Solidification involves the transformation of the molten metal back into the solid state. The solidification process differs depending on whether the metal is a pure element or an alloy.

**Pure Metals**
A pure metal solidifies at a constant temperature equal to its freezing point, which is the same as its melting point. The melting points of pure metals are well known and documented. The process occurs over time as shown in the plot below, called a cooling curve. The actual freezing takes time, called the local solidification time in casting, during which the metal’s latent heat of fusion is released into the surrounding mold. The total solidification time is the time taken between pouring and complete solidification. After the casting has completely solidified, cooling continues at a rate indicated by the downward slope of the cooling curve.

Because of the chilling action of the mold wall, a thin skin of solid metal is initially formed at the interface immediately after pouring. Thickness of the skin increases to form a shell around the molten metal as solidification progresses inward toward the center of the cavity.
The rate at which freezing proceeds depends on heat transfer into the mold, as well as the thermal properties of the metal. It is of interest to examine the metallic grain formation and growth during this solidification process. The metal which forms the initial skin has been rapidly cooled by the extraction of heat through the mold wall. This cooling action causes the grains in the skin to be fine and randomly oriented. As cooling continues, further grain formation and growth occur in a direction away from the heat transfer. Since the heat transfer is through the skin and mold wall, the grains grow inwardly as needles or spines of solid metal. As these spines enlarge, lateral branches form, and as these branches grow, further branches form at right angles to the first branches. This type of grain growth is referred to as dendritic growth, and it occurs not only in the freezing of pure metals but alloys as well. These treelike structures are gradually filled-in during freezing, as additional metal is continually deposited onto the dendrites until complete solidification has occurred. The grains resulting from this dendritic growth take on a preferred orientation, tending to be coarse, columnar grains aligned toward the center of the casting. The resulting grain formation is illustrated below.
**ALLOY METAL**

Most alloys freeze over a temperature range rather than at a single temperature. The exact range depends on the alloy system and the particular composition.

Solidification of an alloy can be explained with reference to Figure 10.6, which shows the phase diagram for a particular alloy system and the cooling curve for a given composition. As temperature drops, freezing begins at the temperature indicated by the liquidus and is completed when the solidus is reached. The start of freezing is similar to that of the pure metal. A thin skin is formed at the mold wall due to the large temperature gradient at this surface. Freezing then progresses as before through the formation of dendrites that grow away from the walls. However, owing to the temperature spread between the liquidus and solidus, the nature of the dendritic growth is such that an advancing zone is formed in which both liquid and solid metal coexist. The solid portions are the dendrite structures that have formed sufficiently to trap small islands of liquid metal in the matrix. This solid–
liquid region has a soft consistency that has motivated its name as the *mushy zone*.

Depending on the conditions of freezing, the mushy zone can be relatively narrow, or it can exist throughout most of the casting. The latter condition is promoted by factors such as slow heat transfer out of the hot metal and a wide difference between liquidus and solidus temperatures. Gradually, the liquid islands in the dendrite matrix solidify as the temperature of the casting drops to the solidus for the given alloy composition.

Another factor complicating solidification of alloys is that the composition of the dendrites as they start to form favors the metal with the higher melting point. As freezing continues and the dendrites grow, there develops an imbalance in composition between the metal that has solidified and the remaining molten metal. This composition imbalance is finally manifested in the completed casting in the form of segregation of the elements.

The segregation is of two types, microscopic and macroscopic. At the microscopic level, the chemical composition varies throughout each individual grain. This is due to the fact that the beginnings of each dendrite has a higher proportion of one of the elements in the alloy. As the dendrite grows in its local vicinity, it must expand using the remaining liquid metal that has been partially depleted of the first component. Finally, the last metal to freeze in each grain is that which has been trapped by the branches of the dendrite, and its composition is even further out of balance. Thus, we have a variation in chemical composition within single grains of the casting.

At the macroscopic level, the chemical composition varies throughout the entire casting. Since the regions of the casting that freeze first (at the outside near the mold walls) are richer in one component than the other, the remaining molten alloy is deprived of that component by the time freezing occurs at the interior. Thus, there is a general segregation through the cross-section of the casting, sometimes called *ingot segregation*. 
Eutectic Alloys

Eutectic alloys constitute an exception to the general process by which alloys solidify. A eutectic alloy is a particular composition in an alloy system for which the solidus and liquidus are at the same temperature. Hence, solidification occurs at a constant temperature rather than over a temperature range, as described above. The effect can be seen in the phase diagram of the lead–tin system shown.

