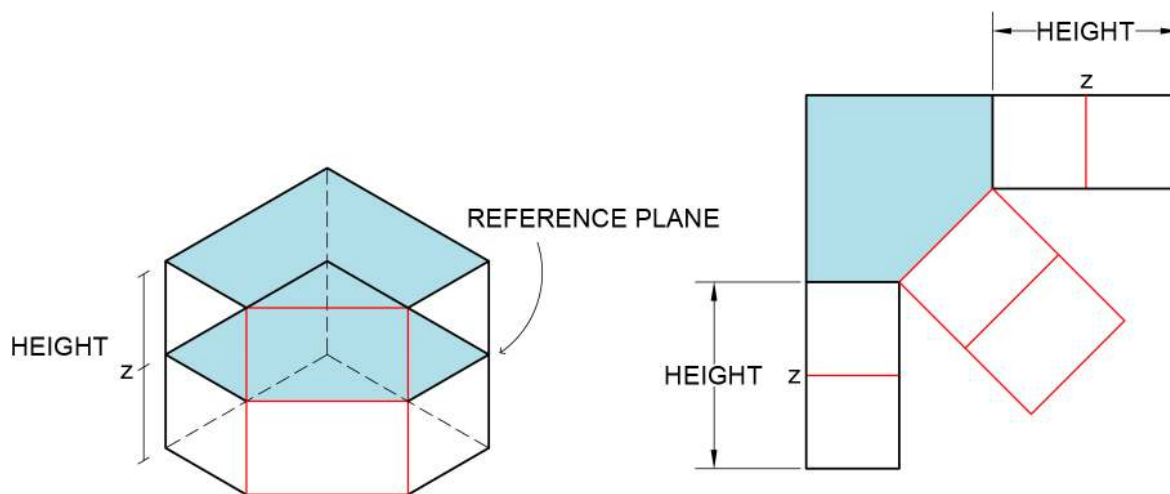
- In a **width auxiliary view**, the reference plane is parallel to the profile plane. It can be located at any position in space along the width direction (the x-coordinate in the figure below). It appears as a vertical edge in the front view and as an edge perpendicular to the line of sight in the auxiliary view..



UNFOLDED GLASS BOX WITH REFERENCE PLANE SHOWN AS AN EDGE ON ALL PLANES INCLUDING AUXILIARY PLANE.

Figure 3.1.6: Reference plane shown in a width auxiliary view.

- In a **height auxiliary view**, the reference plane is parallel to the horizontal plane. It can be located at any position in space along the height direction (the z-coordinate in the figure below). It appears as a horizontal edge in the front view and as an edge perpendicular to the line of sight in the auxiliary view.



GLASS BOX UNFOLDED WITH REFERENCE PLANE SHOWN AS AN EDGE ON ALL PLANES INCLUDING AUXILIARY PLANE

Figure 3.1.7: Reference plane shown in a height auxiliary view.

Example

The example below shows a step-by-step procedure for constructing an auxiliary view.

The interactive model shows the setup for this example, including the glass box, the auxiliary plane, and the reference plane. An object, shown in green, is placed inside the glass box. The object has one inclined surface (P), and the auxiliary plane is aligned parallel to this surface. In this case, the reference plane (shown in red) is positioned against the object's rear face. Rotating the model makes it possible to view the object, the reference plane, the glass box, and the auxiliary plane in three dimensions. The QR code in the lower-right corner can be used to open the visualization on an external device.

1. **Define the line of sight:** Figure 3.1.8 shows a top and front view of the object. In this example, the line of sight is chosen perpendicular to the inclined surface P. Surface P is an inclined surface, perpendicular to the frontal plane, and appears as a full length edge in the front view.

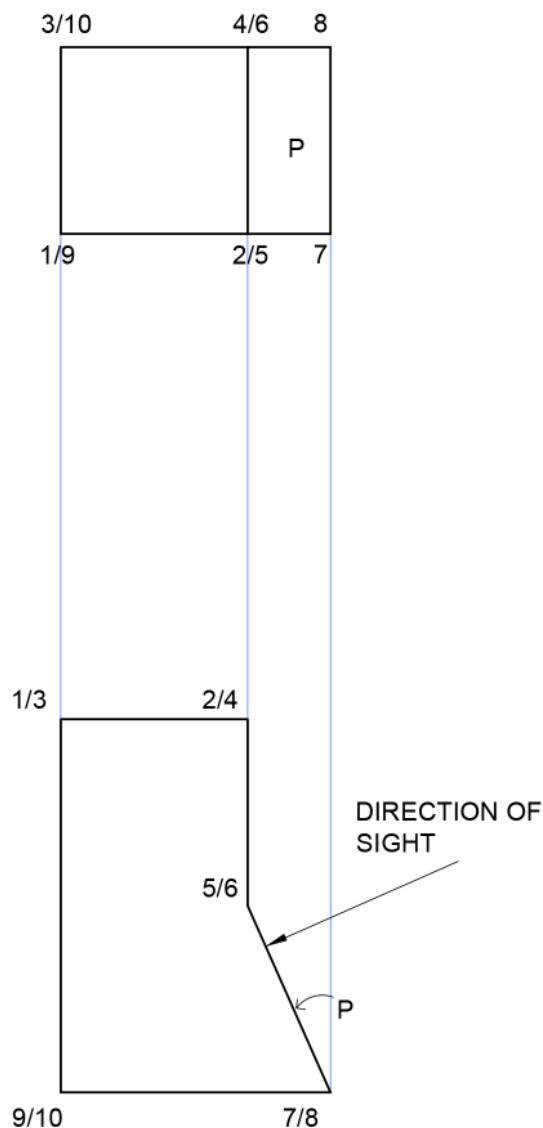


Figure 3.1.8: Front and top views and direction of site for auxiliary view.

2. **Identify the type of auxiliary view:** Determine whether the auxiliary view is a depth, width, or height view. In this example, the frontal plane is the projection plane that is perpendicular to the auxiliary plane. Therefore, this exercise illustrates a depth auxiliary view.

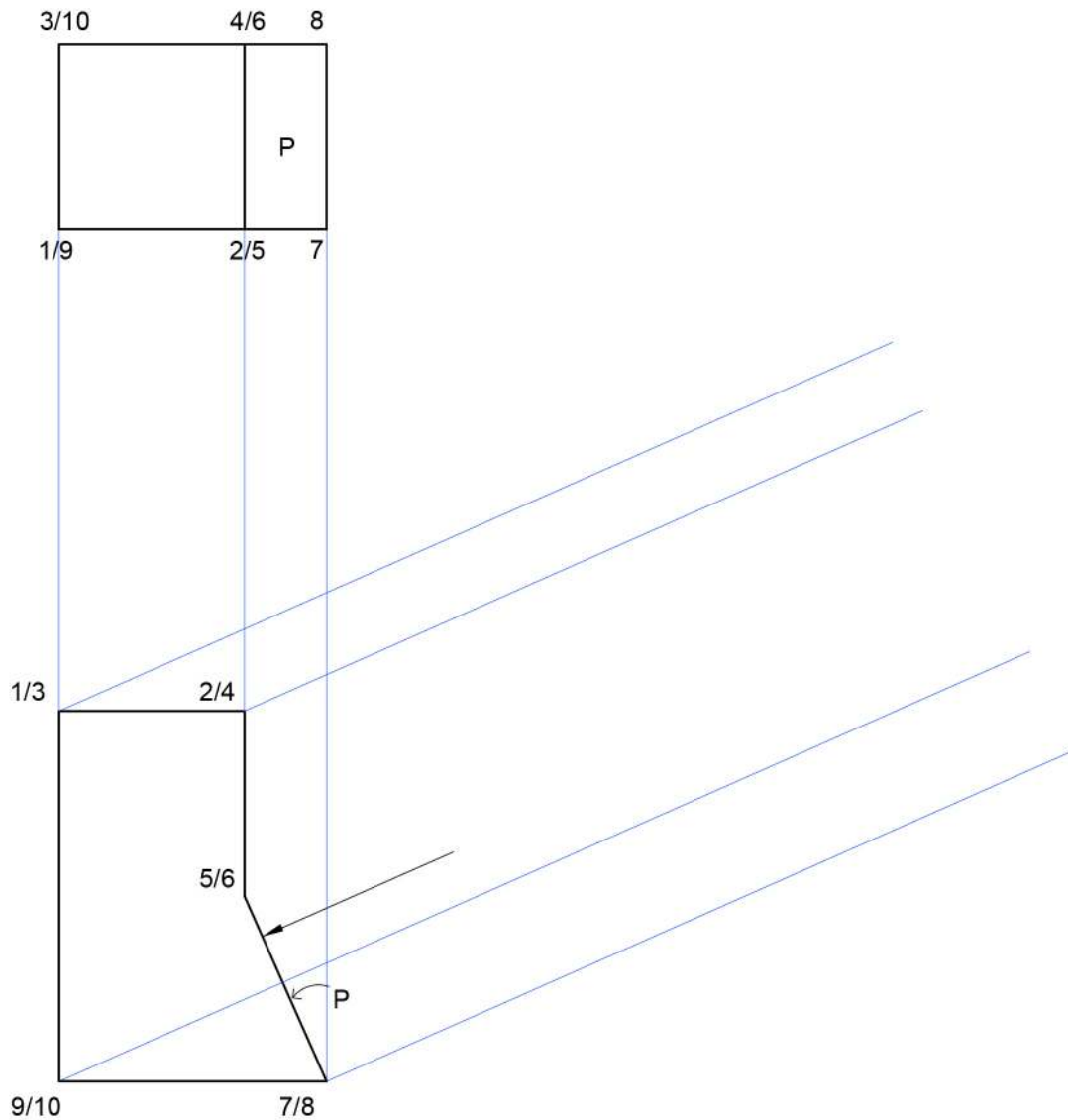


Figure 3.1.9: Vertices are projected on the auxiliary plane from the front view using projectors parallel to the line of sight.

3. **Place the reference plane:** There is not a single correct way to position a reference plane, but it is typically placed so that several vertices of the object lie on it. In this example, the reference plane is positioned against the rear surface, with vertices 3, 10, 4, 6, and 8 lying on the plane. Because the reference plane is parallel to the frontal plane, it appears as a horizontal edge in the top view. In the auxiliary view, the reference plane is shown perpendicular to the line of sight.

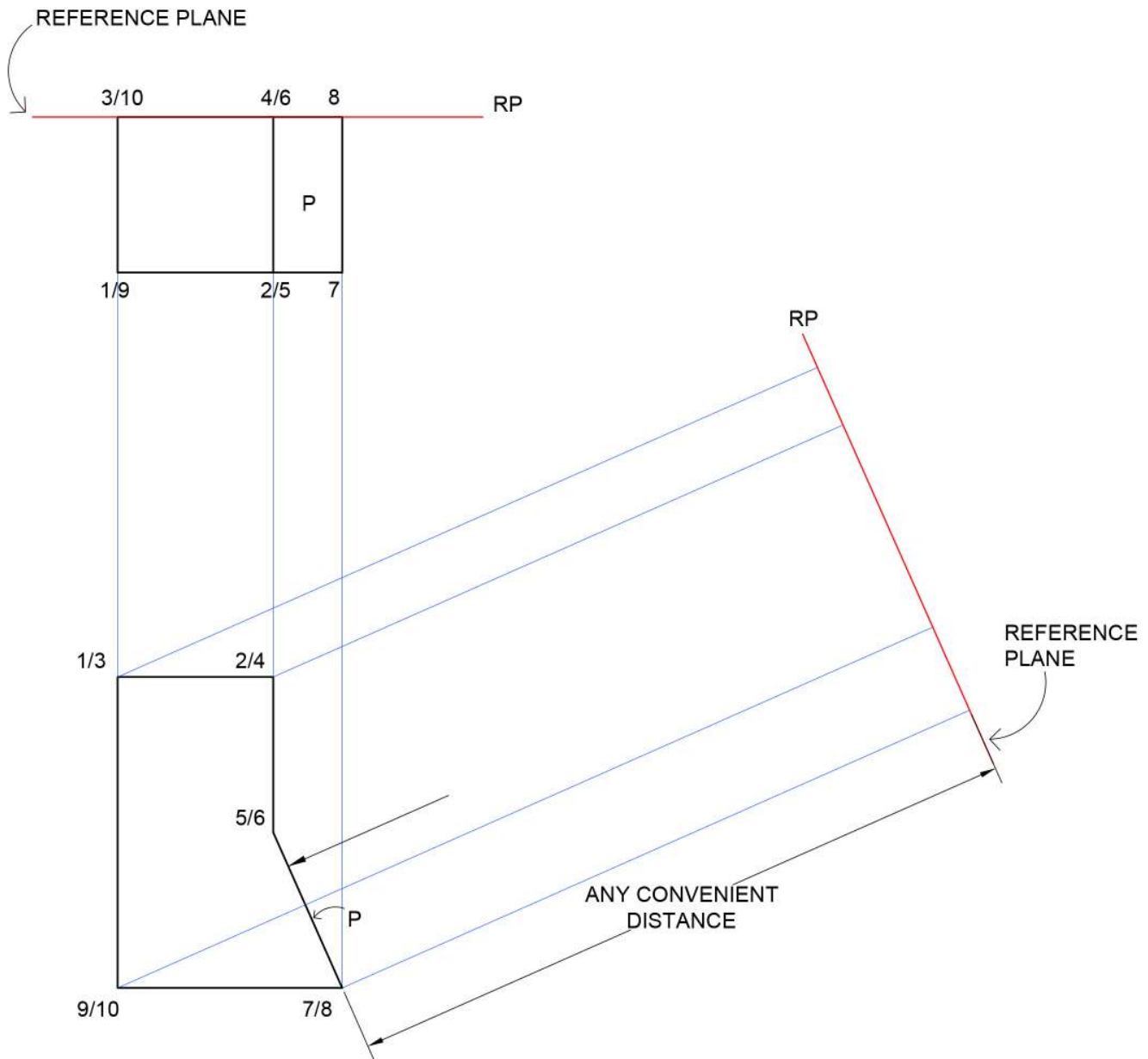


Figure 3.1.10: Reference plane seen as an edge on top and auxiliary views.

4. Project vertices from the plane of projection and transfer depth: In this example, the frontal plane is the plane of projection. The vertices of surface P are projected from the front view; for instance, vertices 7 and 8 lie along the same projector. To determine their exact positions along the projector, the depth must be transferred from the top view. The reference plane can be used to measure depth. For example, vertex 8 lies on the reference plane, so its location is at the intersection of the projector and the reference plane. Vertex 7 is located along the same projector at a distance equal to the object's depth. Similarly, vertices 6 and 5 lie on the same projector, with vertex 6 on the reference plane and vertex 5 positioned at a distance corresponding to the object's depth from the reference plane and vertex 6.

Figure 3.1.11 shows the inclined surface P in its true shape and size as seen in the auxiliary view.

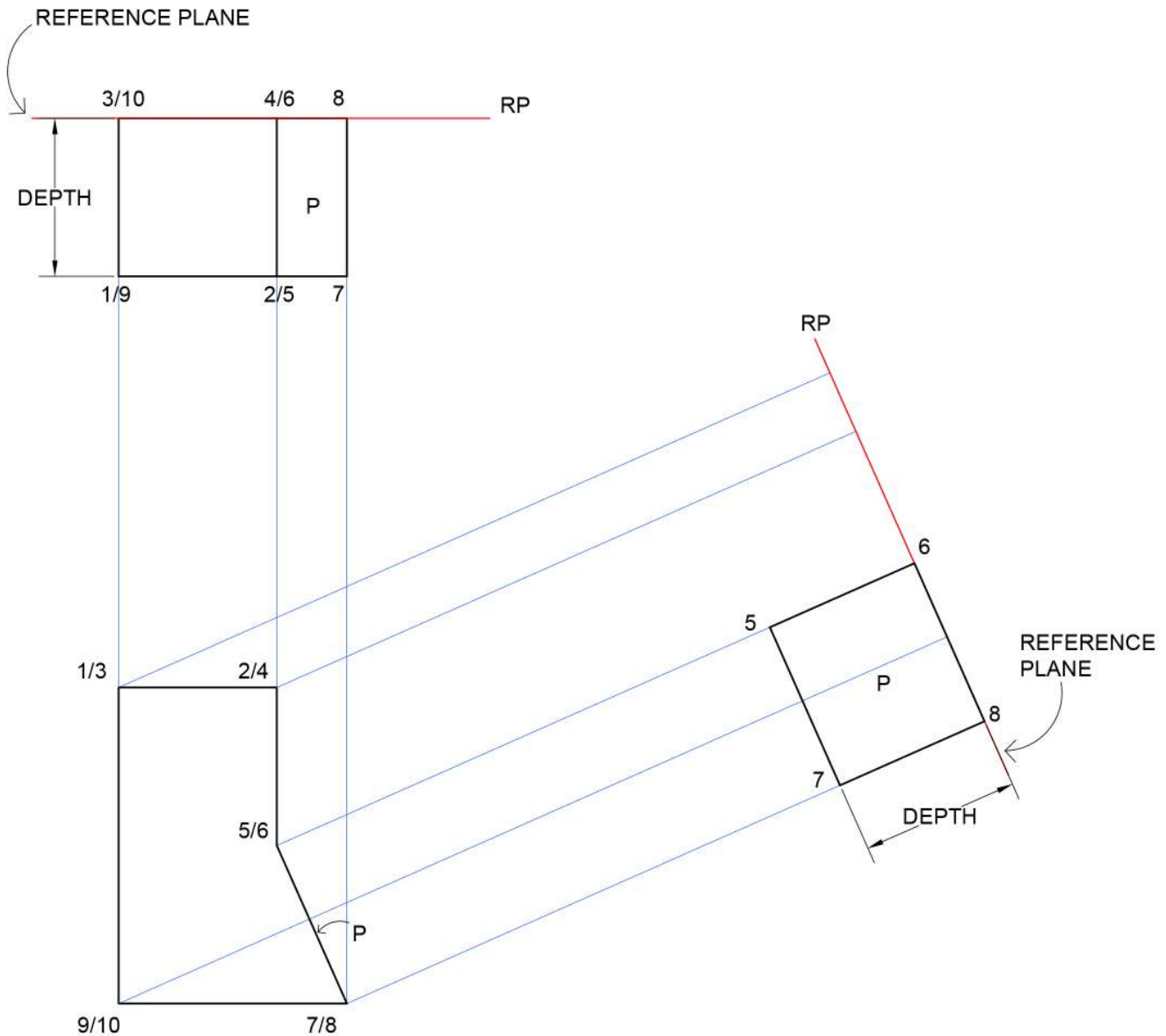


Figure 3.1.11: Surface P seen true shape and size on auxiliary view.

- Repeat for all vertices and identify hidden edges:** This process is repeated for all vertices to represent the entire object in the auxiliary view. Any edges that are not visible in the view should be shown as hidden lines. For example, the edge connecting vertices 9 and 10 appears hidden behind surface P in the auxiliary view.

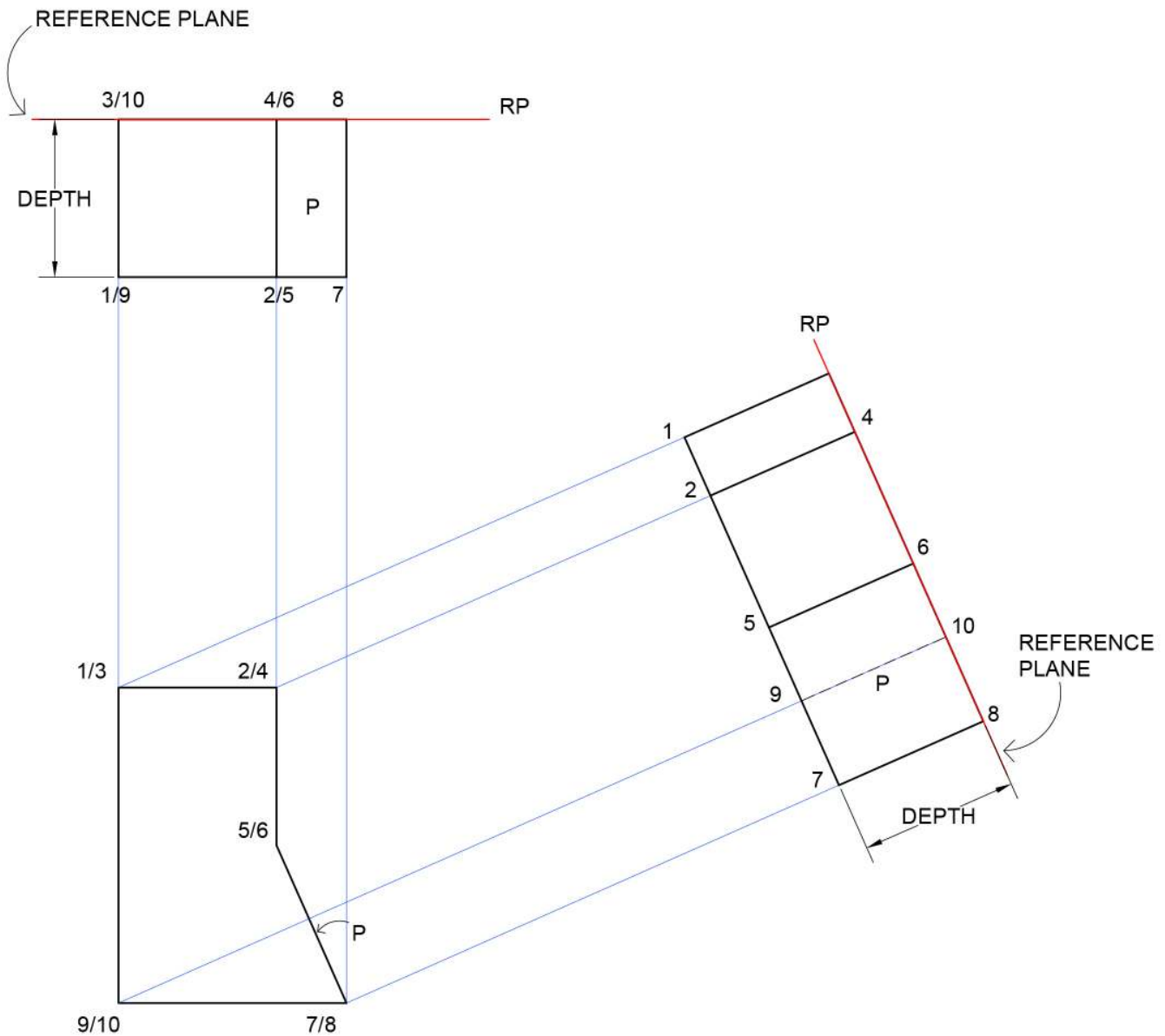


Figure 3.1.12: Complete object seen on auxiliary view.

Note 1

The reference plane can also be positioned in different locations, such as against the front surface or cutting through the object. The image below shows a reference plane cutting through a symmetric object. The placement of the reference plane is at the drafter's discretion; however, it must be consistent across all views.

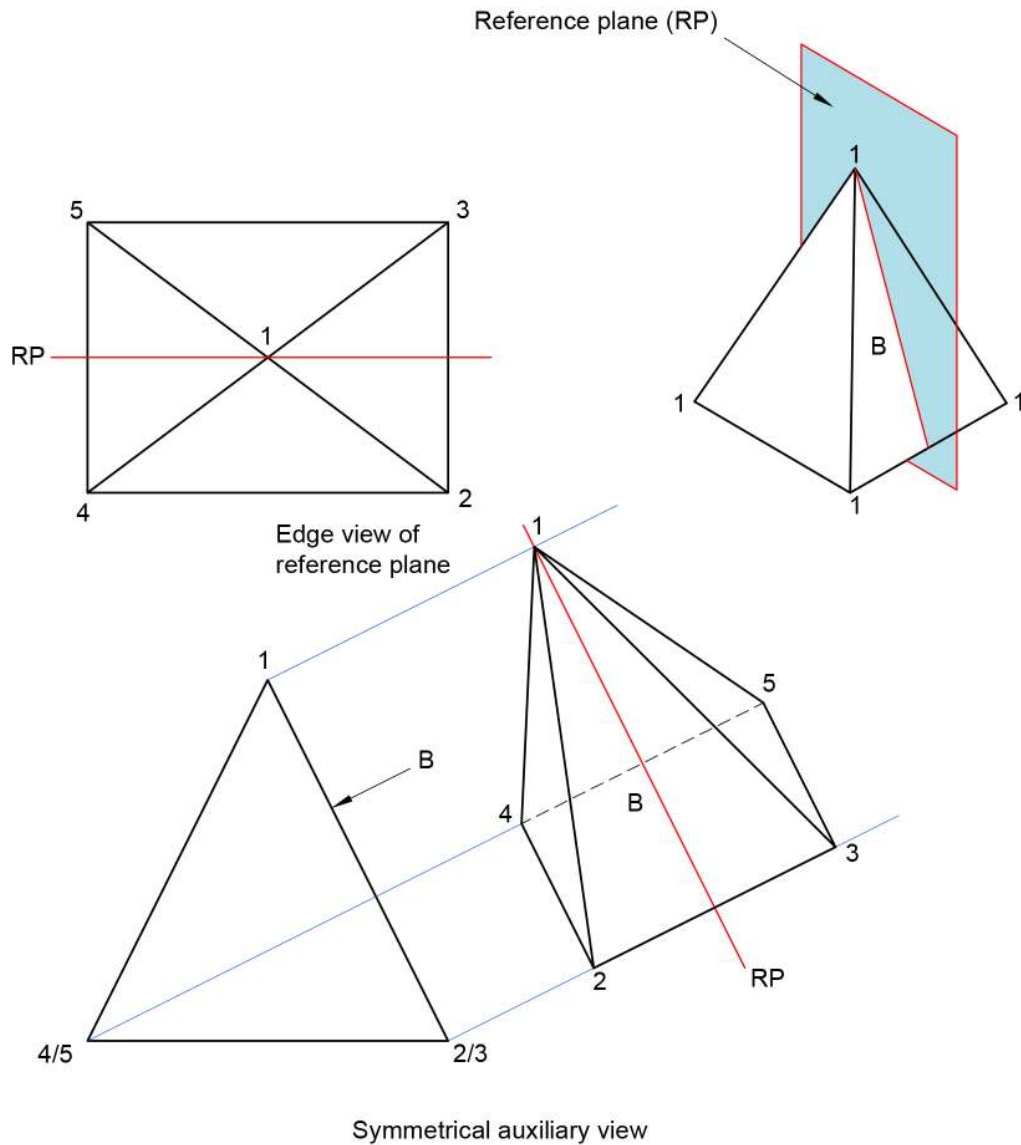


Figure 3.1.13: Placement of reference plane in a symmetric object.

Note 2

The reference plane should always be shown on the standard view that is not the plane of projection, as well as on the auxiliary view. Regardless of its placement, the reference plane appears as a horizontal edge on the top view in depth auxiliary views, as a vertical edge on the front view in width auxiliary views, and as a horizontal edge on the front view in height auxiliary views.

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3.2: Section Views

Learning Objectives

By the end of this section, learners will be able to

1. Describe the different types of section views and their applications.
2. Visualize and construct section views from a given geometry.
3. Explain the placement and purpose of cutting-plane lines.
4. Identify sectioned surfaces within a section view.
5. Apply the correct placement of section views in multiview drawings.

Section views are used to depict and describe the internal features of an object.

For example, in architecture, a vertical section through a building is used to show the vertical relationships between spaces. The figure below illustrates a three-dimensional vertical section through a lobby area. This section shows a double-height space on the ground level where the lobby opens toward the plaza, and another double-height space on the first floor on the opposite side. These variations in floor heights would not be visible in a floor plan view, because a floor plan is a top view and shows the horizontal relationships between spaces.



Figure 3.2.1: 3D section of InterTech, a project designed by Illinois Tech students for the U.S. Department of Energy 2017 Race to Zero competition.

Line types in section views

Section views use several types of lines, including cutting plane lines, section lines, and short break lines (refer to [Module A Section 1.2](#)). Every section view features two primary line types: cutting plane lines and section lines.

- **Cutting-plane lines** are represented as thick dashed lines with arrowheads at each end. The cutting plane line indicates the location where the object is imagined to be cut, while the arrowheads specify the direction of sight for viewing the resulting section.

- **Section lines** are thin, continuous diagonal hatch lines used to indicate surfaces that lie directly on the cutting plane. They are drawn at a uniform angle and spacing to distinguish sectioned surfaces from other visible surfaces located in front of the cutting plane.

Short break lines are irregular, freehand lines used in broken-out sections to separate the portion of the object shown in section from the remainder of the view.

Creating a section view

In a section view, the object is imagined to be cut along a specified plane, a portion of it is removed, and the interior features are viewed. The section view is arranged according to standard orthographic projection conventions.

The example below illustrates an object cut vertically through its full height at the center (see Figure 3.2.2). The right half of the object is imagined to be removed, and the interior is viewed from the right side, following the direction indicated by the arrows of the cutting plane line, as shown in Figure 3.2.3.

Figure 3.2.3 shows the top, front, and right-side section views of the object. In the front view, the cutting-plane line is placed as a vertical line along the center with arrowheads pointing to the left, indicating the viewing direction. The section view is projected from the cutting-plane line.

Beginning at the top of the cutting plane, the first portion intersected is solid material. This surface lies directly on the cutting plane and is therefore represented with section lines in the section view. Moving downward along the cutting plane, the next feature encountered is a small circular hole. The curved interior surface of the hole appears as a rectangle in the section view (refer to [Module B, Section 2.5](#)). This surface is not hatched because it does not lie directly on the cutting plane. Continuing along the cutting plane, surfaces lying on the cutting plane are identified to complete the section.

In this example, the section view is placed in the position of the right-side view, following the direction of sight specified by the cutting-plane line.

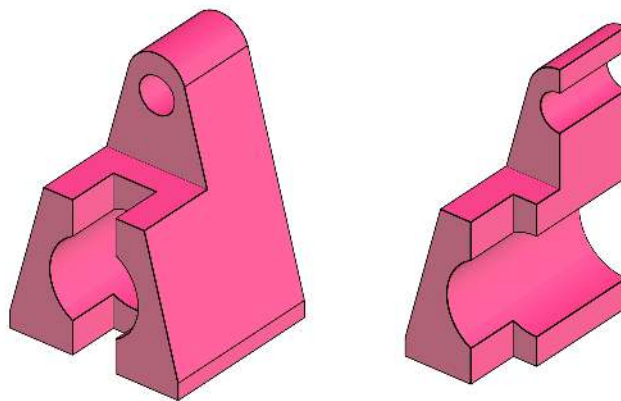


Figure 3.2.2: Realistic views of the sectioned object.

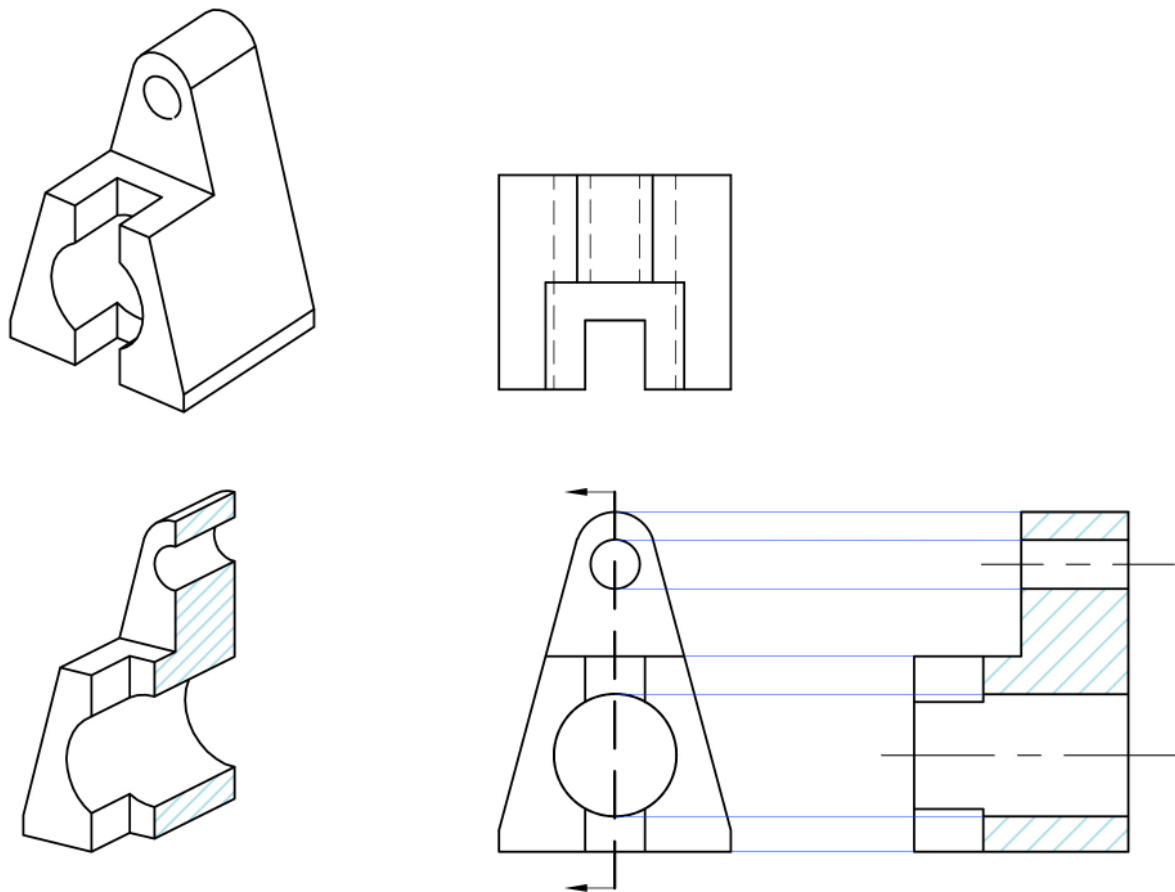
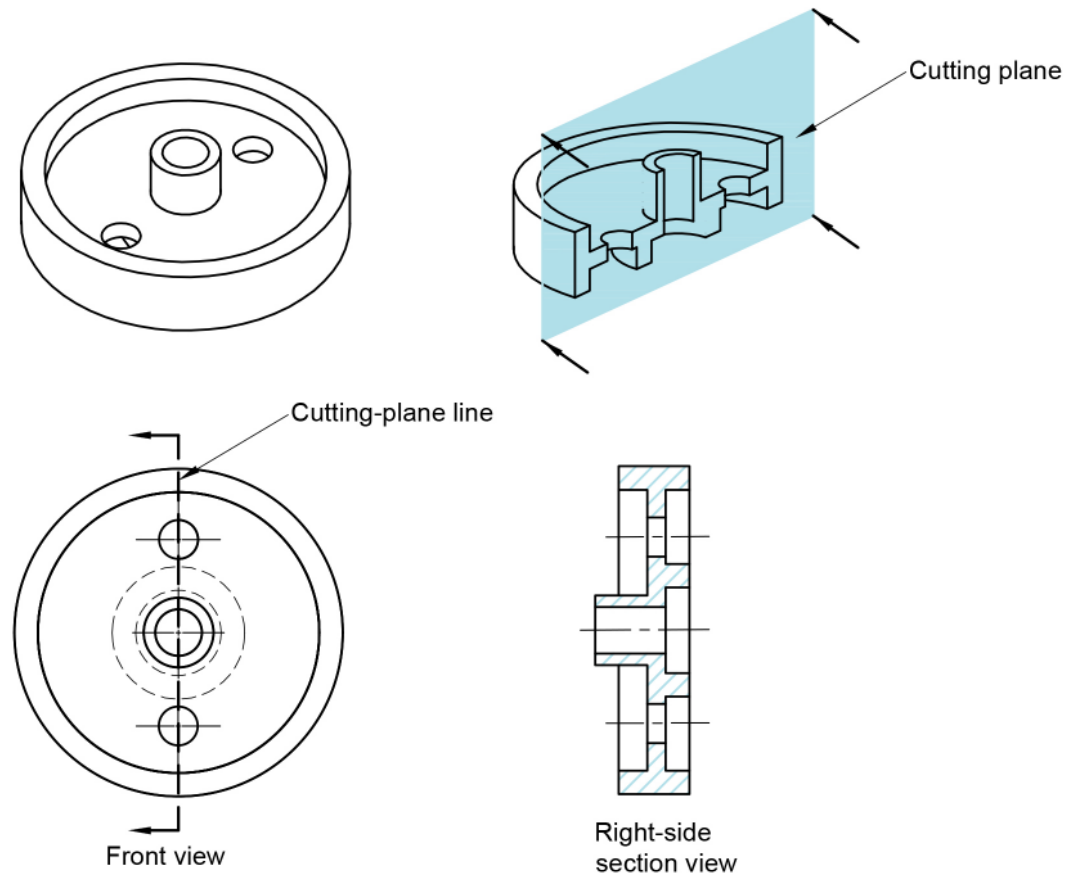


Figure 3.2.3: 3D representations of a sectioned object and top, front, and right-side section views.

Types of section views

Full section: A full section cuts through the entire width, depth, or height of an object. Similar to the example above, Figure 3.2.4 shows that the section cuts through the entire height of the object shown in the interactive visualization below.



FULL SECTION

Figure 3.2.4: Full section: 3D representations of the sectioned object and a front and right-side section views.

Half section: A half section cuts through half the width, depth, or height of an object. A half section view shows one half of the object in section and the other half as seen from the outside.

In the example illustrated in Figure 3.2.5, the object is cut through its center along the width. Only half of the width is sectioned, and that portion is removed. The resulting section view, placed in the position of the front view, displays one half of the object in section and the other half as it would appear in a standard front view. An interactive element helps visualizing the object and half section in three dimensions.

Half sections are particularly useful for symmetric objects, as they allow both the interior and exterior features to be shown in a single view.

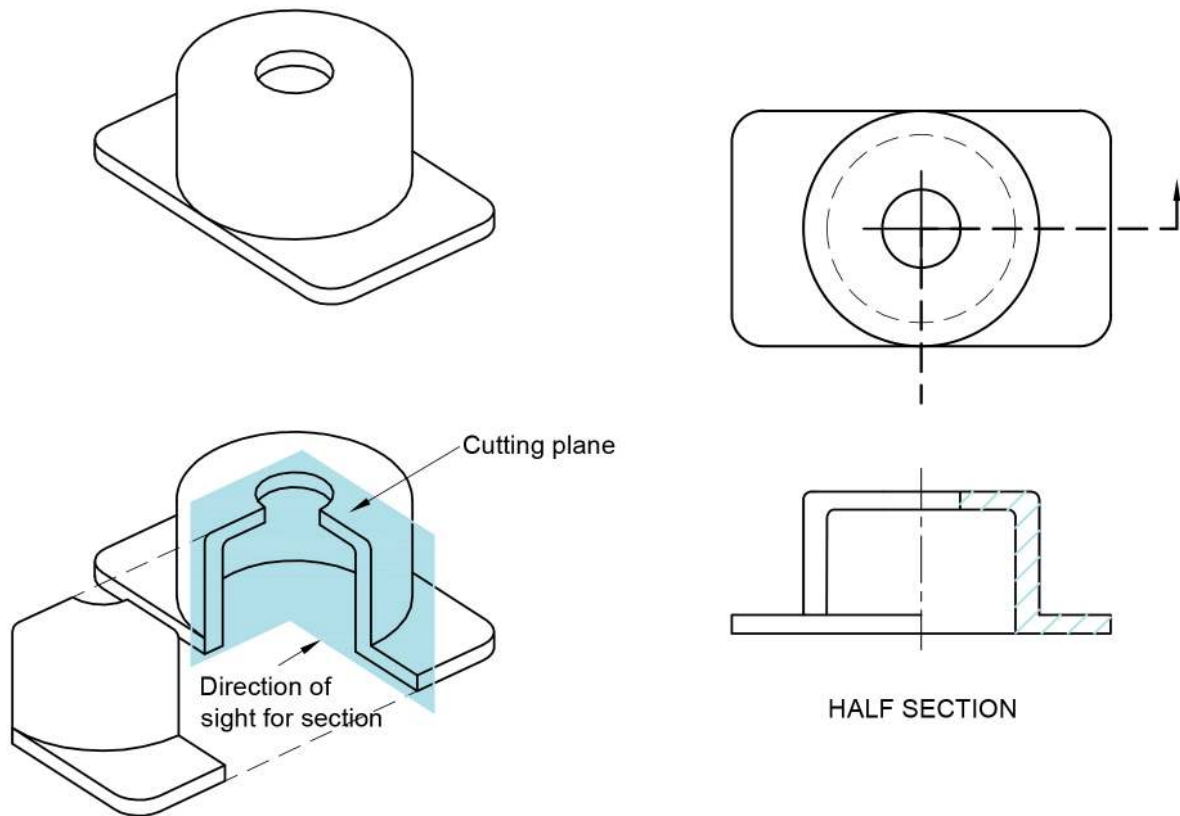


Figure 3.2.5: Half section: 3D representations of the sectioned object and top and front section views.

Offset section: In an offset section, the cutting plane is offset to cut through multiple features that are not aligned on the same plane. An offset section allows several interior features to be shown in a single section view.

In the example illustrated below (see Figure 3.2.6), the cutting plane cuts through the width of the object and is offset to intersect all four holes. The resulting section view, placed in the position of the front view, shows all four holes in one drawing—eliminating the need to create four separate views. An interactive element helps visualizing the object and offset section in three dimensions.

Note

No line is shown in the section view to indicate where the cutting plane changes; the offset is understood from the cutting-plane line in the adjacent view.

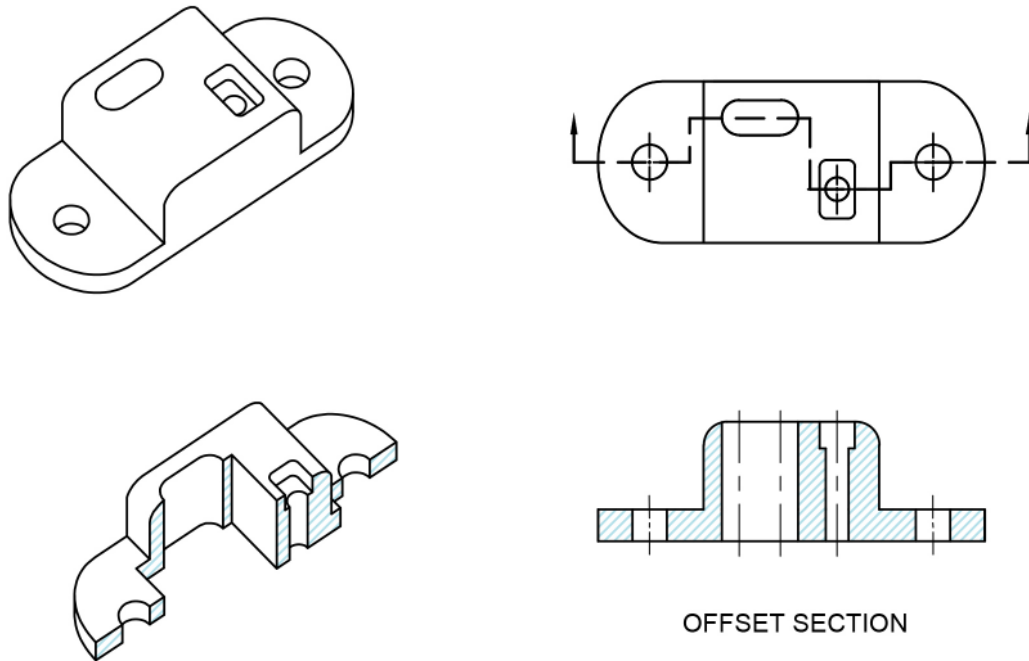


Figure 3.2.6: Offset section: 3D representations of the sectioned object and top and front section views.

Aligned section: An aligned section is a section view in which an inclined feature of an object is imagined to be rotated to align with one of the principal axes. This rotation allows the sectioned surfaces to be shown in their true shape and size, rather than appearing foreshortened.

In the example illustrated below (see Figure 3.2.7), the cutting plane passes through the full height of the object. The lower portion of the object is inclined relative to the right-side plane. Therefore, its surfaces would appear foreshortened in a right-side section view (refer to [Module B, Section 2.6](#)). To avoid this distortion, the inclined portion is imagined to be rotated into alignment with the central axis, and the section view is projected from that axis. This method allows the sectioned surfaces to be shown in their true shape and size.

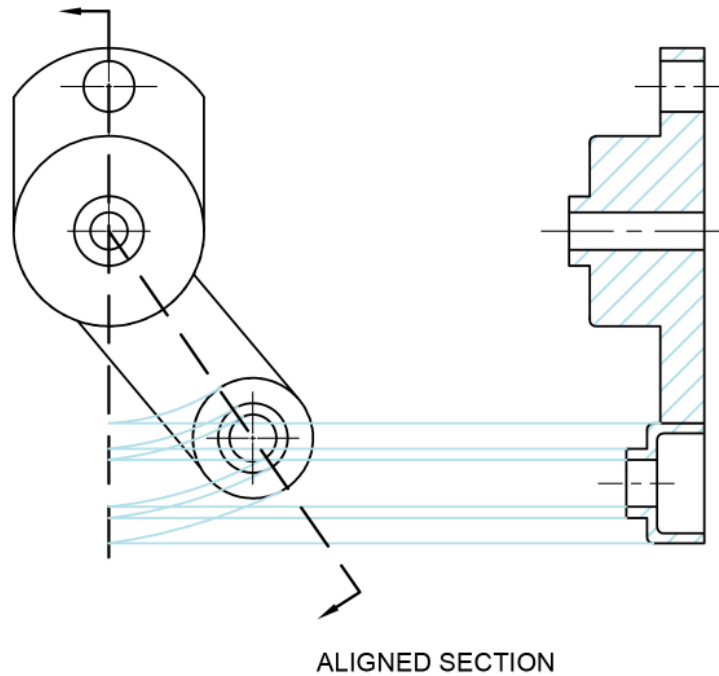


Figure 3.2.7: Aligned section: Front and right-side section views.

Revolved section: A revolved section shows the cross-sectional shape of a feature directly on an existing view rather than as a separate section view.

To create a revolved section, a cutting plane is imagined passing through the cross-section of a part of the object. The cross-section is then rotated 90 degrees about its central axis and drawn in place on the current view.

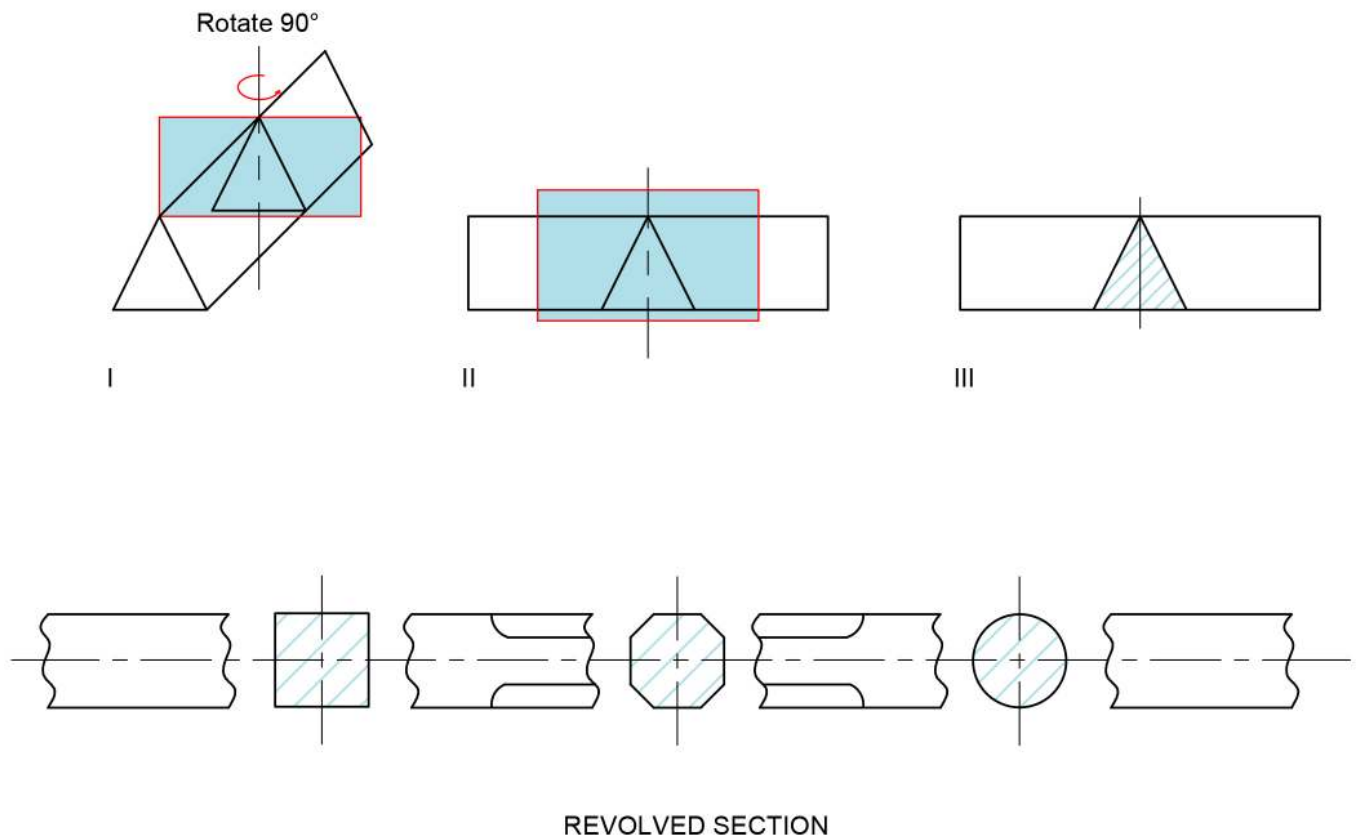


Figure 3.2.8: Examples of revolved section views.

Broken-out section: A broken-out section is used to visualize only one part of the feature in section view. The section view is limited by a short break line, as shown in Figure 3.2.9.