Pure lead has a melting point of 327°C (621°F), while pure tin melts at 232°C (450°F). Although most lead–tin alloys exhibit the typical solidus–liquidus temperature range, the particular composition of 61.9% tin and 38.1% lead has a melting (freezing) point of 183°C (362°F). This composition is the eutectic composition of the lead–tin alloy system, and 183°C is its eutectic temperature.

Lead–tin alloys are not commonly used in casting, but Pb–Sn compositions near the eutectic are used for electrical soldering, where the low melting point is an advantage. Examples of eutectic alloys encountered in casting include aluminum–silicon (11.6% Si) and cast iron (4.3% C).
**SOLIDIFICATION TIME**

Whether the casting is pure metal or alloy, solidification takes time. The total solidification time is the time required for the casting to solidify after pouring. This time is dependent on the size and shape of the casting by an empirical relationship known as *Chvorinov’s rule*, which states:

\[ T_{ts} = C_m \left( \frac{V}{A} \right)^n \]

Where
- TTS=total solidification time, min;
- V=volume of the casting, cm³ (in³);
- A=surface area of the casting, cm² (in²);
- n=is an exponent usually taken to have a value= 2;
- Cm is the mold constant. Given that n= 2, the units of Cm are min/cm² (min/in²), and its value depends on the particular conditions of the casting operation, including mold material (e.g., specific heat, thermal conductivity), thermal properties of the cast metal (e.g., heat of fusion, specific heat, thermal conductivity), and pouring temperature relative to the melting point of the metal. The value of Cm for a given casting operation can be based on experimental data from previous operations carried out using the same mold material, metal, and pouring temperature, even though the shape of the part may be quite different.

Chvorinov’s rule indicates that a casting with a higher volume-to-surface area ratio will cool and solidify more slowly than one with a lower ratio. This principle is put to good use in designing the riser in a mold. To
perform its function of feeding molten metal to the main cavity, the metal in the riser must remain in the liquid phase longer than the casting. In other words, the TTS for the riser must exceed the TTS for the main casting. Since the mold conditions for both riser and casting are the same, their mold constants will be equal. By designing the riser to have a larger volume-to-area ratio, we can be fairly sure that the main casting solidifies first and that the effects of shrinkage are minimized. Before considering how the riser might be designed using Chvorinov’s rule, let us consider the topic of shrinkage, which is the reason why risers are needed.

**Shrinkage**

Our discussion of solidification has neglected the impact of shrinkage that occurs during cooling and freezing. Shrinkage occurs in three steps:

1. Liquid contraction during cooling prior to solidification;
2. Contraction during the phase change from liquid to solid, called solidification shrinkage;
3. Thermal contraction of the solidified casting during cooling to room temperature. The three steps can be explained with reference to a cylindrical casting made in an open mold, as shown in Figure below.
The molten metal immediately after pouring is shown in part (0) of the series. Contraction of the liquid metal during cooling from pouring temperature to freezing temperature causes the height of the liquid to be reduced from its starting level as in (1) of the figure. The amount of this liquid contraction is usually around 0.5%.

Solidification shrinkage, seen in part (2), has two effects.

- First, contraction causes a further reduction in the height of the casting.
- Second, the amount of liquid metal available to feed the top center portion of the casting becomes restricted.

This is usually the last region to freeze, and the absence of metal creates a void in the casting at this location. This shrinkage cavity is called a pipe by foundrymen. Once solidified, the casting experiences further contraction in height and diameter while cooling, as in (3). This shrinkage is determined by the solid metal’s coefficient of thermal expansion, which in this case is applied in reverse to determine contraction.

Solidification shrinkage occurs in nearly all metals because the solid phase has a higher density than the liquid phase. The phase transformation that accompanies solidification causes a reduction in the volume per unit weight of metal. The exception is cast iron containing high carbon content, whose solidification during the final stages of freezing is complicated by a period of graphitization, which results in expansion that tends to counteract the volumetric decrease associated with the phase change.