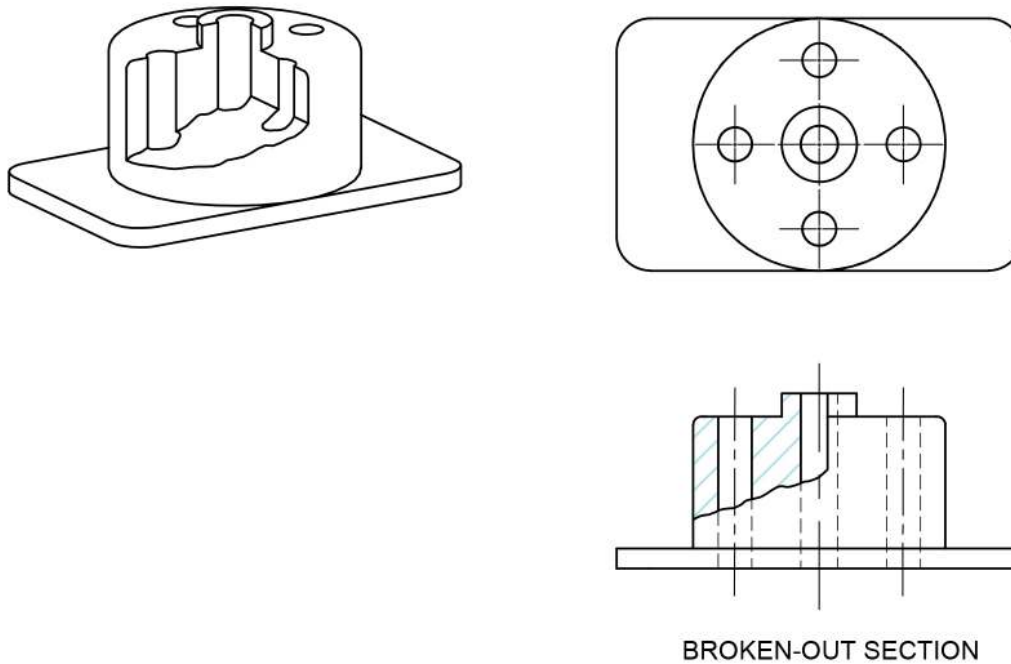


Figure 3.2.9: Broken out section

Note

Webs, ribs, and spokes are not hatched in section views, even if they are cut by the cutting plane (see Figure 3.2.13). This convention avoids making them appear as thick, solid elements.

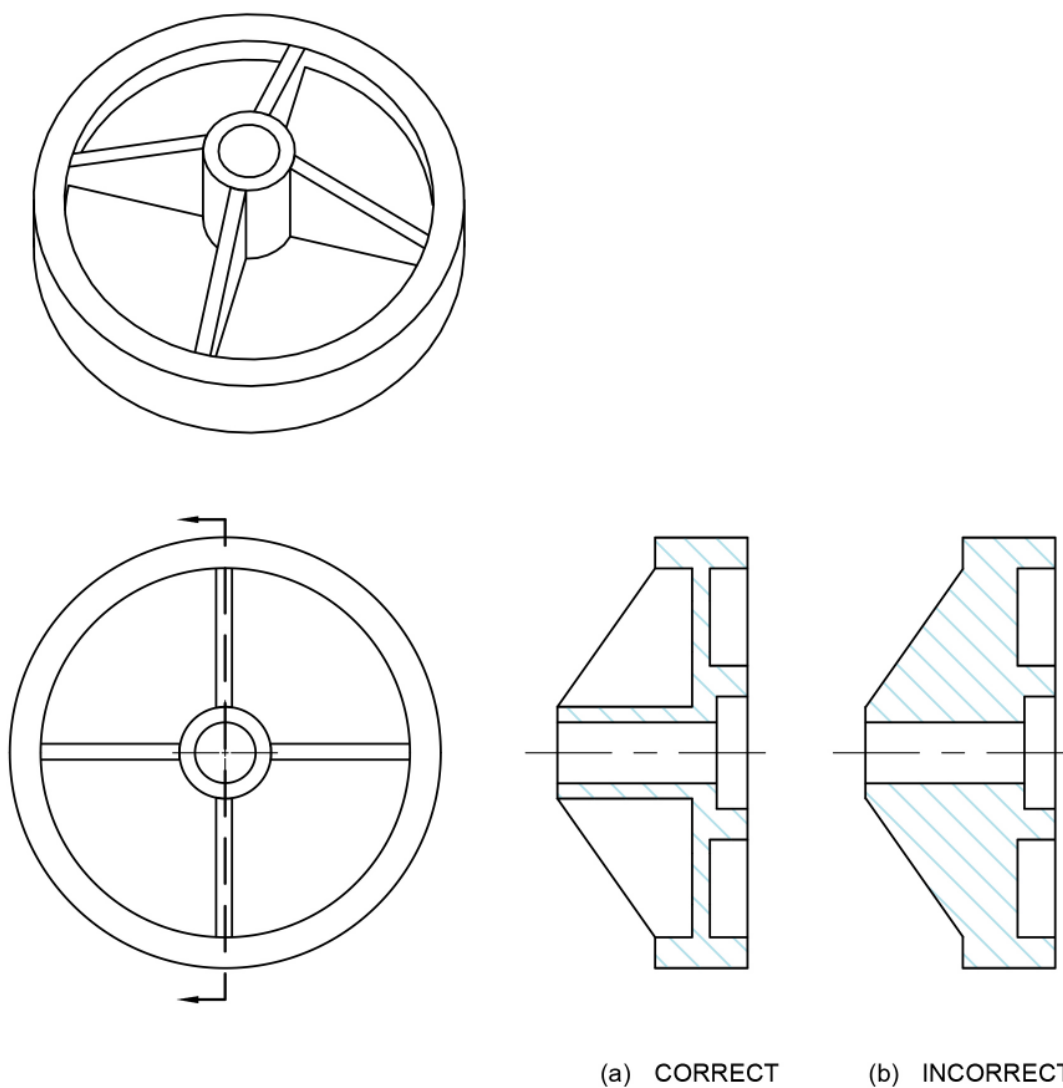


Figure 3.2.10:Spokes in section view.

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3.3: Isometric projections

Learning Objectives

By the end of this section, learners will be able to

1. Define isometric projections and explain their classification within parallel projections.
2. Explain the angles of the principal axes in an isometric projection.
3. Describe the difference in foreshortening of edges in isometric projections and isometric drawings.
4. Describe how circular features appear as ellipses in isometric drawings.
5. Construct an isometric sketch of an object given top and front views.

Isometric drawings are a type of axonometric projection and fall under the category of parallel projections, in which all projectors are parallel and the observer is considered to be at infinity. Like multiview drawings, isometric projections are classified as orthographic projections because the projectors are perpendicular to the plane of projection. A diagram illustrating the classification of projections is shown in [Module B, Section 2.1](#).

However, unlike multiview drawings, axonometric projections, oblique projections (covered in [Module C, Section 3.4](#)), and perspective projections are pictorial projections because they represent all three dimensions of an object in a single view. Isometric and oblique drawings are used to quickly visualize objects in three dimensions, without the visual distortion caused by perspective foreshortening.

In an isometric projection, the object is oriented so that its principal axes form equal angles with the plane of projection.

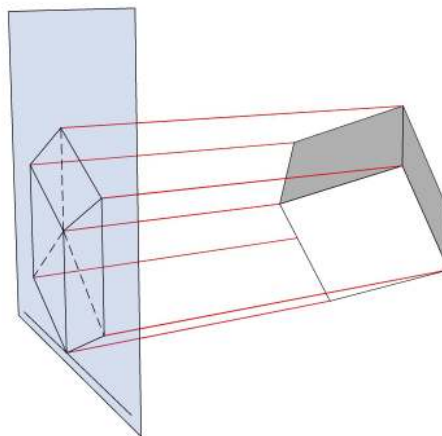


Figure 3.3.1: 3D sketch of isometric projection.

The interactive model below shows an isometric projection of a box in three dimensions. Parallel projectors (in red) perpendicular to the plane of projection are used to project the vertices onto the projection plane.

As illustrated in Figure 3.3.2, the three principal axes form an angle of 120° with each other. The edges drawn in the width and depth directions form 30° angles with the horizontal, while the height is represented as a vertical line perpendicular to the horizontal.

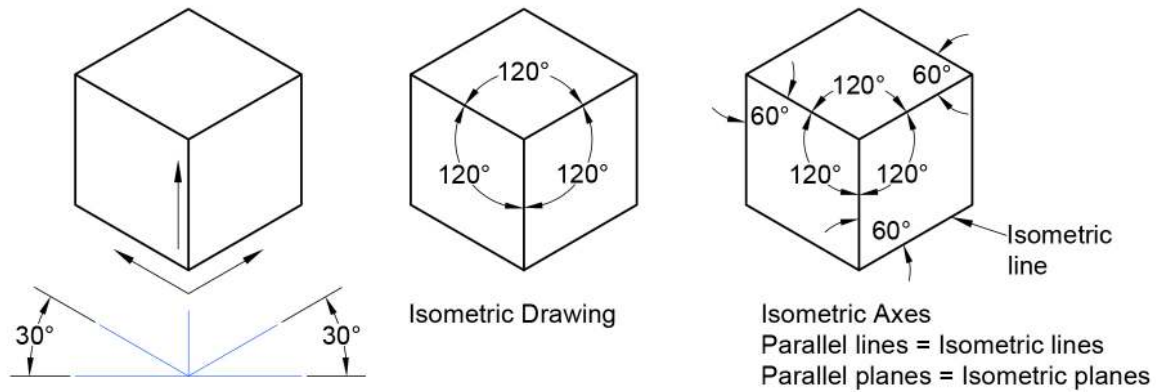


Figure 3.3.2: Isometric axes and angles.

Isometric scale

Since in isometric projections all edges make equal angles with the plane of projection, they undergo the same degree of foreshortening and should be reduced to approximately 80% of their true length. However, because this foreshortening is uniform across all edges, isometric drawings are drawn at full scale for simplicity.

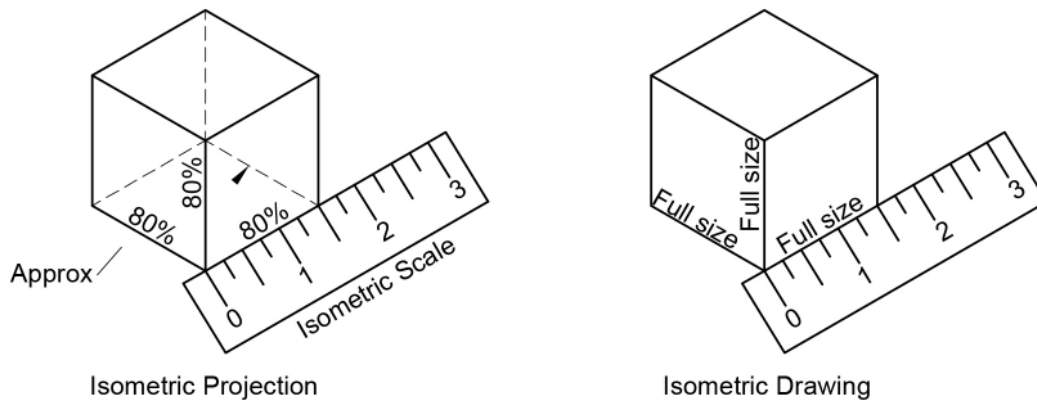


Figure 3.3.3: Isometric projection and isometric drawing.

Circular features in isometric drawings

Due to the object's rotation, circular features in isometric drawings appear as ellipses in all three isometric planes, as shown in Figure 3.3.4.

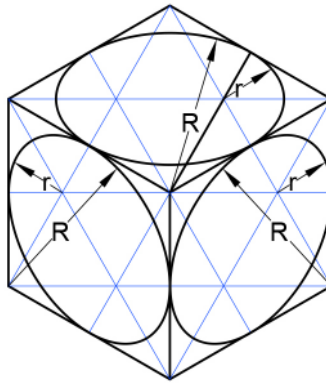


Figure 3.3.4: Circles shown as ellipses in isometric planes.

✓ Example 3.3.1

The example below shows a step-by-step process for constructing an isometric drawing of an object, given its top and front views (see Figure 3.3.5).

1. The first step involves using light guidelines to draw an isometric box that encloses the object. Drawing tools such as a T-square and triangles can be used, as described in [Module A, Section 1.3](#).
2. The object's surfaces are identified and constructed within the isometric box. The object illustrated in the example features one inclined surface.
3. Lastly, the object's edges are emphasized with stronger lines to make the drawing clear.

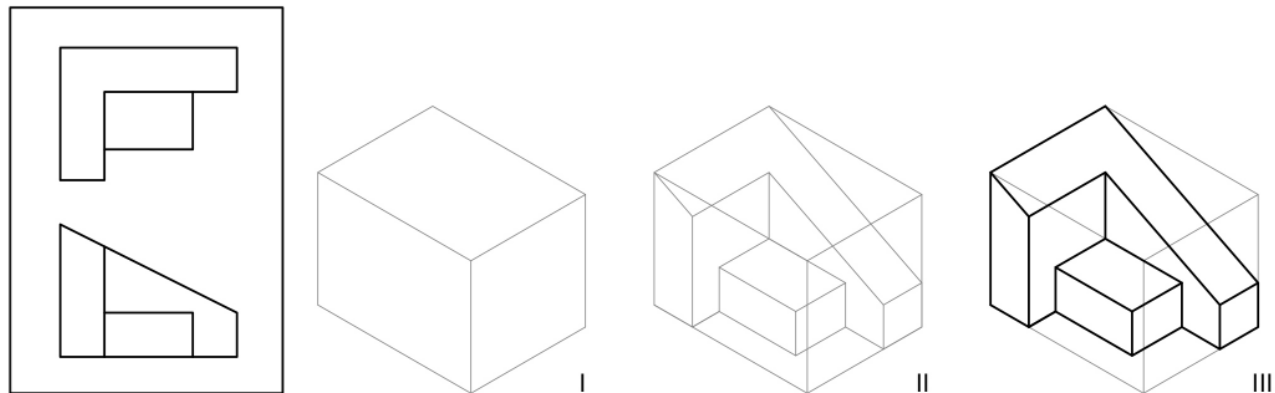


Figure 3.3.5: Example 1: Step-by-step process for constructing an isometric drawing given a top and front view of an object.

📌 Note

Hidden edges are omitted in isometric drawings, unless they are necessary to understand and visualize the represented object.

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3.4: Oblique projections

Learning Objectives

By the end of this section, learners will be able to

1. Define oblique projection and explain how it differs from isometric projections.
2. Distinguish between cavalier and cabinet projections.
3. Describe how circular features appear in oblique drawings.

Similar to isometric projections, oblique projections are pictorial projections used to create quick 3D visualizations of an object. They are a type of parallel projection; however, unlike isometric projections, they are not orthographic projections.

As explained in [Module B, Section 2.1](#), in orthographic projection the projection, lines (or visual rays) form a 90° angle with the plane of projection. In oblique drawings, the projectors remain parallel to each other and the observer is considered at infinity; however, the projectors intersect the plane of projection at an angle other than 90° .

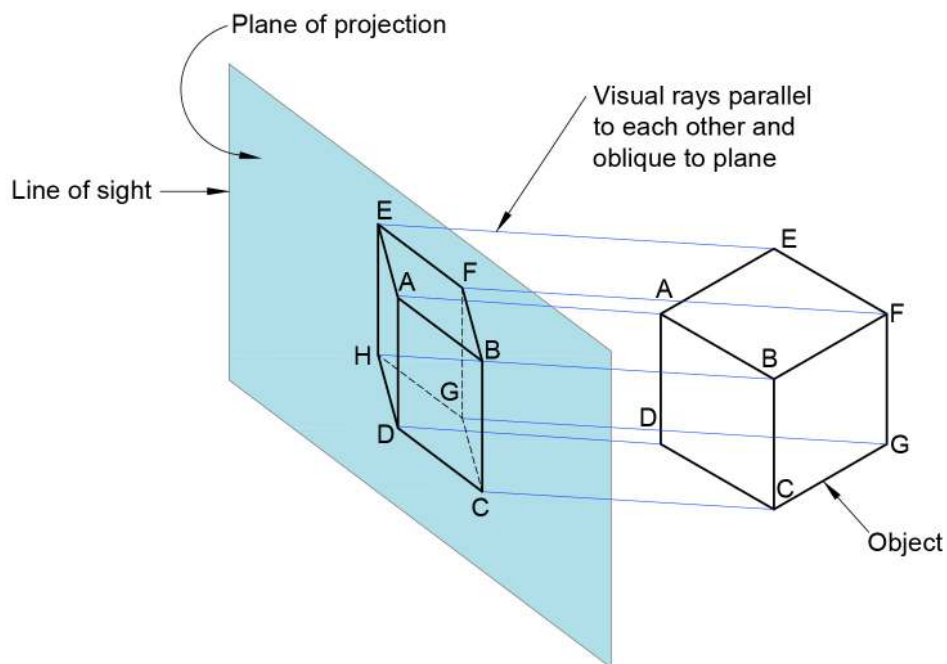


Figure 3.4.1: 3D sketch of oblique projection.

In oblique drawings, surfaces that are aligned with the front plane appear in their true shape and size, as they would appear in the front view. Depth, however, is projected at an angle - commonly 45° - to the plane of projection. As illustrated in Figure 3.4.2, an isometric drawing shows both the width and depth axes forming 30° angles with the horizontal, while in an oblique drawing, the depth axis is generally projected at a 45° angle.

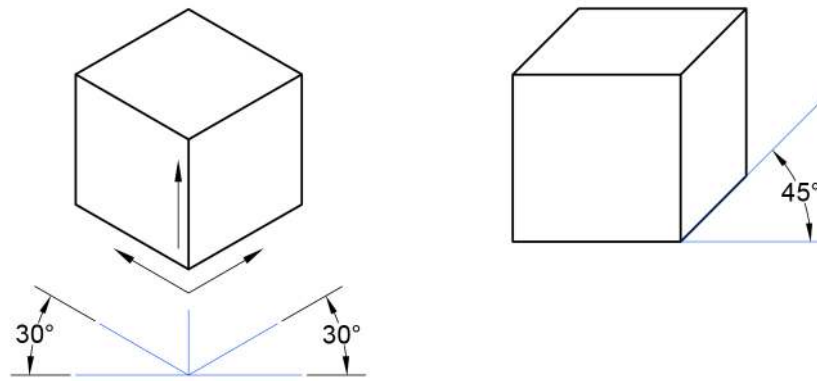


Figure 3.4.2: Isometric and oblique projection.

Oblique projections often appear distorted to the observer because the receding lines remain parallel rather than converging, as they do in perspective projections. Figure 3.4.3 compares a perspective drawing of train tracks with an oblique drawing to highlight the unnatural appearance of oblique projections.

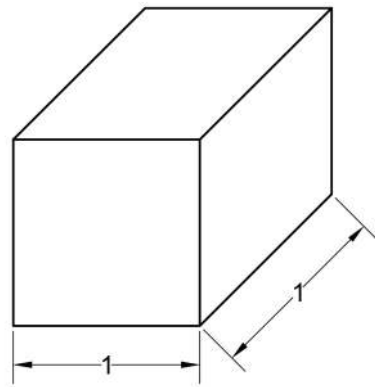


Figure 3.4.3: Perspective and oblique drawing of train tracks.

The distortion in oblique projections becomes more pronounced when the receding lines are drawn at their true length, as in cavalier projections. To reduce this distortion, the length of the receding lines can be shortened. In cabinet projections, for example—commonly used in the furniture industry—the depth is drawn at half its true length (multiplied by 0.5).

- **Cavalier projection:** Depth is drawn at true length.
- **Cabinet projection:** Depth is scaled to half its true length to reduce distortion.

Cavalier Projection



Cabinet Projection

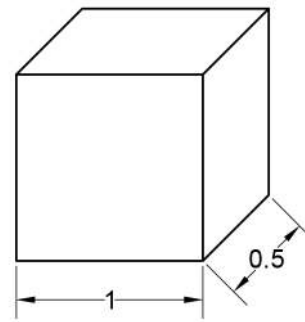
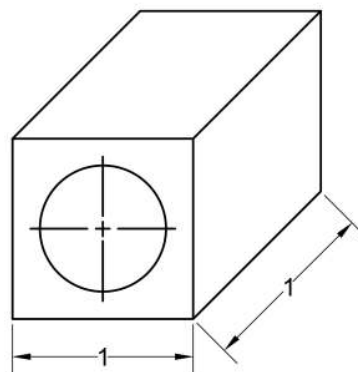


Figure 3.4.4: Cavalier and cabinet projections.

Note

Circular features in oblique drawings are easier to construct than in isometric drawings, as long as the circles are oriented parallel to the front plane. This is because any shape lying on the front plane is projected in its true form and size. Therefore, a circle on the front plane will remain a circle in the oblique view.

Cavalier Projection



Cabinet Projection

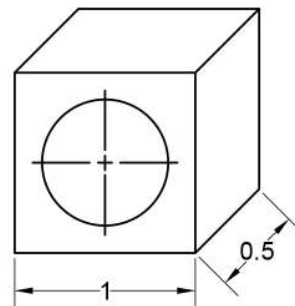


Figure 3.4.5: Circular features in cavalier and cabinet projections.

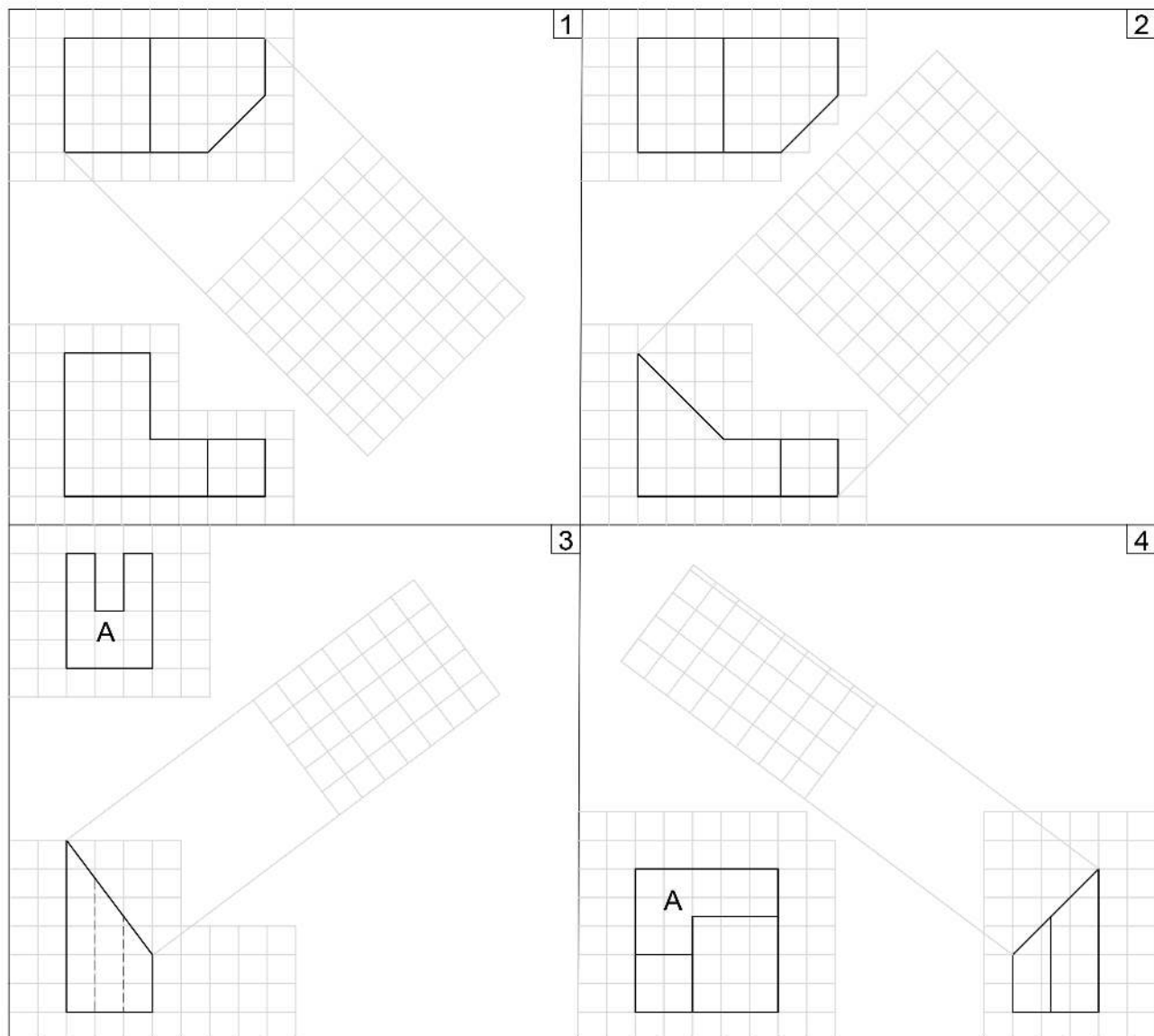
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3.5: Exercises

This section provides exercises that apply the knowledge covered in Module C. Follow the instructions on the sheets.

1. Exercise 1: Auxiliary views . This exercise contains four problems focused on auxiliary views. Learners are asked to design the auxiliary view of a surface or an entire object. For each problem, identify whether the auxiliary view represents width, depth, or height.
2. Exercise 2: Sections views. This exercise includes six problems on sectional views. Based on the cutting-plane line, determine the type of section used (e.g., full, half, offset, etc.).
3. Exercise 3: Isometric and oblique drawings. The top, front, and right-side views of six objects are provided. Using Sheet 2, draw:
 - Isometric projections for Exercises 1, 2, and 3.
 - Cabinet projections for Exercises 4, 5, and 6.

Exercise 1: Auxiliary views



1. DRAW THE AUXILIARY VIEW OF THE ENTIRE OBJECT. TOP AND FRONT VIEWS ARE PROVIDED. PLEASE IDENTIFY THE REFERENCE PLANE ON ONE OF THE TWO STANDARD VIEWS AND ON THE AUXILIARY VIEW. SHOW CONSTRUCTION LINES.

IDENTIFY IF IS IT A) DEPTH, (B) WIDTH, (C) HEIGHT AUXILIARY VIEW. CIRCLE THE CORRECT ANSWER.

2. DRAW THE AUXILIARY VIEW OF THE ENTIRE OBJECT. TOP AND FRONT VIEWS ARE PROVIDED. PLEASE IDENTIFY THE REFERENCE PLANE ON ONE OF THE TWO STANDARD VIEWS AND ON THE AUXILIARY VIEW. SHOW CONSTRUCTION LINES.

IDENTIFY IF IS IT A) DEPTH, (B) WIDTH, (C) HEIGHT AUXILIARY VIEW. CIRCLE THE CORRECT ANSWER.

3. DRAW THE AUXILIARY VIEW OF SURFACE A ONLY. TOP AND FRONT VIEWS ARE PROVIDED. PLEASE IDENTIFY THE REFERENCE PLANE ON ONE OF THE TWO STANDARD VIEWS AND ON THE AUXILIARY VIEW. SHOW CONSTRUCTION LINES.

IDENTIFY IF IS IT A) DEPTH, (B) WIDTH, (C) HEIGHT AUXILIARY VIEW. CIRCLE THE CORRECT ANSWER.

4. DRAW THE AUXILIARY VIEW OF SURFACE A ONLY. FRONT AND RIGHT-SIDE VIEWS ARE PROVIDED. PLEASE IDENTIFY THE REFERENCE PLANE ON ONE OF THE TWO STANDARD VIEWS AND ON THE AUXILIARY VIEW. SHOW CONSTRUCTION LINES.

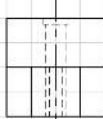
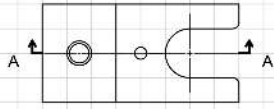
IDENTIFY IF IS IT A) DEPTH, (B) WIDTH, (C) HEIGHT AUXILIARY VIEW. CIRCLE THE CORRECT ANSWER.

Figure 3.5.1: Exercise 1: Auxiliary views

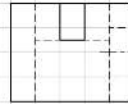
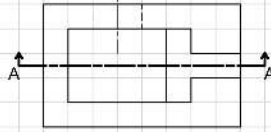
Exercise 2: Section Views

DRAW SECTION VIEWS AS DESCRIBED. IDENTIFY TYPE OF SECTION (E.G. FULL, HALF, ALIGNED, ETC.)

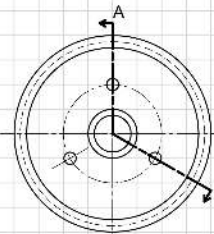
1 DRAW FRONT SECTION VIEW.
TYPE OF SECTION: _____



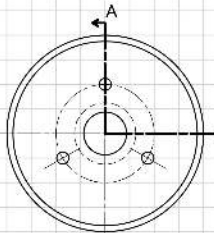
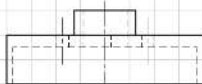
2 DRAW FRONT SECTION VIEW.
TYPE OF SECTION: _____



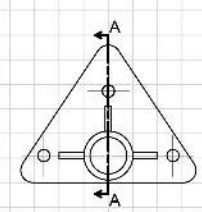
3 DRAW RIGHT SIDE SECTION VIEW.
TYPE OF SECTION: _____



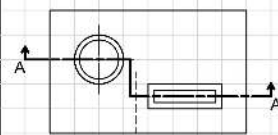
4 DRAW RIGHT SIDE SECTION VIEW.
TYPE OF SECTION: _____



5 DRAW RIGHT SIDE SECTION VIEW.
TYPE OF SECTION: _____



6 DRAW FRONT SECTION VIEW.
TYPE OF SECTION: _____



NAME: _____

DATE: _____

Figure 3.5.1: Exercise 2: Section views

Exercise 3: Isometric and oblique drawings

SKETCH ISOMETRIC (1-3) AND OBLIQUE DRAWINGS OF EXERCISES 4-6 (VIEWS ARE COMPLETE).					
1 SKETCH ISOMETRIC PROJECTION		2 SKETCH ISOMETRIC PROJECTION		3 SKETCH ISOMETRIC PROJECTION	
4 SKETCH CAVALIER PROJECTION		5 SKETCH CABINET PROJECTION		6 SKETCH CABINET PROJECTION	
NAME:			DATE:		

Figure 3.5.1: Exercise 3: Isometric and oblique drawings_Sheet 1

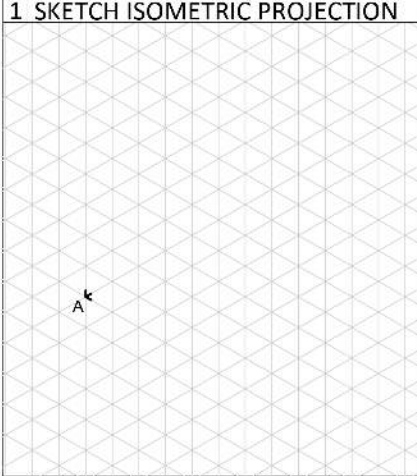
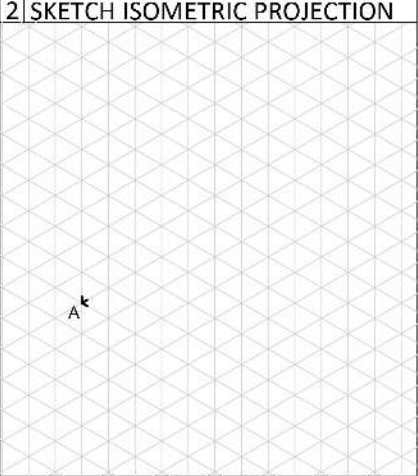
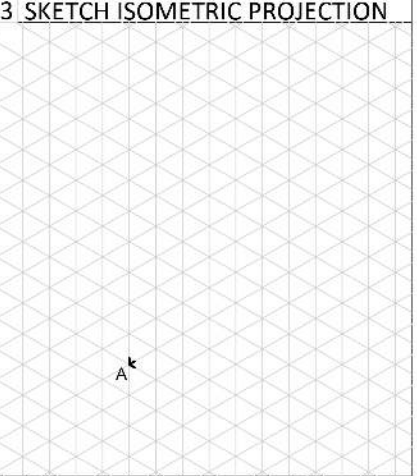
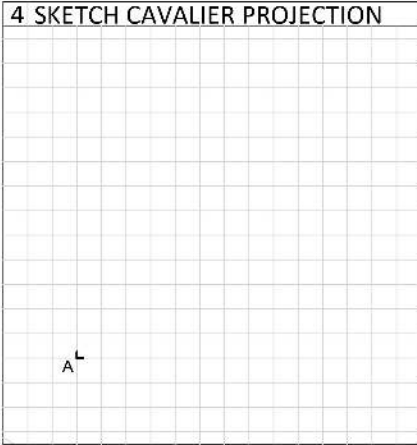
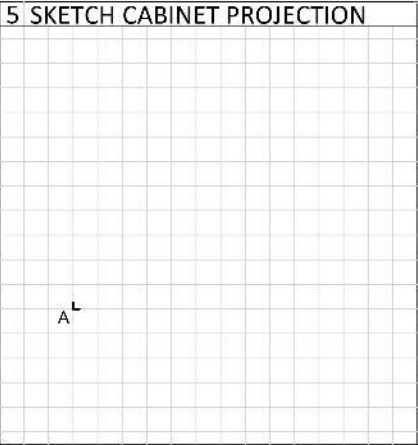
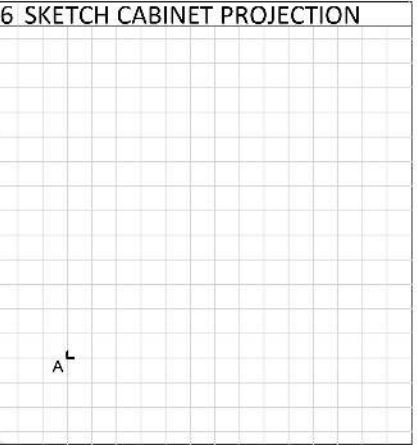
1 SKETCH ISOMETRIC PROJECTION	2 SKETCH ISOMETRIC PROJECTION	3 SKETCH ISOMETRIC PROJECTION
		
4 SKETCH CAVALIER PROJECTION	5 SKETCH CABINET PROJECTION	6 SKETCH CABINET PROJECTION
		
NAME:		DATE:

Figure 3.5.1: Exercise 3: Isometric and oblique drawings_Sheet 2

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CHAPTER OVERVIEW

4: Module D - 3D Printing

- 4.1: What is 3D printing?
- 4.2: 3D modeling and print files
- 4.3: Parts of a 3D printer
- 4.4: 3D Printing Process
- 4.5: 3D Printing parameters
- 4.6: Post processing
- 4.7: 3D Printing example

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4.1: What is 3D printing?

Learning Objectives

By the end of this section, learners will be able to

1. Understand the history of 3D Printing and how the modern 3D Printer came to be
2. Identify how objects are formed in Fused Deposition Manufacturing (FDM) 3D Printing

In the 21st Century, just about everyone is familiar with printing on paper. Many people who own a computer also own a printer or have ready access to one. Over the past few decades, the concept of converting digital information into physical form has expanded beyond paper printing. Today, it includes the ability to create three-dimensional objects through the process of 3D printing.

There are several different methods of 3D printing, and some of them will be briefly discussed in this handbook. This section focuses on Fused Deposition Modeling (FDM), one of the most widely used techniques.

FDM printing works by building an object layer by layer using melted plastics, the most common of which in the consumer market is PLA (Polylactic Acid). A digital 3D model is sectioned into slices, each of a certain height. These slices are translated into machine instructions that direct the printer's extrusion head to deposit material along a path in the X and Y axes. The printer then deposits molten plastic along the programmed paths, forming one layer at a time. The successive deposition of these layers gradually builds up, resulting in a complete physical model.

The history of 3D printing begins with Stereolithography, which is the process of fabricating 3D objects by selectively solidifying layers of liquid resin with a specific wavelength of light via a photopolymerization reaction (Huang et al. 2020). The first patent for this form of additive manufacturing was assigned to Chuck Hull in 1984; he then released the first commercially available 3D printer in 1988 (Haines 2024). Hull's impact on 3D printing is still relevant today, as the STL file format that he pioneered is the primary file format for 3D printing even today (Haines 2024).

The patent for FDM printing was granted to Scott Crump in 1992. Crump described it as "a moveable dispensing head provided with a supply of material which solidifies at a predetermined temperature, and a base member, which are moved relative to each other along "X", "Y", and "Z" axes." (Crump, n.d.) This form of printing became the more commercially viable form of printing, and, moving into the 21st century, 3D printing would increasingly reach the masses. The popularity of 3D printing was bolstered by the expiration of the FDM patent held by Crump's company, Stratasys, which allowed DIY printers for hobbyists and the like to take form (Haines 2024).

Currently, many companies offer affordable FDM 3D printers, which are housed in the homes and workshops of millions of people. Companies continue to push the limits of what 3D printers can do with innovations such as multi-filament printing, conveyor belt printing, printing with organic materials, and even printing with edible materials. The nature of 3D printing makes its applications vast. Medical professionals use 3D printing to create models of biological structures and to construct parts of prosthetics for patients. Architects often use 3D printing to model their designs, and the rapid nature of printing allows them to make adjustments easily. 3D printing is not just for professionals; anyone can design something to solve a problem they have in the real world and have it printed within minutes. At its source, 3D printing provides a way for anyone to bring their thoughts to the physical world.

Definitions: What is 3D Printing?

- Stereolithography: The process of fabricating 3D objects by selectively solidifying layers of liquid resin with a specific wavelength of light via a photopolymerization reaction
- FDM, "Fused Deposition Modeling", is a method of fabricating a 3D object using layers of melted material laid atop one another
- X, Y, and Z Axes: The orientations of 3D space with each letter corresponding to a plane in 3 dimensions.

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4.2: 3D modeling and print files

Learning Objectives

By the end of this section, learners will be able to

1. Understand how 3D modeling relates to 3D printing
2. Be capable of identifying common issues in a 3D Model

The first step to bringing any idea to reality using 3D printing is to create a digital 3D model. Modeling is a separate pursuit and is not the focus of this handbook; however, this section will briefly cover it as it relates to the actual process of printing. Some common programs used for 3D Modeling are AutoCAD and Fusion360 by Autodesk, as well as Solidworks by Dassault Systèmes. Blender and FreeCAD are excellent free alternatives to the aforementioned software. TinkerCAD, Sculpt3D, and Womp3D are much more beginner-friendly modeling apps, and TinkerCAD is available to use in your internet browser after signing up for a free account with Autodesk (see Figure 4.2.1 as an example). All these programs are used to make 3D models, which can be 3D printed.

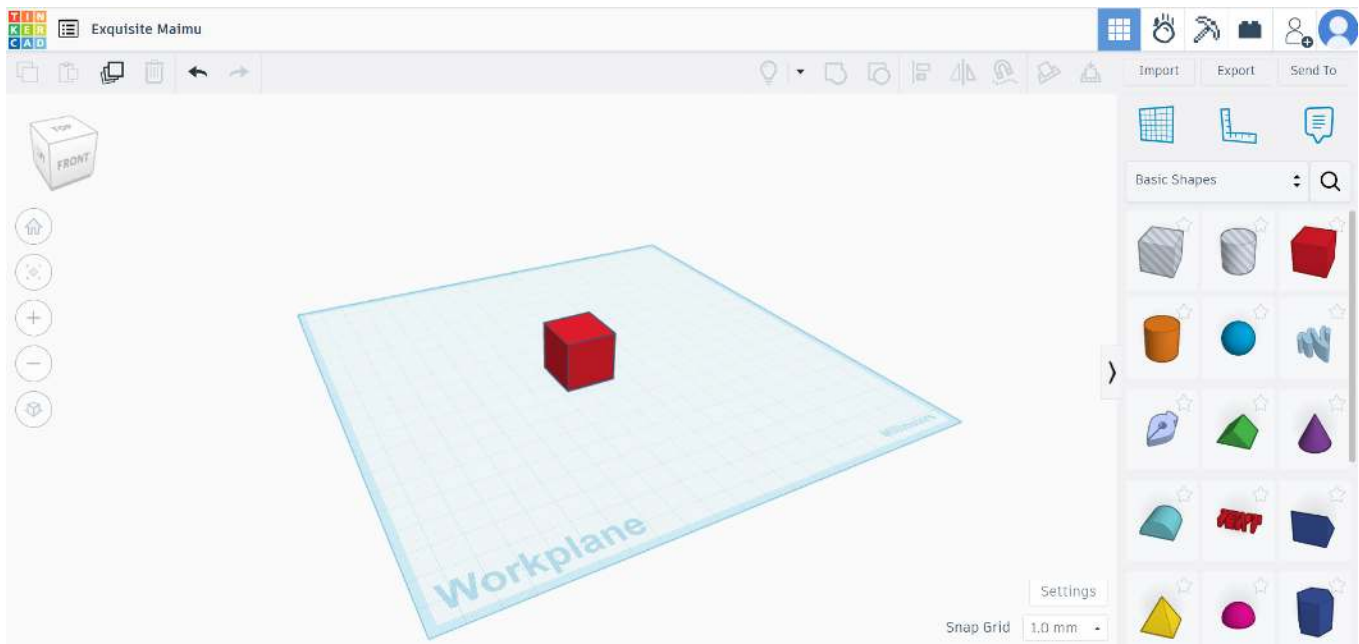


Figure 4.2.1: A screenshot of the TinkerCAD editor working on a browser.

When modeling something intended to work with other objects in the real world, it is important to get accurate measurements; therefore, tools like rulers and tape measures are often used. However, the most useful tool for measuring real-world objects to translate into 3D design is the caliper. Calipers gauge the distance between a set of movable jaws, using either a digital or analog gauge. The adjustable length and ergonomic design of calipers allow them to precisely measure real-world objects and display the distance in an easily readable format. Both analog and digital calipers are available to buy. Digital calipers can usually express measured lengths in both inches and millimeters.

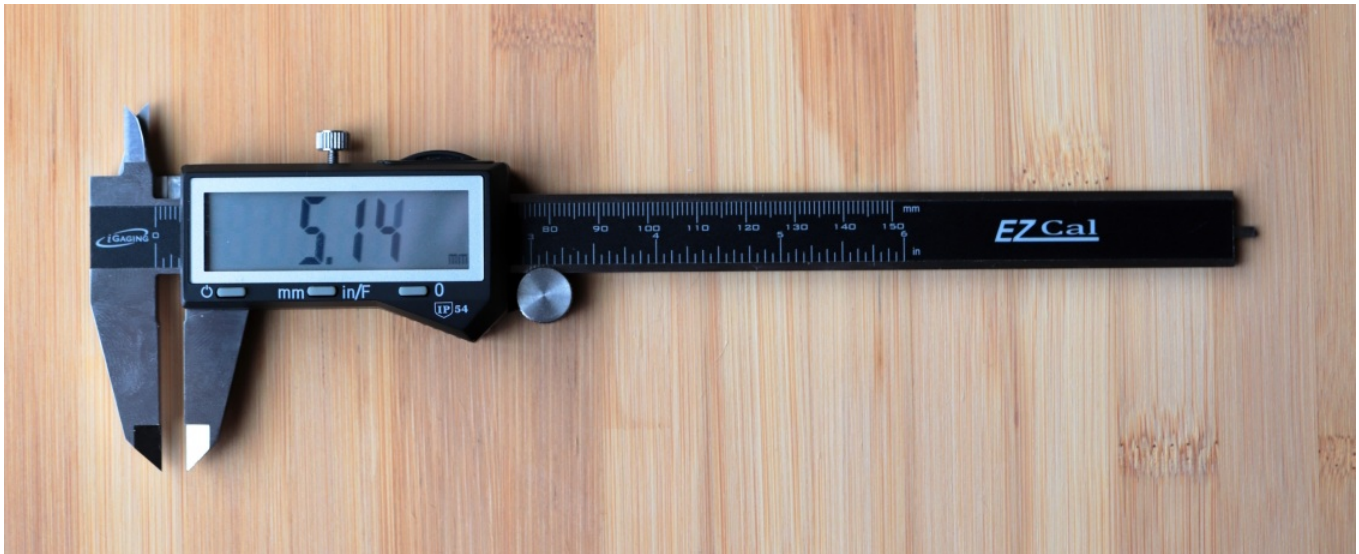


Figure 4.2.2: A pair of digital calipers

The process of creating a model for 3D printing often involves an iterative design process, as shown in Figure 4.2.3. This process includes analyzing and designing a model, printing and testing it, and then evaluating whether it works as intended. If it does not, the model is redesigned using revised measurements and adjustments. These steps are repeated until a satisfactory final product is achieved.

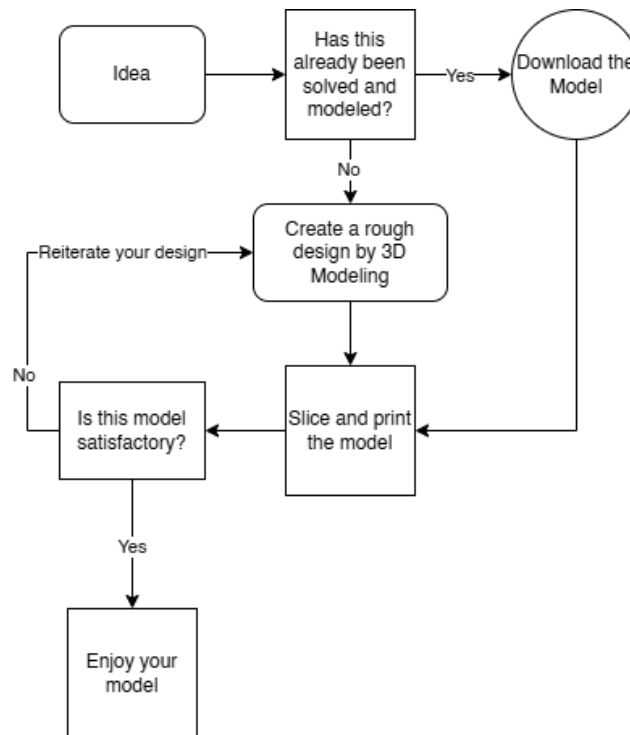


Figure 4.2.3: Flowchart of the iterative design process.

Another way to obtain a 3D model is by downloading one created by someone else. Today, there are numerous online repositories where users share 3D models that can be downloaded—for free or for a fee—and then modified or printed. Popular platforms include Thingiverse, Printables, and MakerWorld. These sites allow users to browse vast collections of models and select designs that fit their needs. In many cases, if someone has an idea for a print, likely, a similar design has already been uploaded to one of these platforms.

After creating a model in the preferred 3D modeling software, the first step toward printing is to export the model into a format that is compatible with the slicing software. While there are many possible 3D file formats – such as .obj, .dwf, and .acis – the most

widely used format for 3D printing is .stl. If this option is not immediately visible, it is often located under the “Other File Types” or “Export as” submenu.

Before exporting, it is helpful to verify a few important details to avoid unnecessary rework later:

- Are the design units consistent with the units intended for printing
- Are all parts of the model that should be joined connected?
- Are all parts model volumetric (solid), or a collection of 2D surfaces?
- Is the scale of the model realistic and sized for printing?
- Have any unused or unwanted elements been removed?

Definition: 3D Modeling and Print Files

- CAD, “Computer Aided Design”, is the process by which 3D models are constructed using a computer program
- G-code or GCODE: Instructional code read by printers. Defines the path the nozzle will take for each layer, as well as the speed at which the filament is extruded at each point along the path.

Note

An STL file or other 3D model file is **not** the same as a GCODE file. A GCODE file is obtained after putting an STL file through a slicing software and is the final file that will be uploaded to the 3D printer. Attempting to print an STL file directly on the printer is not possible and is a common mistake. Your printer will likely fail to recognize the file or refuse to print it.

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4.3: Parts of a 3D printer

Learning Objectives

By the end of this section, learners will be able to

1. Identify the main parts of a 3D printer.
2. Explain the function of each main part of a 3D printer.

The parts of a 3D printer all serve specific functions: to move the hotend in 3D space, to insert filament into the hotend, and to control the printer. Generally, 3D printers use motors that control the X, Y, and Z axes in tandem to move the hotend to the location where filament needs to be deposited, as defined by the GCODE. Core XY printers are the most common archetype of FDM printers. They use motors to control the X and Y axes for the hotend assembly's movement, while the bed moves up and down along the Z axis. However, 3D printers employ various methods to achieve printing. Some printers move the hotend only along the X and Z axes, for example, leaving Y-axis movement to the bed itself.

The popularity and widespread adoption of 3D printing have increased in recent years due to a few factors, including the availability of precision parts and the development of powerful home computing equipment that enables the creation of detailed instructions for the 3D printer to follow.

To 3D print something, all the parts of the printer need to work in concert with precision movement, temperature, and timing. Listed below are the major components of most 3D printers. Read Section 4.4 “3D Printing Process” for more context on how these parts work together.

Build Plate

The build plate is where a print is formed; for many printers, it is controlled by a belt underneath it which moves it in the Y axis. However, some printers have the build plate moving along the Z axis.

The build plate is also sometimes called the print bed, although this term may also refer specifically to the top surface on which a print is built. Different printers use different types of build plates. Most printer beds are heated; however this is not always the case. This is important to take note of when removing a print because a heated bed expedites this process greatly - the heat helps a print stick to the bed, and when the bed cools, the print is very easy to remove. Some build plates are classified as "removable build plates" made from steel that can be removed from the underlying heat bed, allowing the plate to be flexed to release a print from it. Other build plates have a top layer of glass which prevents the print from sticking too hard and being difficult to remove. The most important rule for maintaining a build plate is to avoid scratching it whenever possible. While a scratched build plate works fine, an unscratched plate always works better. Plates should also be kept very clean; isopropyl alcohol can be used, as can a light solution of soap and water.

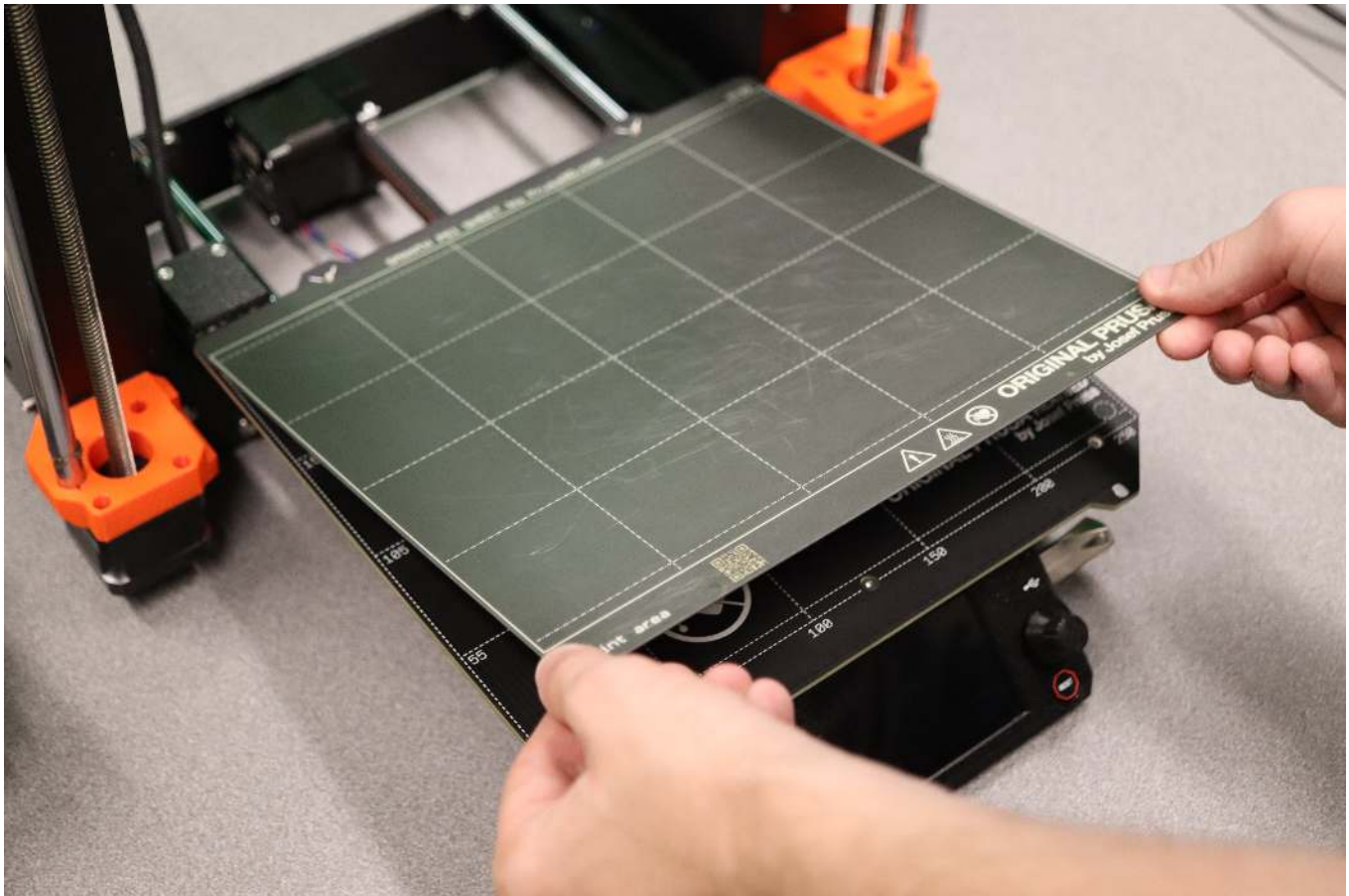


Figure 4.3.1: Prusa bed being removed from the build plate.

Console

The console is the display used to interface with the printer and to see information on the current print and its progress. Generally, it is controlled by a knob or touchscreen. Some 3D printers can be controlled remotely from a computer or a print server, or even a mobile phone. Consoles are typically the part of the printer where the ports to accept SD cards or USB drives are located, allowing for firmware updates or direct loading of print files.



Figure 4.3.2: Prusa Mk. 4 Console displaying the Print, Preheat, Filament, Control, Settings and Info menu options.

Hotend Assembly

The hotend assembly is where the nozzle is located, along with the important parts surrounding it. One or multiple fans surround the nozzle to help regulate the temperature along with the heater block and thermistor. Above the hotend is where filament feeds through either a Bowden tube or directly into the Heater Block, where it is melted. This area also contains the hotend itself, which, in the case of core XY printers, is controlled by a belt drive that moves it in the X axis.

Nozzle

The nozzle is the bottom-most piece of the hotend assembly. It takes the melted filament and funnels it down to a final, fixed diameter before depositing it onto the build plate. Nozzles come in a variety of sizes; however, most printers will come with a 0.4 millimeter (0.016 inch) nozzle out of the box, which can be switched out for a larger or smaller nozzle. A smaller nozzle will result in more detailed prints at a cost of longer print times. A larger nozzle will result in much faster print times, but at the cost of reduced detail and increased filament use.

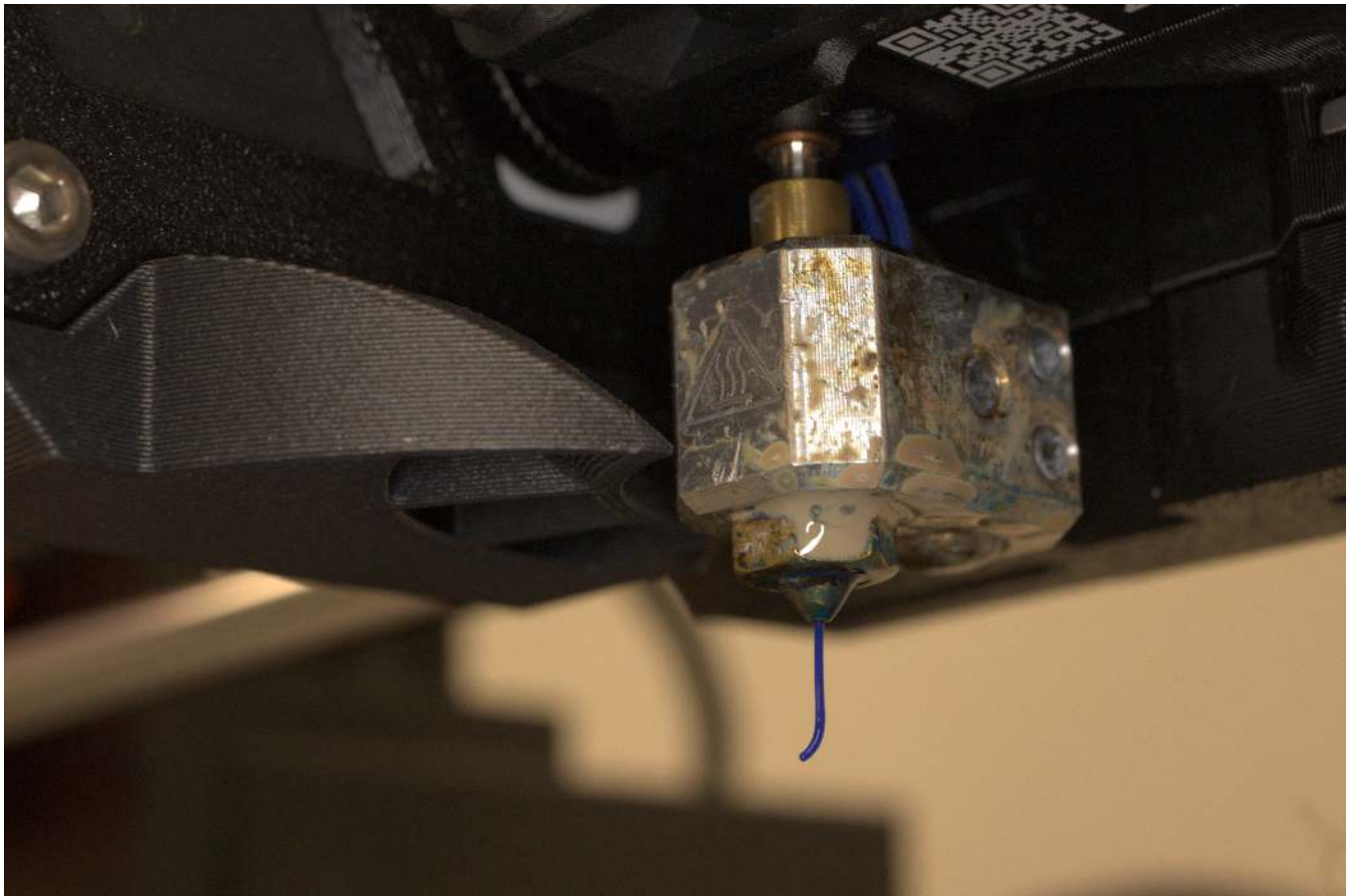


Figure 4.3.3: 0.4 mm Prusa Mk. 4 Nozzle extruding blue filament

Heater Block

The purpose of the heater block is to heat up to the temperature set by the user on the console, and as the extruder feeds filament into it, the filament will melt as it passes through the heater block. The Heater block uses a part called a thermistor to measure the temperature of the block to avoid overheating. This block is what makes up the "hot side" of the hotend assembly.

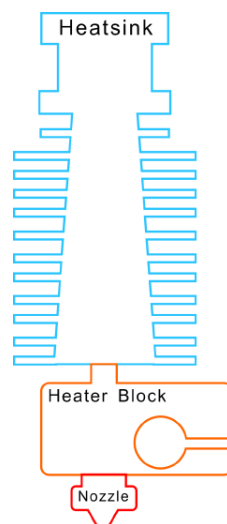


Figure 4.3.1: Diagram representing the components of the hotend assembly and their heat levels by color

Bowden Tube

If a printer does not feed the filament directly into the hotend assembly, it will use a tube made of PTFE (Polytetrafluoroethylene, Teflon), called the Bowden tube, which helps guide the filament from the spool to the hotend. In some cases, the Bowden tube will be placed after the extruder; however, it will serve the same purpose.

Extruder

The location of the extruder varies depending on the type of printer; however, it can usually be situated either directly on the hotend or near the stepper motor that controls the X axis belt drive. The purpose of the extruder is to use a motor to feed filament into the hotend at a controlled and programmed speed. In most printer models there will be a spring system to release the filament from the extruder system and allow free movement of the filament into or out of the hotend.

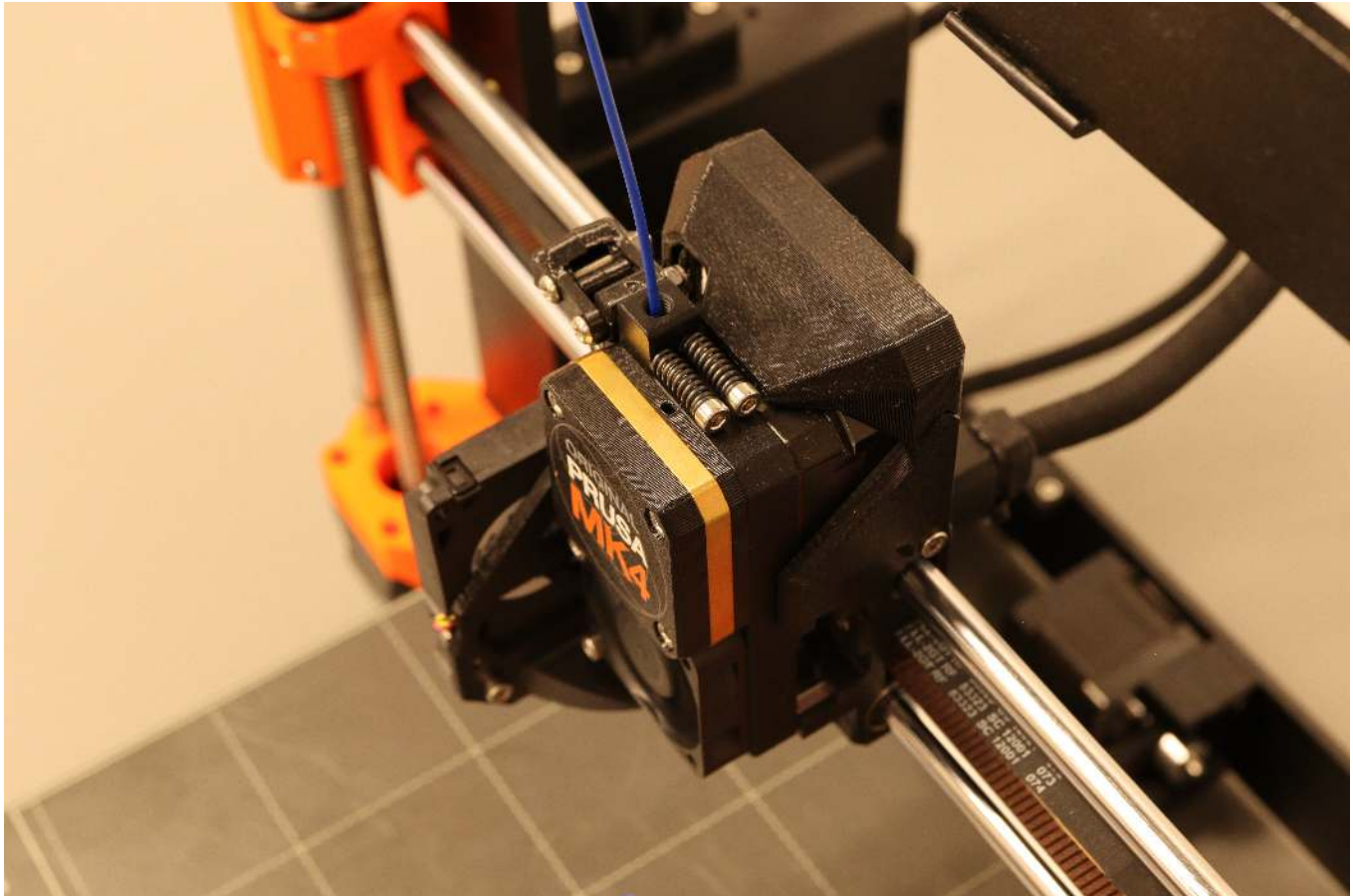


Figure 4.3.4: Extruder assembly on a Prusa Mk. 4 from above.

Definition: Parts of a Printer

- Core XY Printer: A design of 3D printer which uses a stepper motor and threaded rod to move the hotend along the Z axis, a motor and belt to move the hotend in the X axis using a gantry system and finally a belt to move the bed itself along the Y axis.
- Printbed/build plate: The surface which melted filament is laid upon, can be heated and/or removable though not always
- Console: The display used to interact with the printer, excluded on some printers in lieu of an application used for control.
- Hotend: The portion of a 3D printer which contains the heating and extruding mechanisms, generally it is what is moved in 3D space to create each layer of a 3D print
- Nozzle: This is a metal piece of the hotend that is heated up and funnels melted filament into a smaller diameter to be deposited onto the build plate
- Heater block: The heating element used to melt the filament, its temperature is controlled by the thermistor

- Extruder: This is a gear system that grips on to the line of filament and feeds it through the 3D printer

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4.4: 3D Printing Process

Learning Objectives

By the end of this section, learners will be able to

1. Build comprehension of each step of the 3D Printing process
2. Generate a 3D print using the given process

Importing a Model

Before beginning the slicing process, all design work should be completed in the chosen modeling software. While some slicers allow for minor editing, the model should be prepared as completely as possible before slicing. The 3D model should be free of any common errors; examples include incorrect units for measurements, geometry that isn't joined together correctly, etc. The finalized model is then exported—most often as an STL file—to a designated file location and opened in slicing software, such as Cura.

Model Scaling and Orientation

Once the model is loaded into the slicer, its scale should be checked. If the model does not appear, it may be either large or too small and require resizing. Orientation is equally important: the model must be positioned so that it rests on the build plate. Many slicers automatically place one face of the model onto the plate. The optimal orientation should be considered carefully, since 3D models are constructed layer by layer. Overhangs, floating features, or unsupported holes may require additional supports, which increase both print time and filament use. Minimizing the need for supports is the most efficient approach.

Printing Parameters

Once the object is oriented optimally, printing parameters can be adjusted. These parameters are discussed in detail later in this module; however, the process generally begins with adding supports, if necessary. Then, the layer height and wall thickness can be adjusted to dial in the detail and quality of the final print. Thinner layers increase surface detail but also lengthen print time. Additional wall loops strengthen the model, though again at the cost of time. These settings should be tailored to the intended use of the printed object.

Infill density and pattern are also important considerations affecting the structural integrity of a print. For most general-purpose prints, a 15% infill density is sufficient, and it is often the default setting in slicing software. Other settings, such as adding a brim or raft for adhesion, may also be adjusted. Most slicing programs include preset profiles optimized for speed, strength, or detail, which are appropriate for many applications.

Slicing and Loading

Once all parameters have been set, the model is sliced and exported to a storage device such as a USB drive or SD card. At this stage, it is advisable to check the estimated print time before exporting. If the time is too long, parameters such as infill density or layer height can be adjusted to reduce the print time, keeping in mind that changing these settings comes with trade-offs. After slicing, the storage device is inserted into the printer. From the printer's interface, the appropriate GCODE file can be selected, initiating the pre-print procedures such as heating and calibration.

Pre-Printing

The filament type has to be selected before printing begins. The build plate and hotend must heat to preset temperatures; after which, the printer homes to its default positions. A short extrusion line is typically deposited along the edge of the plate to expel any leaked filament or bubbles. After a test line, the printer will then begin to print the model layer by layer. During this phase, monitoring is essential, particularly during the printing of the first layer. If a print is going to fail, the first layer is most likely where the issue can be diagnosed by looking for problems such as poor adhesion, incorrect leveling, or clogged nozzles. If any of these symptoms are detected, the print should be stopped using the console to fix the problem before repeating.

Printing

Once the first layers are established, the print can generally proceed with only periodic monitoring. It is good practice to never leave the room for long periods while a print is running to avoid problems such as massive clogs, electrical issues, and other potential damage to the printer. Continuous supervision is not always necessary; however, for models with particularly challenging features, it is advisable to check the print when those sections are reached.

Removing a Print and Post-Processing

The printer signals the completion of the printing process and moves the print to a suitable position for removal. The method of removal depends on the type of build plate. Removable steel plates can be detached and flexed to release the print. For fixed build plates, the print must be carefully pried off, often using a scraper or a similar flat tool, to avoid scratching the bed. Caution should be exercised to avoid scratching the surface or touching hot components such as the nozzle or heated bed. If the printer has a heated bed, it will also remain warm, but to a much lower temperature than the nozzle; PLA, for example, often requires a print bed temperature of 50 degrees Celsius to 60 degrees Celsius (122 to 140 degrees Fahrenheit), which is comparable to the temperature of hot tea.

Once removed, any supports can be detached by hand or with pliers. Post-processing methods such as sanding, painting, or electroplating may then be applied, depending on the desired finish.

Definition: 3D Printing Process

- Infill: This refers to the pattern a 3D printer uses to fill in the empty, inner space, of the model it is printing, different patterns and the density of the infill are accessed in the slicer parameters
- Slicer: A specialized program that takes a 3D model and sections it into many layers which can be read by the printer as paths for the printer nozzle to take and extrude filament on. Also, the program used to modify various parameters of your model before printing

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4.5: 3D Printing parameters

Learning Objectives

By the end of this section, learners will be able to

1. Understand Printing parameters and how they affect the outcome of a 3D print
2. Develop the ability to adjust parameters in slicing software to fit the needs of different models.

This section outlines the various parameters that must be adjusted before printing a model. Many of these parameters are controlled through slicing software, such as Cura, while others are determined by material and design choices made prior to printing.

Cura is an open-source, freely available program that generates sliced G-code from STL models for 3D printing. As of this writing, it is available for download at from this [website](#). Although this module references Cura specifically, most popular slicing applications include similar features and controls for adjusting print settings.

Choosing a filament

The first decision in the printing process is the selection of the printing material. Filament is the material used in FDM 3D printers. It is typically supplied as a 1.75 millimeter (0.07 inch) cylindrical wire wound on a spool. The type of filament selected is a crucial consideration, as it significantly impacts the physical properties of the print. While many types of filaments are available, the choice depends on the intended application and, in some cases, availability within a classroom or print shop.

- **PLA (Polylactic Acid)** – The most commonly used filament, PLA melts at a low average temperature of 150-180 degrees Celsius (302-356 degrees Fahrenheit) with a glass transition at 55-60 degrees Celsius (121-140 degrees Fahrenheit) meaning it softens significantly at that temperature range (O’Connell 2024). PLA is reliable, not prone to cracking or adhesion issues and does not give off any fumes; however, it isn’t as strong as other filaments, and it can absorb moisture from the air and become brittle.
- **PETG (Polyethylene terephthalate glycol)** – A stronger, high temperature plastic filament which melts at 220-260 degrees Celsius (428-500 degrees Fahrenheit) and a glass transition at 80-85 degrees Celsius (176-185 degrees Fahrenheit) (O’Connell 2024). PETG is best selected for prints used in high stress applications or prints that will be in frequent contact with acidic or alkali compounds. PETG also is odorless and prints well on most surfaces with very good layer adhesion (“Important Advantages of PETG Filament in 3D Printing” 2025). One downside is that this is a relatively low viscosity filament which can be prone to oozing out of the nozzle (O’Neill 2024).
- **ABS (Acrylonitrile Butadiene Styrene)** – ABS filament is a tough, impact resistant filament with a lower melting point of 200-250 degrees Celsius (392-482 degrees Fahrenheit) and a glass transition of 100-110 degrees Celsius (212-230 degrees Fahrenheit) (O’Connell 2024). ABS offers similar chemical resistance and strength to PETG with the disadvantages of poor weather and heat resistance while having more thermal expansion than other materials (“ABS Plastic: Understand the Key Benefits and Applications” 2025) so avoid small gaps in your designs when using ABS. ABS is also known to give off an odor during printing that may irritate those with sensitive respiratory systems.

Importing Model Files

The first step to slicing a 3D model is to import it into the chosen slicing software. This module will reference the free and open-source slicer Cura; however, there are plenty of options for slicing software, and they will have similar features.

In Cura, models can be imported either by dragging the STL file from the file explorer into the Cura window or by using the “File” menu to navigate to the file’s location (see Figure 4.5.1). When successfully loaded, the model will appear on the virtual build plate. Models that appear unusually small or large can be resized during the orientation stage.

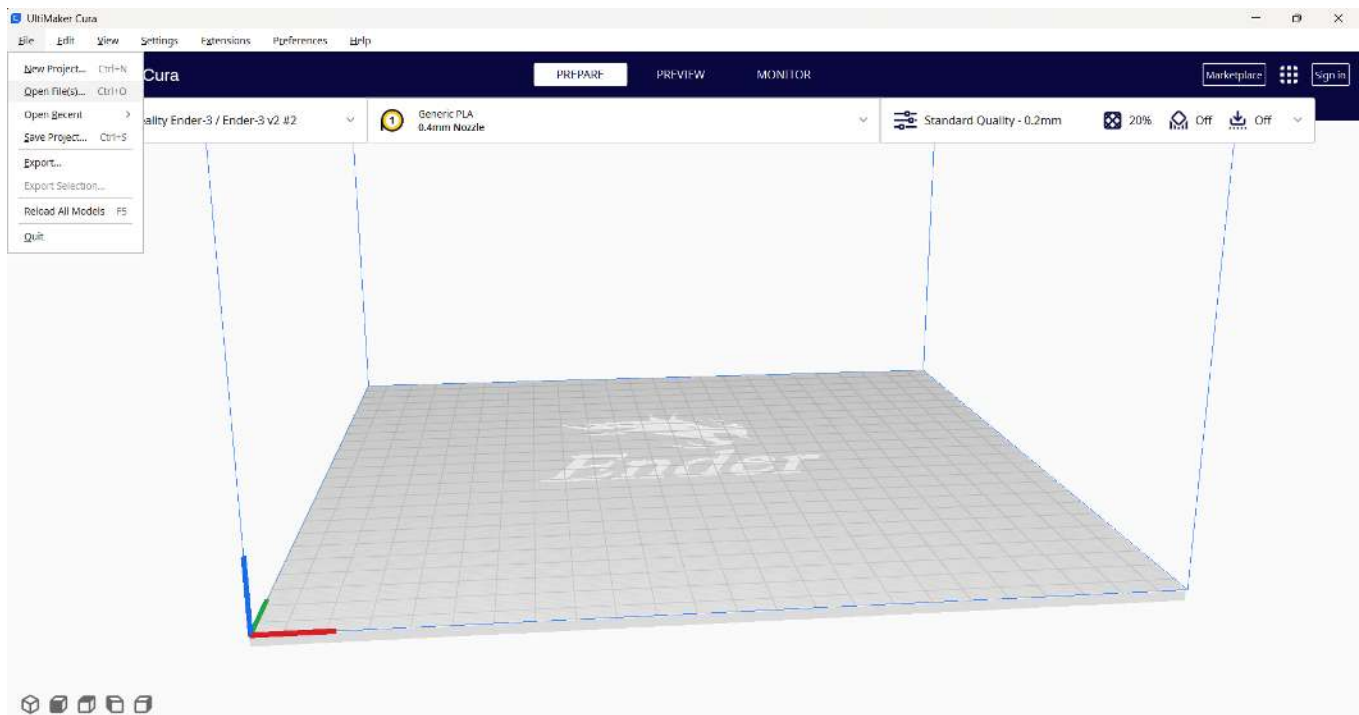


Figure 4.5.1: Importing a file into Cura can be accessed in the "File" menu

Resizing and Reorienting

Left-clicking the model uploaded in Cura causes a set of three arrows to appear, along with a menu on the left side of the screen. Clicking and dragging on these arrows moves the model along the virtual print bed. The menu on the left can be used to input precise movement in each direction. Clicking on the icon just below the movement icon with four arrows or pressing 'S' on your keyboard allows to resize the model. The arrowheads change to cubes, and dragging any of these scales uniformly scales the model in each dimension. There is also an option to enter exact dimensions or a specific percentage scale into the side menu. To scale along only one dimension, "Uniform Scaling" in the side menu must be unchecked, or "CTRL" can be held down while dragging the arrows. Note that this will deform the model along the selected axis. The hotkey combination CTRL + Z undoes any action in Cura.

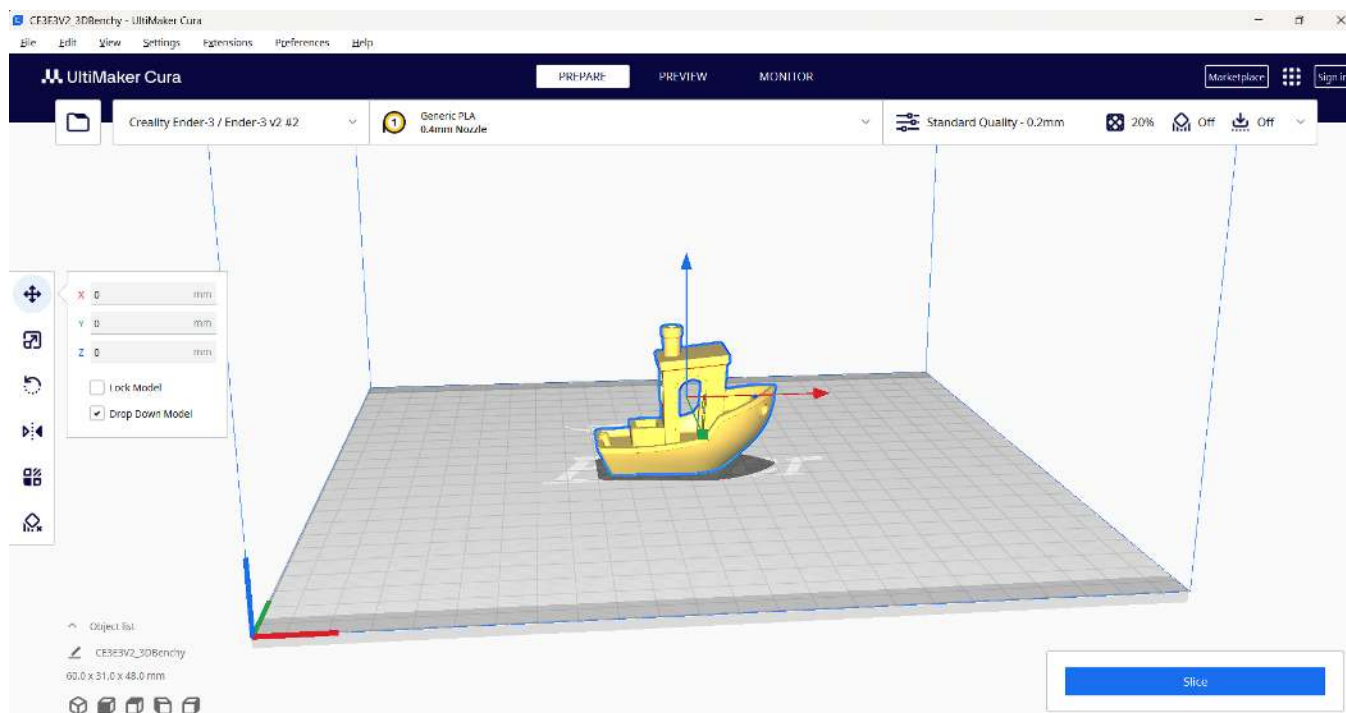


Figure 4.5.2: The reorientation options in Cura

The final option for reorienting a model is the rotate tool. This tool can be accessed by selecting the icon immediately below the resize icon or by pressing the “R” key on the keyboard. When activated, three circles appear around the model, each corresponding to one of the three axes of rotation. To rotate the model, the cursor must be hovered over a ring until it highlights, then clicked and dragged. By default, the model snaps to 5-degree increments, though this can be changed by unchecking the “Snap Rotation” box. The rotation menu also provides three icons: the first resets the object’s rotation, the second ensures the object lies flat on the print bed—maximizing bed contact for adhesion and minimizing the need for supports—and the third aligns a selected face to the build plate for precise orientation. Reorienting the model is an important step in achieving the intended result. Orientation should account for how the model will be printed and how this will influence its strength. The accompanying diagram illustrates this concept.

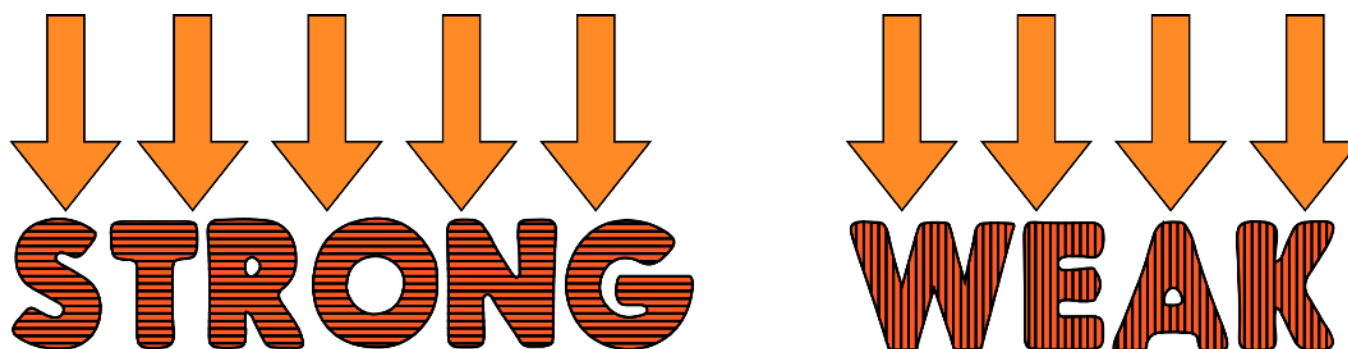


Figure 4.5.3: Diagram demonstrating how the orientation of layer lines can affect the strength of a model.

Layer Height

The layer height determines the thickness of each slice in the model; changing this value will affect both the time required for printing and the print quality. A higher layer height will decrease the total time the print takes by sacrificing resolution, whereas a shorter layer height will increase printing time but add more detail to the model.

Wall Thickness

When a model is 3D printed, it is typically not a solid piece of plastic; the slicing software generates empty spaces within to conserve filament and reduce print time. The part of the model that is visible, the outer skin, is made up of only a few layers of

"skin"; this is called the "wall". The thickness of the wall can be adjusted depending on the level of strength required for the print.

The wall thickness determines the number of skin layers (walls) of the 3D print. Generally, thicker walls will result in a sturdier print, albeit at the expense of increased print time and material usage. This menu also includes the option to change the Z-seam orientation. The Z-seam is a line that forms on vertical prints due to the short pause the nozzle takes after finishing a layer. This pause can leave excess filament in that spot. To avoid having these blobs all over the print, the Z-seam alignment can be used to align these pauses to occur in a user-specified area, along the sharp corners of your model, the shortest path, or randomly.

Infill

Infill is one of the most important parameters to consider when printing a model. In short, infill determines how much of the inside of the print is filled and the infill pattern. It would be expensive, time-consuming, and unnecessary for a model to be a fully solid element; in fact, one of the advantages of 3D printing is that both time and material can be saved by cleverly adjusting how much material is used for the interior of a model. A larger infill density will significantly increase the model's strength, albeit at the expense of longer print times. Generally, for non-functional prints (i.e. prints that will not be used to carry a load, move in some way, or have some functional purpose aside from sitting on a shelf) a good practice is to select a 20% infill or less. If the printed object has to undergo much stress or be used frequently, careful consideration must be given to selecting the infill density and pattern. Slicers come with a variety of patterns for infill, which affect the print's strength. Benedict O'Neill from Wevolver (O'Neill 2024) provides the benefits of each infill pattern as follows:

- **Grid** - Strong 2D infill for vertical prints
- **Lines** - Quick 2D infill
- **Triangles** - Strong 2D infill with shear strength
- **Tri-hexagon** - Strong 2D infill; the strongest included in Cura
- **Cubic** - Strong 3D infill, good for functional parts
- **Cubic Subdivision** - Strong 3D infill with good strength/weight ratio, but slow
- **Octet** - Strong 3D infill with high strength but poor top surface quality
- **Quarter Cubic** - Strong 3D infill good for thin parts but poor top surface quality
- **Concentric** - Flexible 3D infill useful for bendable low-infill parts and strong high-infill parts
- **Zig-Zag** - Quick 2D infill useful for PETG prints
- **Cross-Flexible** - 2D infill Useful for bendable parts only in the horizontal direction
- **Cross 3D-Flexible** - 3D infill useful for bendable parts in all directions
- **Gyroid** - Strong 3D infill that is aesthetically pleasing but slow to slice
- **Lightning** - Quick infill which uses less material for lightweight/low strength prints

Supports

Adding supports to a model allows printing just about any imaginable shape. Supports are temporary structures that the slicing software can automatically generate while preparing to slice the model, allowing for printing models with parts that are floating above the build plate or other parts of the model. If the design includes floating geometry, the slicer will often recommend adding supports.

Adding supports is done in Cura by choosing "Generate Support" in the print settings, which will bring up three options. The first option is "Support Placement"; this determines where supports are generated on the model. By choosing *Everywhere*, supports will be generated underneath any overhanging parts, even if they hang over other parts of the model. "Touching Buildplate" only generates supports when the overhanging parts are located directly above the buildplate. These options should be carefully considered, because the removal of supports may leave marks or blemishes on the model.

If the model has holes that require the filament to bridge large gaps without any existing filament to support it, the "Everywhere" placement should be selected to ensure a more stable structure. If the model does not have any holes that need support, but does have large 90-degree overhangs over the print bed or floating structures, the "Touching Buildplate" option should be enabled, which will place supports from the bed to your overhanging structures.

Bed Adhesion

Several parameters adjust the adhesion of the print to the bed. Bed Adhesion is one of the most important aspects of 3D printing, so it is best to do everything possible to ensure that the print stays on the bed. The first step in achieving this is editing these parameters. The first parameters are rafts & brims. The following parameter, which can improve bed adhesion, is the Z offset.

Note

This section was written for Cura version 5.4.0; there may have been an updated release since the time of this writing, so the information provided is not guaranteed to be current.

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4.6: Post processing

At this stage, the printer has completed every layer of the model and should display a message on the console indicating that the print is finished. Post-processing includes removing the print from the bed, removing supports, sanding and deburring, priming and painting, as well as methods for joining multiple prints.

Removing Print from the Bed

When the print has finished, the printer moves the nozzle up, the print bed forward, and begins to cool down. Allowing the print bed to cool down will facilitate the removal process. The process for removing prints varies depending on the type of print bed. The two main types of print beds include removable and non-removable.

If the print bed is removable and bendable, it can be removed from the printer by gripping the edges, which will generally protrude past the heated element of the bed. Often, beds are attached with magnets, which makes them easily removable. Keeping the grip at the edges and refraining from touching any other part of the bed is crucial for maintaining a clean printer and prevents the need for constant leveling and cleaning before printing. Once the removable bed is detached, and if the print has not detached itself already, the bed can be gently bent from the sides, which should release the print from the bed. Soft cracking or popping noises may indicate that the print has detached from the bed. If the brim or any other flat parts of the print are still attached, they can be removed using a flat instrument, such as a scraper, being careful not to scratch the bed itself. A scraper made of a material that is softer than the print bed can be used to avoid scratching; there are, in fact, many models of scrapers that can be downloaded and printed. If bending the bed does not release your print, a scraper can be used to separate the print from the bed. Alternating wedging and gently bending the plate can help release the print.

The process for beds that are not removable, such as glass beds, is similar. The first step involves allowing the bed to cool down before starting to remove the print. If pulling the print from the bed does not work, a scraper can be used to wedge underneath the print while pulling upwards to attempt to separate it from the bed. Touching the bed with bare hands should be avoided to prevent future adhesion and leveling issues. It can be helpful to wear gloves during the removal process.

If these attempts fail, the bed can be heated to the glass temperature of the filament to remove the print while it is still heated. Special attention must be paid to avoid burning hands or deforming the model during this process.

Removing Supports and Rafts

Supports are designed to be easily removed from prints; however, caution must be taken during removal to avoid damaging the print. For supports that are easily accessible, it is best to begin by holding the main print firmly while using the other hand to detach the supports. The process usually starts by pulling the supports straight off. If that does not work, twisting or prying the supports may help, although this method carries the risk of the supports breaking in half instead of separating cleanly. When a print has finished recently and the printer settings are well-calibrated, supports typically come off cleanly and with minimal effort. In cases where supports are more stubborn, tools such as needle-nose pliers, small tin snips, or nippers can be very effective for removing and cleaning up remaining pieces. The same principles apply if the model includes a raft, although rafts are often easier to remove than supports. Removal generally begins by prying at the edge of the raft; if this is unsuccessful, pliers can be used to gain a better grip. Should the edge snap off with no grip points remaining, a flat and sturdy tool may be wedged between the print and the raft to separate them, allowing for easier removal.



Figure 4.6.1: A pair of wire cutters commonly used to clean up 3D Prints

Sanding and Deburring

Due to the nature of 3D printing, prints may appear less smooth than intended. In such cases, the surface can be refined using a deburring tool or sandpaper. This process is not required for every print, but for decorative pieces such as helmets or props, sanding can significantly enhance surface quality and enhance the overall appearance of the model. A deburring tool is particularly useful for removing excess material cleanly before sanding. If a deburring tool is not available, similar results can be achieved with a hobby knife or tin snips.



Figure 4.6.1: Deburring tool used to clean up the edges of 3D prints

Before sanding a 3D print, it is important to wear appropriate Personal Protective Equipment (PPE) depending on the material being used. Recommended PPE for sanding 3D prints may include a respirator—particularly when using dry sandpaper—and gloves, as plastic particulates can remain on the skin for an extended period. Sanding can be done by simply rubbing the print with sandpaper; however, for a smoother finish, applying a filler such as wood filler or Bondo auto filler (with proper PPE) and allowing it to dry before sanding will result in a cleaner surface with fewer visible layer lines.

Priming and Painting

Painting a 3D-printed model can be done either immediately after printing or following sanding and deburring. Acrylic paint provides a quick and straightforward option for most prints, though the finish may not be as smooth. A finer and more polished result can be achieved with spray paint and primer. Many resources exist for advanced spray-painting techniques, but the basic process is as follows. The model should first be cleaned of any debris, then suspended with fishing line or hanging wire. If hanging is not possible, a cardboard enclosure can be used as an alternative. To fully conceal the filament's original color, apply two to three coats of spray primer before the final paint color. Preventing paint from pooling or dripping is essential, so proper spray technique is key. Each pass should begin off to the side of the model; the paint is applied in a quick, steady motion across the surface, with the spray released once it clears the edge of the model. This process should be repeated on all sides, minimizing overlap if multiple passes are necessary. Primer coats must be allowed to dry completely, with drying time varying according to temperature and humidity as specified on the can. Once the model is primed and dried, the final spray paint color can be applied using the same technique. Typically, no more than two coats are required on a well-primed model. A final layer of polyurethane or shellac may be added to seal and protect the paint finish.

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4.7: 3D Printing example

This section includes an .stl file of a chess piece (pawn) for 3D printing.

▯ [Pawn.stl](#)

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CHAPTER OVERVIEW

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5.1: Instructor's Guide to 3D Printing

Introduction

This guide serves as a supplementary appendix to the Introduction to Engineering Drawing and Design text; in particular, to Module D, which focuses on the basics of 3D printing. While the audience for Module D is the student learner - providing them with sufficient background to understand how to bring their engineering models into reality through fabrication - this guide is intended for the instructor, who it is assumed will be managing access and usage of the actual 3D printer and its associated workspace.

You - the instructor - may be interacting with a 3D printer in a variety of circumstances. You may have your own 3D printer in your classroom or academic department, or you may know where to access one on your campus. You may be interested in incorporating 3D printing into your curriculum but are still yet at the stage where you're considering purchasing one. In some circumstances, you may have been given a 3D printer and are now wondering what you need to do to take advantage of it in an instructional context.

This guide is not intended to be a comprehensive manual that will walk you through each step of the "proper" way to run a 3D printing workspace. The variety of possible circumstances its readers may find themselves in is too diverse for that endeavor, and as with any creative pursuit, things can get messy. Rather, the goal of this text is to equip the reader with basic tips and advice which you will hopefully find useful in streamlining your use of 3D printing for instruction. In addition to that, it is hoped that the reader will be emboldened in their confidence that 3D printing is both a valuable and achievable component of their curriculum.

The authors of this guide draw from their experiences working in a university library makerspace which has facilitated access to 3D printing in a variety of contexts. Print-on-demand - where students submit print files and later pick up the finished prints - is the core service, but staff of this makerspace have also offered interactive instruction in a variety of contexts, from formal classroom visits to one-on-one 3D printing coaching as well as training makerspace student assistants themselves. The hands-on, trial-and-error experience gained from developing these services informed the tips and tricks that will follow here, and we sincerely hope that they aid you as you join us in the greater enterprise of sharing 3D printing knowledge with the next generations of students.

Using This Guide

Content in this guide is organized into three main sections intended to flow in a logical progression. [Setting Up a Workspace](#) provides advice on how to equip your classroom or instructive space with a 3D printer and its accessories, as well as tips on how to ensure a secure and safe environment. You may also choose to train students or other staff on using the 3D printer, and we have included lessons learned from our experience.

[Printing as a Service](#) follows from the establishment of the 3D printing workspace to its practical use. Again, the degree to which the reader may offer access to their 3D printers will be diverse; this section serves as a starting point, sharing tips and things to consider. The text that this guide accompanies assumes that the reader will involve students in nearly every step of the 3D printing process - idea to drawing to model to sliced GCODE to final print - which will require attention to time management, communication, and clear boundaries regarding access to the 3D printer itself. This may not be the case for all readers, and some may choose to handle all 3D printing on behalf of their students.

Finally, [Technical and Logistical Considerations](#) includes advice on the technical aspects of 3D printing that, in a class which assumes to be introducing basic 3D printing concepts to students, may be advanced to the point that they should hold the attention of the instructor only. This section will discuss the management of various print files and software; advice on completing a large set of prints equitably and expeditiously; and customizing your printer for various tasks. Modern, consumer-level 3D printers are remarkably reliable; however, there are often still print issues that must be diagnosed and solved, and so this guide will wrap up with a treatment of common problems and potential fixes.

Each section may reference other parts of this guide, but the authors have attempted to allow the reader to refer only to the portions of the guide that are relevant to their own setup. As this guide is written to supplement an Open Educational Resource, readers are also encouraged to remix and reuse it in whole or part in their own instructional materials, in the spirit of collaboration and open principles.

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5.1.1: Choosing a Printer

Choosing the printer that's right for you can be a confusing process, especially if you aren't all that familiar with what you want out of a 3D printer. Choosing a 3D printer mostly comes down to a few categories

Price

The biggest factor, when it comes to purchasing a 3D printer will always be the price. Although printer prices have declined steadily in the past few years, a good 3D printer is still a considerable investment. While there are printers online for as low as \$100, the precision and consistency required for 3D printing doesn't work well with the cheap parts used to make these printers. Perform some research online. Seeking advice from 3D printing hobbyist forums, rather than from material published by 3D printer companies themselves, is recommended, as discussions will be more frank and unbiased. Several companies appear over and over again in online discussions as generally recommended, with entry level printers in the \$300 to \$800 range.

Reliability

If you intend to use your 3D printer often, but you're just starting out in your 3D printing journey or you need to minimize printer repair downtime, reliability is a big factor in what printer you want to purchase. Generally, it is advised to stick with the big names in 3D printing, which you will discover through researching online hobbyist communities; however, newcomers to the market often appear and careful brand research is advised. A reliable 3D printer can often come at the cost of a higher price tag because the reliability comes from a more careful design, more durable (and therefore expensive) materials, and more precise machining and production of parts. Often, 3D printers come semi-assembled or as kits to make yourself. If you choose the latter, make sure you are equipped with the appropriate tools to assemble your printer. At the very least, you will need an electronics screwdriver set with phillips, flathead, and hex-head bits, both metric and imperial.

Print Area

Depending on what you intend to print, the print area can be a very important factor to consider. If you want to print large pieces like Helmets, prop weapons, armor, or even furniture, you are going to want a larger bed. Generally a print area of 250 mm x 250 mm will fit most prop items like helmets and such, but some models on the market can support print volumes exceeding 800mm x 800mm x 1000mm (with proportional price tags). It's possible, and one may even say fairly easy, to break up a large model into smaller parts for printing and reassemble them with glue. A large-format printer is therefore not explicitly necessary for large-format printing, though it does make the process more efficient with less print post-processing.

Use Case

If you are buying a printer for your own personal and recreational use, you really can't go wrong with any of the ones previously mentioned. However, if you are using your printer for volume printing in an instructional or workshop setting, you really want one that is reliable and easy to repair; some manufacturers even design their printers to use 3D printed parts themselves, and this allows you to print a set of replacement parts right away after you set the machine up. If it's only for your personal or classroom use, you could also save some money by purchasing a printer kit. These are kits containing all the parts needed to assemble a 3D printer yourself; reputable companies like those listed above pack them with easy-to-understand instructions that make assembly not-too-complicated and can lessen the financial impact of buying a fully-assembled printer. Your classroom may not have the necessary space for assembly; therefore, buying a prebuilt printer would save you many hours of assembly and be easier to transport to the room you will be using.

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5.2: Setting Up the Workspace

Just as there are many approaches to setting up a space for instruction, your combination of considerations when preparing your classroom for 3D printing will be wholly your own. You may choose to keep your 3D printer directly within your instructional space, or you may decide to house your printer in a departmental space so it can be shared with colleagues. You may even aspire to set up your own Maker Space and provide campus-wide access to the equipment to some degree. Each deployment case brings its own challenges.

Choosing a Space

In terms of the basic area of desk space occupied, a 3D printer may require, perhaps, a square two feet on a side. Some printers have moving parts which will require some empty space for clearance; for example, some printers have beds that move on the Y-axis (forward and backward), so they must have space behind the printer for clearance. While it's not required that a 3D printer be connected to a computer at all times (since most 3D printers can accept print files via USB drive or SD card), you may choose to have a dedicated computer next to the printer if one is available to allow for on-the-fly slicing or model corrections. Be sure that your space has enough power outlets and, if a desktop computer is used, ethernet ports for internet connection.

As described in the next section, [Equipment and Supplies](#), you'll find a variety of tools and accessories very helpful as you use your printer, so be sure to allow storage space for them. A small shelf or cabinet for tools, safety equipment, consumables like tape and glue, and spare parts is extremely helpful for both space efficiency and ease of retrieval when you need such supplies. 3D printing can, unfortunately, also result in a certain amount of filament waste; be sure to have a receptacle for trash nearby as well.

One major consideration in terms of storage space is the raw material used for 3D printing - plastic filament. Filament is sold on large spools, usually weighing 1 kilogram and measuring about one foot in diameter. Filament is sold in a wide variety of colors, textures, and properties, and you'll probably want to stock more than just black or white filament. Depending on your throughput, you may need to have more space for filament rolls than the 3D printer itself. Read more about filament storage in the "Ventilation, and Climate" section below.

Modern 3D printers are less disruptive than in the past, both in terms of noise and odor. However, you should still take this into consideration - a 3D printer operating openly in the same space that you're trying to lecture can be disruptive, and probably annoying. If possible, try to set up your printer in an enclosed and reasonably soundproof space, but not so tucked-away that it will be difficult to check on active prints occasionally. Some have achieved success in building a tabletop soundproof enclosure for their printers, which has the added benefit of creating an enclosure with uniform internal temperature - this helps ensure successful prints immensely, to the point that many commercial 3D printers are themselves enclosed.

You may also consider instruction itself when setting up your 3D printer. Do you plan to gather your class around the printer to explain how it works, or to demonstrate it while it prints? Make sure this is possible regarding open space around the machine. Consider putting your printer on a rolling cart so you can move it out of its enclosure for demonstrations when needed, but be sure to use a cart with sturdy wheel locks to prevent vibration. On that note, vibration and leveling are important considerations. A 3D printer's motors will produce a fair amount of momentum, and if a table isn't sturdy enough, it will wobble and vibrate during a print. This can, of course, cause print errors, so choose a solid and sturdy table. The surface should be reasonably level, but this is less of a consideration than you might assume. It's more important that the various parts of a printer are level *with respect to each other* than for the printer itself to be level with respect to the ground, and most printers include an automated process for regularly ensuring internal alignment of parts.

Finally, after your prints are complete, they will - in most cases - require some form of finishing, be it support removal, sanding, or painting. If you expect these activities to occur in your 3D printing shop, you must provide space for it. It need not be a dedicated, clear work space - if you're working in a classroom, students will be able to finish their prints at their desks or workstations, if enough supplies are available for them to use. But keep this in mind when thinking about the place you intend to set up as your "3D print shop".

Security and Access Control

3D printers are expensive and desirable machines, so it's as important to maintain security against theft as it would be for any valuable technology. Beyond that, however, consider who should have *access* to the machine. As described in the section [Shop](#)

Rules and Training, you may decide to train students or colleagues on the direct use of a 3D printer, or you may opt for a mediated style of access where 3D print files are submitted to you and you alone hold the expertise in operating the printer. The least advisable practice would be to allow anyone to use the printer at any time regardless of their skill level. Lack of understanding of the operation of a 3D printer can lead to costly errors both in terms of money spent on repairs and printer downtime. It's highly recommended to deploy a method of access control to your 3D printer; it may be in a locked room to which only a select known few have a key, or you may develop a system of trust with your students on who is allowed to use it.

Some printers allow you to program user access controls whereby a password must be inputted on the control panel in order to use it. If you're unable to otherwise secure your printer physically, consider this method of access control. A tried-and-true method of access control - used in industry, for example - is to physically disable the 3D printer when not in use by removing an essential part. Most 3D printers have detachable power cables, for example; consider setting up a practice in your classroom where only the power cable is locked up, and students must "check it out" from you in order to use the device.

Ventilation and Climate

3D printers work by heating plastic filament up to its melt temperature and depositing it, layer by layer, on a (usually) heated print bed. A series of fans are typically installed on the printer for fine temperature control during this process. The filament needs to stay liquid enough to flow onto the build plate, but it must harden almost immediately so that the next layer is able to be deposited upon it. If you've ever been near melting plastic, you'll know that some formulations produce odors and fumes when they melt, and these can be irritating to those with sensitive respiratory systems. In addition, some substances are known to change volume depending on temperature, a property called thermal expansion, and conversely to shrink when cooled.

Because of possible production of irritating odors, it's not advised to run a 3D printer in a space continuously occupied by people, though some filaments give off less odor than others and may be better tolerated. If a 3D printer must operate in an occupied space, be sure to have adequate ventilation. However, a balance must be struck between ventilation and thermal uniformity of the printer's actual build volume. If a model experiences an extreme thermal gradient - that is, part of the model is much cooler or warmer than another part - it may warp due to thermal contraction; in the worst cases, it may warp to the point that it peels itself off the print bed and ruins the whole print. Once again, this is why many printers are built to enclose the print volume entirely. You may be tempted to set up a room fan near the 3D printer for ventilation, but be cautious of causing a thermal gradient in doing so. Similarly, try to locate your printer in a room that is not noticeably drafty, uncomfortably cold, or located in direct sunlight.

Humidity is another consideration when thinking about your printer, and in particular, when thinking about storing your myriad rolls of filament. Some filament formulations are sensitive to air humidity. Polylactic acid or PLA, one of the most popular 3D printing filaments, is infamous for its property of hygroscopicity - the tendency to absorb moisture from the air. When PLA absorbs too much moisture, a host of frustrating print failures can occur. Print layers may not adhere to one another properly, the surface of the model can appear blobby and uneven, or there may be bed adhesion issues. You may hear pops and hisses from the hotend as air evaporates directly out of the filament following heating. The worst effect of "wet" filament is its tendency to become brittle on the roll. This can easily cause a failed print if your filament breaks off as it's being fed into the hotend, and if the filament shatters *within* the hotend, it can be a big headache to disassemble and clear out.

There are a number of ways to ensure that your filament stays dry. Many brands are shipped inside resealable, plastic zipper bags; don't throw these away! Always return your filament to its bag after use to keep it dry. Silica gel packets can be purchased cheaply from online retailers, and they can help immensely to absorb moisture from the air before your filament can. Add a couple packets to each filament's bag when storing them away. You may even consider investing in weatherproof plastic tubs with sturdy gaskets to store your filament rolls and keep out moisture. At the author's maker space, filament is organized into such bins, with each bin serving a bonus purpose of organizing filaments of the same color together, one color per bin.

If you find that the worst has happened and your filament has become moist and brittle, there are ways to rescue it. Commercial "filament dryers" are available online that heat one or more rolls of filament to a preset, optimal drying temperature to drive off moisture. Some hobbyists have reported success with drying filament rolls in home kitchen ovens, but this practice should be done at your own risk. Plastic filament melts at a particular temperature known as its melting point, and in terms of printing, have recommended printing temperature ranges - for PLA, this is between 180 degrees C (356 degrees Fahrenheit) and 220 degrees C (428 degrees Fahrenheit). However, they often have "glass transition" temperatures much lower than their melting points at which they begin to soften and deform significantly - for PLA, this temperature is 55-60 degrees C (131-140 degrees Fahrenheit). To

adequately dry a roll of filament, you must heat it to a high enough temperature to efficiently drive off moisture without hitting the glass transition temperature: 40-50 degrees C (104-122 degrees Fahrenheit) seems to be a good target, so be certain that whatever heating method you use allows for fine enough temperature control not to exceed that.

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5.2.1: Equipment and Supplies

Recommended Tools

After buying your 3D printer you are pretty much set to print anything, this does not mean that there aren't a few things you can buy to make your life easier. In fact, many commercial 3D printers on the market come with an accessories kit containing some of the following tools and supplies.

One tool that will make 3D printing easier is a **scraper** to aid you in getting prints off the bed. There are specialty print scrapers sold online that you can buy, or a paint scraper from a hardware store will generally do the trick. Buying a relatively soft scraper rather than a metal scraper will decrease the chance of scratching your bed while removing a print, so plastic or hard rubber is generally advised. If you'd like to avoid the cost of purchasing one, you can even print your own scraper from one of many files uploaded online.

Another useful tool to buy after your printer would be some **nippers**; these small snips will help you clean up your prints after they are off the bed and come in handy for trimming the ends of your filament when they break or bend out of shape. They're often sold at hobby stores or used in fine electronics work; you might also see them advertised as **flush-cut nippers**.

Needle-nose pliers can be handy for removing print supports. Specialized versions for jewelry making can be found in hobby stores and can be purchased with a variety of shapes and angles to get at hard-to-reach parts of a print.

Hobby knives can be very helpful for finishing prints but be careful about including them in an open shop's collection of tools - it's very easy to cut oneself if such tools aren't used properly. Plumbers and pipefitters will be familiar with "**deburring**" tools that clean the edges of pipes after they have been cut; these tools are also useful for similar purposes to clean up the edges of 3D prints. Consider purchasing a cheap set online.

Occasionally, you may need to remove a clog from your printer's nozzle. The hole in most standard print nozzles is 0.4 millimeters, which is quite thin; thinner than most sewing needles, thumb tacks, or pins. A common tool-of-the-trade among 3D printing hobbyists for clearing nozzle clogs is, surprisingly, **acupuncture needles** - widely available online. Sharp and made of durable spring steel, these needles are a great addition to your toolkit. Take caution when clearing nozzle clogs - metal acupuncture needles can transmit the heat from a hot nozzle very quickly, so be sure to use insulated gloves when trying to clear a clog.

There is a good chance that you will need to remove very small machine screws from your printer for repair or adjustment. Invest in a good set of **electronics screwdriver bits** for this purpose; be sure to get phillips, flathead, and hex-head bits at the very least, both metric and imperial.

Measurement tools are also essential, especially if you need to print a model that replaces a real-world object or must interact with an existing item. **Small rulers** are recommended, and metric is generally preferred for 3D printing projects. The best measurement tool might generally be considered to be **calipers**, which can be purchased in both digital and analog forms. These measurement devices often allow for accurate measurements of up to one-hundredth of a millimeter and are quite easy to use after some practice.

3D printing can, unfortunately, result in a certain amount of filament waste. For day-to-day projects, consider including a **small tabletop trash receptacle** so you can store filament fragments and keep your workspace tidy. This will give you the small convenience of not having to walk to the nearest trash can each time you must throw away a few grams of waste.

Cleaning Supplies and Consumables

FDM 3D printing can cause a certain amount of clutter as waste filament is generated, but luckily, it's generally not messy in the sense of regularly requiring the use of cleaning solutions - except for the very important practice of keeping the print bed spotless to encourage good print adhesion. If oil, dust, or filament residue is allowed to accumulate on the print bed, future prints will have a harder time sticking to it at the first layer, and print failures will become more frequent. Stock isopropyl alcohol (IPA) wipes or a bottle of IPA with some paper towels and wipe the print bed down frequently. If you're experiencing really tough bed adhesion issues, you can wash your bed with dilute soap and water, ensuring that you dry the bed thoroughly before printing again.

Your printer is a machine with moving parts. It likely came, from the factory, fully lubricated with machine oil or lithium grease, and your printer may have been packed with extra grease. You may consider purchasing additional grease for long-term sustainability; refer to your printer's manufacturer documentation on the proper grease to purchase.

Depending on what you plan to print, you may choose to stock sandpaper to help remove leftover supports or layer lines. Purchase a variety of grits; when sanding, remember to always start with the coarser grit and work down to the finer grit. Filaments such as PLA do not, admittedly, sand very well, so take this into consideration.

It's almost inevitable that one of your prints will break shortly after it's complete. For PLA filament, good old hardware store super glue (cyanoacrylate glue, or CA glue) works very well. If you're unable to clamp or hold your parts together, you can purchase CA glue accelerant spray; simply apply CA glue sparingly to your parts, then hold them together and spray with the accelerant lightly.

Safety Supplies

We will expand on this section within the [Safety](#) page of this section, but for the sake of completeness, we will list some recommended safety equipment here. The greatest personal safety risks in a 3D printing workshop are, in no particular order, burns; cuts; and electrical shocks. Equip your space accordingly.

Of course, no work space would be complete without a simple **first aid kit**. Purchase a pre-made one, or put one together yourself. Band-aids, gauze and tape, and other supplies for protecting small injuries are of course recommended.

Parts of a 3D printer get hot enough to exceed the boiling point of water and are therefore capable of inflicting severe (but localized) burns. **Insulated gloves** are highly recommended when performing any maintenance or troubleshooting that brings you close to a heating element. Paper towels themselves can be useful for manipulating hot parts; 3D printers generally do not get hot enough to burn paper unless they're experiencing some other issue.

When removing supports from a print, excitement may breed carelessness, and small filament fragments may become airborne at high velocities. When removing prints from beds or removing supports from prints, a pair of **safety glasses** is never a bad idea.

Inventory Control

Once you equip your space with tools and supplies and organize them to your liking, and as you use your printer over time, you'll start running out of consumables at varying rates, particularly filament. A small shop may be able to get by with ordering supply restocks ad hoc, but a busier shop may not be able to weather the few days it will take for new supplies to arrive.

Consider implementing an inventory control system. It need not be complex or use specialized software; a simple checklist on a clipboard can work to keep track of the current state of inventory. A system is only as good as its dedicated use, however. If you choose to implement inventory control, you should also establish guidelines on who is responsible for auditing the supplies and on what timeframe. You may also implement a system where shop users must indicate when, for example, a spool of filament or a bottle of alcohol is used up, and deduct it from the inventory sheet. Keep an eye on your inventory so that you will know when you need to order supplies ahead of time and avoid shop service interruptions.

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5.2.2: Shop Rules and Training

Establishing Shop Rules

The degree to which you must create (and enforce) shop rules will be informed by the number of people authorized and trained to use your 3D printing workspace. If you plan to be the sole operator of the 3D printer itself, then your rules may focus on authorization and access; however, if you plan to train some or all of your students to use the 3D printer directly, your list of rules will likely need be much longer. This section will not presume to supply you with a list of recommended rules; rather, we would like to share some points of consideration. Your shop rules will probably want to create boundaries that enforce the following:

- When the machine can be operated and by whom
- Shop organization and cleanliness
- Safety in the work space
- Proper operation of the equipment
- Rules governing equitable access to the equipment
- Communication guidelines
- Print parameter limits (maximum print time, filament use, etc.)

When the Equipment Can Be Used and By Whom

These rules will govern the shop hours, security, and accessibility. Will students be able to use the 3D printer outside of class? Must an instructor be present when the 3D printer is in use? Perhaps you have trained a subset of your class on using the 3D printer, and you want to ensure that at least one of them assists with each print. Is your 3D printer in a locked room, and if so, how will you manage access to the key or code?

Shop Organization and Cleanliness

Consider having a dedicated place for each accessory tool for your 3D printer and require your students to replace the tool to its designated spot when they're finished with the tool. Require students to clean up any filament waste at the end of their print. Ensure that all students understand that they must return any spools of PLA to airtight containers to prevent absorption of moisture from the air. You may include a rule requiring students to clean the build plate before or after each print. In the author's maker space, a bottle of isopropyl alcohol was provided with paper towels; students chronically forget to replace the cap, causing the alcohol to evaporate.

Safety in the Workspace

3D printing is generally a safe endeavor, but there are certainly ways to receive injuries, particularly burns and cuts. Students should be aware of the dangerous parts of 3D printing, and rules which seek to protect students from harm should be implemented; for example, students should be forbidden from touching the hot end or the build plate when the 3D printer is in operation. If sanding will occur in your workspace, students should wear a mask or respirator. Eye protection is another important consideration. Safety goes hand-in-hand with shop organization as well. Ensuring that tables and chairs are put away and that the immediate area around the 3D printer and prep space are clear to prevent trips or bumps could require one or more rules.

Proper Operation of the Equipment

Users of a 3D printer should of course have received training on its operation, even if such training was limited to careful study of its product documentation. Rules governing the proper operation of the equipment should therefore serve as a reminder for what students should already know about the equipment, and should be limited to the most important points to prevent damage, waste, and failed prints. An example of a rule of this type regards the first layer of a print, which is the most critical part of the print process; it's at this point that a print is most likely to fail due to poor adhesion with the print bed. If a multi-hour print is allowed to proceed, but the print didn't properly adhere to the bed, the result will be a serious mess that could even cause expensive damage to the 3D printer. Anyone operating the 3D printer should start their print and then observe the first few layers to ensure good bed adhesion. After that point, they should still continue to check on their print every so often; the frequency will depend on the nature of the print. It's sometimes safe to let a 3D printer run for long periods unattended, even overnight; but in an instructional setting with 3D printing learners, this may not be recommended.

Equitable Access to 3D Printers

In the author's experience, some students will be very excited to use the 3D printer to the point that they want to use it all the time, excluding classmates from accessing the device. This enthusiasm is of course admirable, but access to the 3D printer must be fair and equitable. Consider setting up a print queue as described in the section of this guide titled [The Print Queue](#). Students will be able to list their print jobs in first-come, first-served order, and you can set up guidelines on how many jobs a student can have waiting in the print queue at any one time. You may also consider setting up designated times during the week or month for "Free Print" if you would like to allow the more motivated students to access the 3D printer a bit more.

Communication

Students should know who they should contact if they have an issue with a 3D printer, and how to communicate with one another regarding access to the device. If you plan to run a "public" print shop - providing printing services to folks outside of your classroom, such as the campus community - you will need to establish guidelines for how patrons should communicate details about their projects with you, how they you will communicate back to them if you have questions about their projects, and how they should pick up their 3D prints. More information about communication is provided in the [Printing as a Service](#) section of this guide.

A final point to consider as you build your list of shop rules is to strike a balance between strict enumeration and trust. A list of rules that is too long will be difficult to remember, and while it is of course recommended that you create a poster or sheet of your rules and post them in your workspace, consider that the mere act of posting a list of rules doesn't guarantee enforcement. Communication, coaching, and immediate - but respectful - correction when rules are violated will be key to compliance.

Print Parameter Limits

3D Prints can take a long time, often on the order of hours. In a learner setting, it's not advisable to allow 3D prints to progress for too long unsupervised. Also, to ensure fair access to the 3D printer, no single print should be allowed to monopolize the available print time. For a 3D printer, time is as much a finite resource as filament, perhaps even more so. You may consider implementing rules that put a cap on how long a 3D print job can last. Students may need to split their print job up and glue it back together after their prints are complete, or they may need to adjust layer height, infill, and wall slicing parameters to reduce their print's timeframe. You may want to advise students to orient their prints to minimize support material waste as well, though this may be kept at a simple advisement rather than a concrete rule, as some models may require a particular orientation to print properly which is un-optimized for waste generation.

You may choose to enforce constraints or guidelines on file names used for STL and/or GCODE files and require students to save such files to a designated file directory on a computer or your organizations cloud storage service. Requiring students to include their name or ID number, the date, the filament color, and one to two descriptive words in the filename will be helpful if you implement a print queue, providing information about a print to facilitate its proper printing and match it back up with its owner when printing is complete. Again, more information about using a print queue can be found in the [The Print Queue](#) page of this guide.

Training Tips

You may find that your institution already has a 3D printer for you to use, and an accompanying expert who can help you skill up on the equipment. However, the case may be that *you* are the resident expert on 3D printing simply by virtue of having one, either from purchase or from having a printer given to you. If your vision for your 3D print shop includes a high volume of print jobs, or if you want to use your 3D printer in an instructional capacity rather than merely churning out prints, you'll likely want to share knowledge about 3D printing with colleagues or students.

Module D of this text is intended to be a concise overview of the basics of 3D printing for a student who is interested in bringing a digitally-drawn model into reality, and it may serve as a good baseline of content for your training efforts. Learning the absolute basics on operating a 3D printer can take only an afternoon or so; however, if you would like to involve other students or colleagues in troubleshooting print or model issues, you will need to provide them with more theoretical background on how a 3D printer operates and how the different slicing parameters inter-operate within the slicing software.

You should also consider your service model for your 3D print shop. A "service model" isn't necessarily something that only a public print shop benefits from; even if you only have one 3D printer that will only be used by your own class of students, your vision for how your students interact with the device could be considered a "service model". In the author's maker space, there are two service models with regard to 3D printing: **Print-on-Demand** and **Maker Appointments**. If a student has already created an STL model file and knows how they want it to be printed, they can simply submit the file to an online form with details about their print (scale, filament color, etc.), and the shop will print it for them. If, however, the student has an idea for a project but feels they would benefit from a consultation on the best way to 3D print it, they can request a Maker Appointment. A team of student assistants in the maker space have received basic training on both simple modeling and 3D printing basics (we call them "maker liaisons", and patrons of our maker space can book time with a maker liaison to discuss the particulars of their project. This has additional benefits beyond a mere print-on-demand service in that it includes an instructive component to the patron's use of the space.

Maker Liaisons, in the above Maker Appointment context, are students who receive additional training in the form of two 2-hour lecture sessions and a 2-hour hands-on session. The lecture sessions include a discussion of basic 3D modeling with a hands-on activity using TinkerCAD as well as a session on the theory and practice of 3D printing, including any issues that may need troubleshooting. Finally, the hands-on session invites new Maker Liaisons to the maker space to try out what they have learned. Maker Liaisons are encouraged to work on personal 3D printing projects in between appointments to sharpen their 3D printing instincts and give them practice on both the printing process itself and navigating issues that arise. A major theme of inviting 3D printing into an instructional curriculum is its value at teaching the iterative mindset - that failure can be productive as long as we learn from it and improve over time. Failure is certainly the best teacher in a maker space, and creating an atmosphere of support and encouragement to foster growth through failure is very important when training for 3D printing.

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5.2.3: Safety

The brevity of this section belies its importance. Modern 3D printers are actually quite safe machines; the most popular consumer models are designed to protect users from the most dangerous heated parts, and they have safeguards designed to prevent the devices from experiencing thermal runaways which could start a fire. Safety should always be the first consideration when working with any equipment with either moving or heated parts, and 3D printers have both. Let's discuss some potential dangers and mitigations.

Burns

The nozzle of a 3D printer can reach temperatures exceeding 250 degrees Celsius (482 degrees Fahrenheit), much higher than the boiling point of water. The bed of a 3D printer can reach up to 70 degrees Celsius (158 degrees Fahrenheit), which is about the temperature of hot tea or coffee. Depending on the length of direct skin contact, either surface can cause severe burns. When a 3D printer is in operation, the best practice is not to touch it at all. If a heated element must be interacted with (such as the case when cleaning a dirty or clogged nozzle), always wear insulated, oven-safe gloves.

Mechanical Injuries

A 3D printer operates by moving along all three dimensional axes. It does this by using a series of motors, belts, cams and rods, all moving in synchronization. Depending on the design of the printer, some of these elements may be exposed without a protective case. This provides for ease of access to these parts for maintenance, but it also creates a risk for mechanical injuries. Again, a 3D printer in operation must not be touched; most printers allow for a print to be paused if touching a printer in progress is absolutely necessary. Fingers can be pinched or crushed; loose jewelry or hair can become tangled, and parts that are wedged or stuck where they shouldn't be can shoot out without warning.

Generally, safety glasses aren't necessary during normal operation of a 3D printer. However, you may want to have some on hand for users who are removing supports from their models or using caustic chemicals like superglue.

Cuts

Cuts are most likely to occur to the hands or fingers at two times during the 3D printing process: when using excess force removing prints from a print bed, and when using cutting tools to remove supports from a completed model. Always use measured force when removing items from a print bed and advise others working in your print shop to do so as well. When using hobby knives to remove supports or otherwise clean up 3D printed models, always use a new, sharp blade - dull blades require more force to cut, and using more force than necessary with a blade results in loss of control that can lead to injury.

Respiratory Issues

Most 3D printing filaments are relatively safe in terms of the fumes and odors they produce; an exception may be ABS, which is known to produce mildly irritating fumes when melted. Regardless, some users may have sensitive respiratory systems which cause them to experience issues with any form of exposure. Your 3D printing work space may benefit from having a painting respirator as part of its equipment kit, which can be purchased at any hardware store. A respirator can also be handy when sanding 3D models; no one wants to inhale fine plastic particles into their lungs!

There are also commercial devices available which can scrub the air of a space of hazardous fumes or particulate matter, or pull fumes directly from your 3D printer. Often, these devices are advertised to be used with laser cutting machines as well. If your budget allows and your space is small and poorly ventilated, considering acquiring such a device.

Hazardous Substances

This guide has previously advised that print beds should be cleaned periodically with isopropyl alcohol (IPA), generally 70-90%. IPA is an irritant, a toxin, and is highly flammable in both liquid and vapor form. It's important to store it in an appropriate fire-resistant cabinet and to replace the cap when not in use to prevent the buildup of hazardous vapor.

Often, 3D prints must be glued together for a variety of reasons. CA glue, or superglue, is one of the best economical adhesive choices for most filament types. CA glue is cured when exposed to moisture, so if it gets on skin, it hardens almost instantly. Take

care to apply CA glue only sparingly to surfaces that will adhere to prevent overspill, and it's not a bad idea to wear latex or nitrile gloves when gluing a large number or surface area of parts.

Other forms of 3D printing, including stereolithography ("resin" printing) have their own safety considerations, particularly regarding hazardous substance exposure. This guide is, however, focused on FDM printing. if you're interested in working with stereolithography, the authors strongly encourage you to perform research on safety protocols to protect you and others who will work in your print shop.

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5.3: Printing as a Service

The degree to which you offer access to your 3D printer will depend on your goals with the device; regardless, one way of framing access control is viewing it in terms of a service model. Who are your "customers" or "patrons"? What is your capacity? What suite of offerings will you provide to your users? It may be that your intent with your 3D printer is merely to print instructional models to use in class; for example, an engineering course instructor may print mechanical models for demonstration, or an anatomy instructor may print models of bones to demonstrate how they fit together. In those cases, the instructor is the only "patron", so the service model as such is quite simple indeed.

3D printing as a practice in an instructional context has grown beyond mere production; the availability of easy-to-use commercial printers, as well as the demand from an advancing workforce for technical and creative problem-solving skills, has elevated its position from the closet to the lectern. Your students will benefit from interacting with 3D printing if you have the time, motivation, and inclination. The skill of iterative thinking - taking a raw idea and refining it through repeated creation, assessment, and recreation - is invaluable, and can be translated from the 3D printing context to nearly any creative endeavor. 3D printing has the benefit of being cool, too.

The Service Model

If you're convinced of the value of sharing access to your 3D printer with students and/or colleagues, first think about the following with regard to your service model:

- **Level of Interaction** - How do you want your patrons to interact with the 3D printing process? You may choose to keep direct access to the equipment relatively locked down, only accepting print submissions in the form of STL files. You may want a mediated access model, where patrons can book time with an expert to discuss their project and help guide them through the printing process. You may even want to run an "open shop", where patrons are invited to come at any time during open hours and freely use shop equipment. Each level of interaction brings its own challenges unique challenges. Simply offering a print-on-demand service on the one end of the spectrum is streamlined, precluding the need for direct face time with patrons, but it requires a carefully developed asynchronous communication system to establish the patron's printing requirements and accept STL print file submissions. An open shop, on the other side of the access spectrum, is relatively hands-off in the day-to-day, but requires that visitors have expertise in operating the shop equipment - and where else will the receive that instruction but from you, the shop manager?
- **Nature of Services Rendered** - Are you a print shop, working on customer invoices to deliver finished goods? Or, are you a consulting firm, helping to educate and guide customers to develop their own finished products? As mentioned previously, you may choose to operate as an open shop, where patrons are either assumed to have existing expertise or you provide robust training on the use of shop equipment. This point admittedly overlaps somewhat with the prior note; it can help to reframe your concept of what you want to do with your space in different ways to identify potential challenges.
- **Bandwidth** - It's natural to get excited about having a new 3D printer and wanting to share it with anyone who expresses vague interest. Remember that resources are limited - time and money of course, but even motivation can be finite, as anyone who has experienced burnout can attest. The consequences of "biting off more than you can chew" can range from that burnout to printer downtime due to damage from mismanagement or neglect, or even injury if a workspace isn't properly equipped with safety equipment and protocols. Make sure that your service vision aligns with your bandwidth.
- **Communication** - This will be expanded upon in a later section, but think about how you will interact with your patrons. If you will be operating a sort of "closed shop" model where direct access to the 3D printer is not available to patrons, your communication with them will likely need to be asynchronous and electronic. Will your patrons submit print jobs via email, or via an online form of some kind? If you will allow your patrons to book time in the space, how will you accomplish that? There are a number of online services for scheduling meetings that you can take advantage of, and your institution may contract with a technology platform like Google or Microsoft which provides an app for schedule management. You should also be sure to clearly communicate your services rendered and, possibly more importantly, the boundaries of what services you are able to provide. Manage your patrons' expectations according to your bandwidth. Be clear about any shop rules you may have developed, and if you expect your patrons to follow posted rules, be sure not to break or bend them yourself! Setting an example will go a long way towards compliance.

Your local circumstances will determine the initial parameters of your service model, but remember that such things can, and will, evolve. Taking a cue from the idea of “iterative thinking,” start with an approach that works for you now, while staying flexible enough to adapt as your circumstances change. You may discover new capabilities in yourself, your colleagues, or your students that you didn't expect. Or, you may find that an expectation you held before starting didn't bear out - don't be afraid to discard any policies or procedures that you put in place which no longer align with your reality.

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5.3.1: Communication

A functioning 3D Printing service or workshop will require coordination between more than one person; depending on the service model, there may be several layers of communication required for smooth operations. Workshop managers will of course need to communicate with patrons regarding their prints and projects; if your workshop model is supported by a team of staff, even if they're unofficial student helpers, you'll need to establish lines of communication with them as well as set expectations on how they should communicate with patrons.

Communication with Patrons

Your patrons will, of course, need to know how to contact you to gain access to your 3D printer. If you plan to communicate directly with patrons electronically (as is, of course, the norm nowadays), consider providing them with an "official" shop method for doing so rather than using your own personal contact information. For example, set up a free Gmail account associated with your shop. At the author's institution, which uses Microsoft apps, a special "shared email inbox" was created, and access to it was configured for all shop student staff. An added functionality of setting up a shop account with Google or Microsoft is access to other cloud-based apps, such as calendars or cloud file storage. Your shop calendar can be configured to represent the shop's public hours, and you can often embed such calendars in web pages or social media.

Your patrons will hopefully have an STL model file ready for printing, and so you will need a method of collecting these files and organizing them. Google Forms allows for file uploads, and you can also include questions on the form that will help you print a model with minimal further communication with the patron. Consider questions like:

- The patron's name
- The patron's email address
- The desired filament color
- The desired dimensions of the final print (x/y/z, in clearly stated units of measurement)
- The date the print is needed by
- The number of copies of a model to be printed
- Any special properties the print should have (e.g. "lightweight", "very strong", "very detailed")
- An agreement checkbox to your shop's rules of use
- The STL file upload field (if the form allows for one)

Be sure to include a brief paragraph at the top of the form indicating what can and cannot be printed, and what file format patrons should use for their models; sometimes, patrons will attempt to upload GCODE files, which are printer-specific and may not correlate to your printer model. If your shop has rules prohibiting the printing of inappropriate items (models protected by copyright, offensive items, weapons, etc), clearly state so on this form.

If you plan to implement a "maker appointment" model where patrons can seek direct advice on their projects from you or your shop staff, you should develop a method of booking appointments to prevent double-booking and manage your shop's human bandwidth. Both Microsoft and Google have methods of creating a booking form that connect to the respective platforms' calendar apps; other online services, like youcanbook.me, offer free tiers for booking pages. If your booking form allows for customizable questions, consider the following for maker appointments:

- Briefly describe your 3D printing project.
- Do you have an STL ready to print, or do you need modeling advice?
- What program did you use to create this model?
- In what ways can the shop best help you with your project?
- Is this project supporting classwork, or is it a personal project?
- Any or all of the questions listed above for a print-on-demand form

Again, try to include as much important information as you can on the form to manage patron expectations regarding what you can and can't print, and what level of assistance you can and can't provide. Make sure, also, that the form is configured to email the patron to give them a record of the time and location of their appointment.

Finally, after your patron's print is complete (which may or may not occur during a maker appointment, depending on the print time), you will need to establish how to deliver the print to them. Recommendations for this can be found in the [Managing Prints](#) section of this guide.

Communication with Shop Staff

If you intend to train a "staff" of folks to help you handle 3D printing projects - whether paid student workers or simply designated students in your classroom - it will be important that the team works together to implement a consistent workflow. Be sure to set clear work expectations regarding the operation of equipment, the organization of the work space, and the manner of interaction with shop patrons - preferably in writing. A short handbook that you can give your staff containing shop rules and work rules is helpful, and your staff will be grateful for it. Communication is, however, a process rather than a one-time act. Observe your staff and provide gentle, constructive coaching if you notice their quality of work diverge from expectations, and be certain that your attention and manner of correction is equitable to all staff.

One of the reasons you may consider to train a team to help run your work space is so that your attention can be diverted elsewhere. Your staff need to know how to contact you when they need to ask you a question or they need your support. Be sure to clearly communicate the manner that you would like staff to contact you (email, phone, in person), the expediency with which you can provide a response to them, and the acceptable time frame within which they can communicate with you.

Finally, your staff will possibly be communicating directly with patrons themselves, depending on how you have set up your service model. They should treat such interactions using a customer service approach; they should be polite, inquisitive, and helpful. If you intend for shop staff to directly help patrons with their 3D printing projects (rather than merely print them on-demand), consider communicating boundaries. To expand on this point, shop staff should know what they are expected to be the experts on, and what the patron should be the expert on. Patrons may come to your space with models they downloaded online, or with models that were designed with any number of modeling software; your shop staff can't be experts at all of the modeling software available. They will be experts, though, on your 3D printers and the software that runs them. Enthusiastic shop staff may also, in good faith, tend to "take over" a patron's project; it will be important for staff to be patient with patrons and let them solve some of their own project problems if they should arise. The staff member's primary responsibility will be the final printing step.

If you choose to create a free email account for your shop as recommended above, consider giving your staff access to it. This will protect the privacy of your staff when they communicate with patrons; otherwise, they may be tempted to use personal devices and accounts for shop communication. You can also take advantage of other cloud apps like calendars to set up internal work schedules or cloud-based file repositories; more information on this can be found in the [Managing Prints](#) section of this guide.

Privacy and Intellectual Property Considerations

If a patron has created their own 3D model, it is considered their own intellectual property. Modelers can also choose to apply a Creative Commons license to their model; there are many online platforms for sharing models such as Thingiverse, Printables, and MakerWorld that allow users to apply a CC license to their models. When a patron shares an STL model with you, the safest assumption is that they reserve all rights to it. Don't reprint or re-share the model without the patron's written permission, and be sure that this is also communicated with any shop staff you may manage. Don't host patron-submitted models on cloud storage services in such a way that they are freely and publicly available; if you upload them to a cloud storage service (like Google Drive, Box, or OneDrive), make sure that the destination folder is secure and shared only with affiliates of your workshop. GCODE files, which are derivatives of STL models specifically for printing, should also be considered sensitive intellectual property and treated the same way. In fact, it is a good practice to keep patron-submitted STL files only until after they have been printed, and then delete them entirely afterward. If your patrons have emailed their STLs to you as attachments, delete those emails and attachments as well.

Intellectual property concerns extend beyond the patrons' own creations; they may ask you to print a model that they found online and didn't actually create themselves. If you suspect that any such model is within copyright, it's quite appropriate to ask your patron to provide you with a link to the original file so you can determine its license, and refuse to print the model without provenance. It may be a good opportunity to recommend that the patron try their hand at modeling themselves and develop their own skills.

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5.3.2: Managing Prints

Your workspace is set up; you have your filaments and supplies. You've learned all you need to know about operating your printer, and you've trained up any staff you need to help you. You've created an email inbox for your 3D print shop and you have both a print submission form and an appointment booking form ready to send to your patrons. What now? How can you start - you know - actually printing for your patrons, be they colleagues, students, or other community members? Running a functioning print shop brings a host of logistical challenges that you will need to address; some advice follows below.

Managing Model and Print Files

You will be accepting STL model files and converting them into GCODE print files using the slicing software of your choice; you may have opted for an open-source, free slicer like Orca, or your 3D printer may have come with an app for you to use. It will be important for you to develop a plan for keeping files secure and organized. This will be especially true if the workshop staff who are slicing models aren't necessarily going to be the ones who are printing them, and such a situation is likely to arise if you plan to have your 3D printer running around the clock.

Once again, how you organize your print files will depend on the number of people who will need to have access to the 3D printer and the slicing software. It may be enough for you to have a single computer (likely the one that has the slicing software installed) on which all model and print files are stored, if you're the only one who will actually be printing. If you expect others besides yourself to use the printer, consider organizing your files in a secure cloud storage platform, as recommended in the previous [Communication](#) section. Be sure that the cloud storage folder which contains your files is secure and shared only with those who need access to it.

A strong recommendation that we can offer is the development of a filename convention system. Your users will be submitting STLs with all sorts of names which may or may not allow them to be traced back to the original patron. Renaming the files in such a way that you can match them up to the requestor will be vital when the prints are complete and it's time to deliver the prints. Be thoughtful with this - you may want to protect your users' privacy in your filenames. At the very least, use only patron initials; you can also use student or campus ID numbers, or an abbreviation of them. Your filenames should also include the date, and possibly include specific detail down to the time of receipt of the file. If you expect to handle a high volume of prints such that you need to implement a queue, this will be incredibly important to ensure your service is fair and equitable. Your computer may not have a built-in way to display an STL file, though some operating systems do. While working in your shop and interacting with your patrons, it will be natural to refer to models according to what they represent - a model might be a wheel, or a chess piece, or a dinosaur, etc. Assigning a one to two word description of the model itself to the filename may be helpful to identify it when it's ready to move to the slicing software.

After your STLs are sliced and converted to GCODE for final printing, you may want to include some additional data in the GCODE filenames to smooth out the printing process. If you have more than one model of 3D printer in your workspace, you can include the printer model in the filename of the GCODE file so the person who will print it will know which printer to use, as GCODE is printer model-specific. You may also allow your users to print with different colors of filament, so it could be helpful to include even that information in your filenames - that is, the color of filament that the user wishes to use for their print. Place the print-specific details at the front of the file, as matching a GCODE file to the appropriate printer is very important; printers won't accept files generated for a different model, and if they do, the results can be unpleasant.

Be careful of formatting for your filenames; some printers have computer control systems that may not recognize files if they include certain characters in their filenames. Avoid punctuation aside from dashes or underscores, and it may be a good idea even to use only lowercase letters. Here are some example filenames that you may consider using:

File Type	Template	Example
STL Files	[Student ID Number]-[Date of Submission]-[Time of Submission]-[Brief Description].stl	0123456-081325-10am-turtle.stl
GCODE Files	[3D Printer Model]-[Filament Color]-[Student ID Number]-[Date of Submission]-[Time of Submission]-[Brief Description].GCODE	prusa_mk4s-blue-0123456-081325-10am-turtle.GCODE

The Print Queue

Regardless of the service model you choose to make your 3D printer accessible, one limiting factor you will always face is time. While there are ways that you can slice a model to minimize the time it will take to print, often a model will take several hours to print, and keeping track of what the next print ought to be can be a challenge particularly while continuously accepting new STL file submissions or maker appointments.

Organizing a print queue can be very helpful when trying to offer print service fairly and expeditiously. You can keep track of the stage each print job is occupying at any one point in time, and you can use it to maintain statistics and history data for your print shop's output. This is a concept that requires no specific technology to implement; in the author's maker space, the print queue started out as an ad hoc whiteboard list of upcoming prints. The main factors for your success with a print queue are A) that it contains all the print data you or someone else would need to immediately move to the next print job when the last one is finished B) that it is easily accessible to all those who may need to view or interact with it and C) your procedure for using the print queue is clearly communicated and adhered to. Let's look at an example from the author's maker space.

3D Printing Queue									
<u>Printer</u>	<u>Date/Time</u>	<u>Requestor's ID</u>	<u>GCODE File Name</u>	<u>Filament Color</u>	<u>Estimated Print Time</u>	<u>GCODE Generated By</u>	<u>Print Started By</u>	<u>Print Complete?</u>	<u>Patron Notified?</u>
Prusa Mk 4	11 Nov 2024, 10:00 AM	01234567	prusa_mk4-red-01234567-111124-10am-turtle.GCODE	Green	3 hrs	Aisha Khan	David Okafor	Yes	Yes
Prusa Mk 4	2 Dec 2024, 3:00 PM	31415926	prusa_mk4-black-31415926-021225-3pm-cosplay.GCODE	Black	4 hrs 30 min	Mei-Lin Chen	Aisha Khan	Yes	No
Prusa Mk 3	3 March 2025, 1:00 PM	20394895	prusa_mk3-black-20394895-030325-1pm-jewelrybox.GCODE	Black	2 hrs 15 min	David Okafor	Sofia Petrova	No	No
Lulzbot Taz 6	18 May 2025, 1:00 PM	60594838	lulzbot-red-60594838-180525-1pm-potterystamp.GCODE	Red	1 hr 10 min	Carlos Mendes		No	No

The names and ID numbers used in this example are fictional.

As new STL files are submitted, they are processed in the slicing software to generate GCODE. The GCODE files are then renamed according to the shop's established file naming conventions, and they are uploaded to the secure shared cloud storage drive for all shop workers to access. Then, an entry is created in the print queue document - in the author's case, an online shared Microsoft Excel file - with print settings obtained from the slicing software. Remember that GCODE files are printer-specific, so the printer model must be selected before exporting the GCODE file. If you have more than one model of printer in your shop, you may decide to use a particular printer when exporting GCODE based on that printer's specific properties (print speed, print bed size), its projected availability (estimated from other prints in the queue and their print times), or whether the color of filament you need to use is already installed.

After a new entry is placed into the print queue, the "Print Started By" column is left blank until someone starts the print. Similarly, the last two columns - "Print Complete?" and "Patron Notified?" - are set to "No" until either of those values is true. This print queue document is accessible electronically to all shop staff, and they are expected to check it frequently as printers complete projects and update the queue.

You may choose to go analog with your print queue and stick with a whiteboard for organizing this information, but if you go that route, be sure to copy the information down before you erase it so you have a good record of your shop's output. Another practice would be to have a separate print queue for each of your 3D printers, if you have more than one - this can also be electronic, or it can be on a clipboard that is kept near each printer. In the author's maker space, we even started putting sticky notes on printers with requestor IDs and estimated completion times - in addition to using the print queue - just for an extra layer of clarity and efficiency.

Delivering Completed Prints

Finally, after your patron's print is complete, you must notify them that it's ready to pick up. Nowadays, the most obvious method of notification will be via email, which you have hopefully collected on your print submission or maker appointment booking form. Consider stocking resealable plastic bags that can be written upon with a permanent marker. Then, when a print is complete, put it in the bag and write the requestor's ID number and the date. If you charge money for filament used, write the cost on the bag as well. Often, 3D prints will have support structures attached; it's advisable to leave these structures on a patron's print and let them remove the waste. You may choose to provide patrons with tools and space to do so if you can.

Designate a pickup location in or near your print space; try to be as secure as you can. At the author's institution, there are short-term-use lockers that students can use by inputting a single-use code. These lockers are also used for 3D print pickup; the code is set by shop staff, and the locker number and code are emailed to the patron when they're notified that their print is ready for pickup. If you're using a 3D printer in a classroom, you can set aside part of a lecture to pass out prints that were completed since the last lecture.

It's easy to forget to go back to your print queue and indicate when a print is complete and when a patron has been notified that they may pick it up; don't overlook this step! You may end up with a box of unclaimed prints, and your patrons will wonder what happened to their projects.

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5.4: Technical and Logistical Considerations

The remaining sections of this guide are a brief overview of device-related considerations. Most commercial 3D printers are surprisingly reliable, and with proper maintenance, can be operated without major issues for a long time. Especially during the early period of ownership where you are still learning how to use your 3D printer, though, mistakes will be expected and almost inevitable. Refer to the [Device Troubleshooting](#) page for advice on how to deal with the most common issues, like bed adhesion problems, nozzle clogs, and mechanical problems.

Most commercial 3D printers evolved from hobbyist designs using off-the-shelf parts, and so they are surprisingly modular. 3D printing companies will offer accessories and upgrades for purchase, and you may consider these depending on your 3D printing application. For example, if you find that the level of detail your standard 0.4 mm print nozzle can achieve is unsatisfactory, consider replacing it with a finer 0.2 mm nozzle. Consider the recommendations in the [Modifying Your 3D Printer](#) section.

Regardless of whether you are troubleshooting your printer due to issues or whether the disassembly of your printer is a self-inflicted headache from attempting an upgrade or modification, you can always find help on the web. If you have a popular model of printer, take solace in the knowledge that you're almost certainly not the first person to have experienced your particular issue, and someone else has posted both their problem and the solution online. You may also reach out to the manufacturer of your printer if you have issues; or, as is the case with many popular manufacturers like Prusa, MakerBot, and BambuLab, there is robust documentation online for your reference.

Your most important takeaway - if your printer isn't printing, don't despair! You can fix it with patience, research, and a willingness to risk short-term failure in order to achieve long-term success. 3D printing as a practice often requires perseverance and iteration. Writing from experience, the relief and triumph you will feel when you tune your printer back into working shape are worth the pain and effort.

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5.4.1: Modifying your 3D Printer

Modifying the Nozzle

The simplest modification you can make to your printer would be to add a new nozzle. Changing a nozzle is useful to know whether the nozzle that came with your printer is broken or if you want to fine tune your printer experience. Nearly every printer has a different method for changing it's nozzle, so it would be best to consult the manual that came with your printer for this procedure. Nozzles can come either larger or smaller than your default 0.4 mm, larger nozzles will significantly increase the amount of filament that your printer will use on each layer which, in turn, will increase the efficiency of your prints at a cost of reduced detail. These nozzles can be useful for producing fast prototypes and other prints you aren't very concerned about the detail and tolerances. Smaller nozzles will be almost the exact opposite, providing much finer layer lines and consuming less filament.

Octoprint

A huge upgrade you can make to your printer is setting up OctoPrint. This is a custom, 3D printing focused operating system (OS) for the Raspberry Pi family of mini computers which allows you to fully control and monitor your printer remotely, as well as create timelapses of your prints and plenty of other features. Setting up OctoPrint requires a Raspberry Pi (3B, 3B+, 4B or Zero 2 are recommended) or an android device, an SD card and SD card reader if your computer doesn't have one, a USB cable to connect to your printer if it has a USB port (otherwise you can connect to your printer via WIFI), and a webcam if you want to monitor your print using OctoPrint. The setup process only takes around 15 minutes and is rather easy, resources to continue this can be found with a simple web search.

Multi-filament system

Another upgrade that should be considered, if the printer supports it, is a multi-filament system. These systems allow you to load and use multiple filaments for one print and are extremely useful for producing commercial products and models. One thing to consider when using these printers is a waste collection basket. Printing in multiple filaments generates waste each time the filament switches - these waste products need to be removed from the plate and, with some models, will be ejected from the plate. You will need a basket to collect the waste, otherwise it will be ejected onto the table holding your printer. Some slicing software also allows you to print an entirely separate model using the waste instead, at the same time as the model you're printing in multi-color. If you were planning to paint a model anyway, or if the color of the model doesn't matter, this is a great option for saving filament waste.

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5.4.2: Device Troubleshooting

Basic Nozzle clogs and jams

Perhaps the most common issues you will encounter when working with a 3D printer are clogs and jams. A basic clog is caused by filament backing up into the nozzle. The first thing to try in such a case will be to set your printer's nozzle temperature to the upper recommended limit for your filament type. After waiting for the nozzle to heat up, if the clogged filament has not exited the nozzle, you can instruct the printer to advance the extruder to try and force the stuck filament out. If this method works, you should see a dark, discolored chunk of filament exit the nozzle and the clog will be cleared. If the clog persists, you can use a fine needle (usually included with your printer) to poke into the nozzle while it is heated and hopefully dislodge whatever clog may be inside. Please take caution when doing this; metal needles can transfer heat to your fingers surprisingly well!

The last resort when dealing with clogs will be to perform a "cold pull", which is essentially putting a sacrificial piece of filament into your nozzle to pick up any debris that may be causing the clog. First, heat the nozzle to a melting temperature and unload any filament that is in the printer. Once unloaded, cut a strand of filament long enough to go through the hotend to reach the nozzle and have a graspable portion on the outside for you to hold. Once cut, stick the filament strip into the hotend (where the filament would normally enter) until it reaches the end of the nozzle and cannot move any further. Then, wait for around 15 seconds and swiftly pull the strip of filament out; you should be able to see any dirt or debris attached to it once removed.

No filament is extruding

If your model only printed part of the way, in addition to a nozzle clog, you may have experienced a tangle or break in the filament roll. Inspect the filament roll and make sure it is properly inserted into the hotend and that there are no tangles in the roll that prevent it from rolling or feeding. A break of the filament at any point can cause your print to work fine at first, as it works with whatever remaining filament it has until it runs out and no filament is extruded. Filament can break if it is sitting in a moist environment for too long; PLA filament, in particular, is hygroscopic and becomes brittle as it absorbs moisture from the air. Before printing, be sure to check for any breaks. If you see one simply preheat the nozzle, unload the broken filament fragment from the extruder, then reload the remaining filament from the roll.

Prints will not stick to the bed

Often, as a model is being printed, it will lift off the print bed. There are a number of reasons this may occur. The most common is build up of hand oils and other debris on the bed. To remove this, wipe the print bed with isopropyl alcohol or, in more serious cases, with soap and water and allow the plate to dry.

If your model is not flat on the bottom or if it is positioned such that it is floating in the air in the slicer, your printer will attempt to extrude filament in thin air, resulting in a mess of filament which is often referred to as "spaghetti". To fix this, ensure that the base of your print is flat or otherwise enable supports to fix it. If you encounter this issue, check that your model is not floating above the build plate in the slicer.

Another reason your prints may not stick is an improperly leveled bed. Refer to the following section for tips on fixing this issue.

Leveling

Leveling is the process of keeping the printbed flat with a roughly 0.1mm gap between the bed and the nozzle at every point on the bed. Ensuring a level print bed is very important for the quality of a print, and having an unlevel bed will often result in the print failing to adhere and will ruin the print. Maintaining a level surface will avoid a lot of problems in the future, so you may want to reference back to this section often. Note that this process will ensure that the bed is level with respect to the movement of the hotend; this isn't the same kind of leveling that you must do when hanging a picture frame, and we won't be using a bubble level for this process.

Before leveling a bed, it is important to reference your printer's manual to find out exactly how the print bed is controlled. In fact, many modern printers have an auto-leveling feature, so you may not need to manually level the bed at all. For many printers, however, there will be up to 4 leveling knobs at each corner underneath the print bed, and you will need to level the bed at each of these locations to ensure an even surface. There are many methods for leveling a printer's bed, some of them easier than others;

however, the simplest to perform will use a piece of paper to gauge the correct distance between the nozzle and the bed. To perform this method, begin by “homing” the printer, which will return all moving parts to a default location. This option will often be found in the “Calibration” menu on the printer, however, consult your printer’s manual to find where this setting is on your printer. The hotend should end up right above the first leveling knob. If your home fails or the nozzle presses into the bed, you may need to adjust your z offset to correct this. The Z-Offset setting essentially controls the default distance between your nozzle and the print bed. When the offset is 0, the nozzle will have no extra space other than what you have leveled it to. After the printer has successfully homed, you will want to preheat the bed to the maximum amount you will be using (generally 60° C is a safe amount to heat to) which will ensure that your leveling accounts for any expansion caused by the bed heating up. Once the bed reaches its final temperature, slide a small section of paper which is roughly 0.1 mm thick underneath the nozzle. The tension that it has with the nozzle will tell you how much space there is between the two. If you cannot fit the paper underneath the nozzle or it is very hard to move the paper while it is under the nozzle, you need to lower your bed using the leveling knob below. Keep sliding the paper underneath the nozzle until there is noticeable tension on the paper while moving but it is not hard to move. If you feel no tension while sliding the paper, you have too much space between the nozzle and the bed and you must raise the bed using the leveling knob. Once you reach the desired tension, use the printer console to move the nozzle upwards a little to avoid scraping the print bed when moving it to the second leveling knob. Then use the console to move the nozzle until it is above a different knob and lower it until your Z coordinate is at 0. Then repeat the previous leveling steps for this knob and the remaining two knobs. Once you have leveled the printer at each knob, your bed should be level relative to the movement of the hotend and you can run a test print to ensure your adhesion is correct.

Blobs

Possibly the worst problem you can encounter while printer is called a "Blob". This occurs when your printer encounters an issue while printing that pushes the extruded filament up towards the nozzle, this can often happen due to a piece of the print dislodging and sticking to the nozzle. With the extruded filament being pushed up towards the nozzle, all of the filament for your print accumulates and hardens around the nozzle and hotend forming a blob of filament. The best method to remove this is to heat up the nozzle as hot as you can, heat up the blob using a heat gun or other apparatus and begin to pull the blob from the hotend piece by piece. Of course the easiest way to avoid having a blob form is to monitor your print and stop it when you see an anomaly like a dislodged piece of your print sticking to the nozzle, or if your printer is printing "spaghetti".

Bed Adhesion Issues

Often, as a model is being printed, it will lift off the print bed. There are several ways this can happen. The most common of these is build up of oils and other debris on the bed. In order to fix this, wipe the print bed with isopropyl alcohol or, in the most serious cases, with soap and water and allow the plate to dry.

Another cause of bed adhesion issues is an unlevelled bed; fixing this is as easy as re-leveling the bed as described above.

Slicing software can automatically generate a number of additions to your model to promote bed adhesion, including brims, skirts, and rafts. Explore the options available to you in your slicing software's documentation.

Loose Belts

After using a printer for a long time, you may encounter a loose belt, often indicated by inaccuracies in the printer's movement. To fix a loose belt, remove the belt according to the procedure provided for your specific printer and either reapply it with the correct tension or replace the belt if it is damaged. Occasionally these inaccuracies will be caused by incorrect tension in the belt, either too tight or too loose, so first try to adjust the tension of the belt if that option is available to you.

Broken Gears

You can tell if a gear is broken without having to disassemble anything by checking if it is slipping. A slipping gear will move forward briefly and then move backwards quickly. A broken gear must first be cleaned, as sometimes gears like the extruder gear can chew through old filament and become stuck and ineffective. If the gear's functionality does not return after being cleaned or if it has visible breakage, it is best to replace the gear fully.

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Glossary

Center line | Thin, dashed line used to indicate the central axes of circular features or geometries.

Computer Aided Design (CAD) | the process by which 3D models are constructed using a computer program

Console | The display used to interact with the printer, excluded on some printers in lieu of an app used for control.

Cutting plane line | Thick, dashed line with two arrows on the end used to describe where a section is cut through an object and the direction of sight.

Extruder | a gear system that grips on to the line of filament and feeds it through the 3D printer

Fused Deposition Modeling (FDM) | A method of fabricating a 3D object using layers of melted material laid atop one another

GCODE | The file obtained after putting an STL or other 3D object file through a slicing software which contains the instructions for the printer to use in order to print a specific mo

Heater block | The heating element used to melt the filament, its temperature is controlled by the thermistor

Hidden line | Thin (0.3mm) and dashed line that indicate edges that are hidden in the current view.

Hotend | The portion of a 3D printer which contains the heating and extruding mechanisms, generally it is what is moved in 3D space to create each layer of a 3D print

Infill | The pattern a 3D printer uses to fill in the empty, inner space, of the model it is printing, different patterns and the density of the infill are accessed in the slicer parameters

Nozzle | a metal piece of the hotend that is heated up and funnels melted filament into a smaller diameter to be deposited onto the build plate

Printbed/build plate | The surface which melted filament is laid upon, can be heated and/or removable though not always

Section line | Thin, continuous line used to identify the surfaces of an object that lie on the cutting plane

Slicer | A program that takes a 3D model and sections it into many layers which can be read by the printer as paths for the printer nozzle to take and extrude filament on. Also, the program used to modify various parameters of your model before printing

Stereolithography | The process of fabricating 3D objects by selectively solidifying layers of liquid resin with a specific wavelength of light via a photopolymerization reaction

Visible line | Thick (0.7mm) and continuous line representing the visible edges of an object

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