Compensation for solidification shrinkage is achieved in several ways depending on the casting operation. In sand casting, liquid metal is supplied to the cavity by means of risers. In die casting the molten metal is applied under pressure.

Pattern-makers account for thermal contraction by making the mold cavities oversized. The amount by which the mold must be made larger relative to the final casting size is called the pattern shrinkage allowance. Although the shrinkage is volumetric, the dimensions of the casting are expressed linearly, so the allowances must be applied accordingly. Special “shrink rules” with slightly elongated scales are used to make the patterns and molds larger than the desired casting by the appropriate amount. Table below lists typical values of linear shrinkage for various cast metals; these values can be used to determine shrink rule scales.
**DIRECTIONAL SOLIDIFICATION**

In order to minimize the damaging effects of shrinkage, it is desirable for the regions of the casting most distant from the liquid metal supply to freeze first and for solidification to progress from these remote regions toward the riser(s). In this way, molten metal will continually be available from the risers to prevent shrinkage voids during freezing. The term directional solidification is used to describe this aspect of the freezing process and the methods by which it is controlled. The desired directional solidification is achieved by observing Chvorinov’s rule in the design of the casting itself, its orientation within the mold, and the design of the riser system that feeds it. For example, by locating sections of the casting with lower V/A ratios away from the riser, freezing will occur first in these regions and the supply of liquid metal for the rest of the casting will remain open until these bulkier sections solidify.

Another way to encourage directional solidification is to use chills—internal or external heat sinks that cause rapid freezing in certain regions of the casting. Internal chills are small metal parts placed inside the cavity before pouring so that the molten metal will solidify first around these parts. The internal chill should have a chemical composition similar to the metal being poured, most readily achieved by making the chill out of the same metal as the casting itself.

External chills are metal inserts in the walls of the mold cavity that can remove heat from the molten metal more rapidly than the surrounding sand in order to promote solidification. They are often used effectively in sections of the casting that are difficult to

**TABLE 10.1 Typical linear shrinkage values for different casting metals due to solid thermal contraction.**

<table>
<thead>
<tr>
<th>Metal</th>
<th>Linear shrinkage</th>
<th>Metal</th>
<th>Linear shrinkage</th>
<th>Metal</th>
<th>Linear shrinkage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloys</td>
<td>1.3%</td>
<td>Magnesium</td>
<td>2.1%</td>
<td>Steel, chrome</td>
<td>2.1%</td>
</tr>
<tr>
<td>Brass, yellow</td>
<td>1.3%–1.6%</td>
<td>Magnesium alloy</td>
<td>1.6%</td>
<td>Tin</td>
<td>2.1%</td>
</tr>
<tr>
<td>Cast iron, gray</td>
<td>0.8%–1.3%</td>
<td>Nickel</td>
<td>2.1%</td>
<td>Zinc</td>
<td>2.6%</td>
</tr>
<tr>
<td>Cast iron, white</td>
<td>2.1%</td>
<td>Steel, carbon</td>
<td>1.6%–2.1%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
feed with liquid metal, thus encouraging rapid freezing in these sections while the connection to liquid metal is still open. Figure 10.9 illustrates a possible application of external chills and the likely result in the casting if the chill were not used.

As important as it is to initiate freezing in the appropriate regions of the cavity, it is also important to avoid premature solidification in sections of the mold nearest the riser. Of particular concern is the passageway between the riser and the main cavity. This connection must be designed in such a way that it does not freeze before the casting, which would isolate the casting from the molten metal in the riser.

Although it is generally desirable to minimize the volume in the connection (to reduce wasted metal), the cross-sectional area must be sufficient to delay the onset of freezing. This goal is usually aided by making the passageway short in length, so that it absorbs heat from the molten metal in the riser and the casting.
Shrinkage

1. Determine the shrink rule to be used by pattern makers for white cast iron. Using the shrinkage value in Table 10.1, express your answer in terms of decimal fraction inches of elongation per foot of length compared to a standard 1-foot scale.

2. Determine the shrink rule to be used by mold makers for die casting of zinc. Using the shrinkage value in Table 10.1, express your answer in terms of decimal fraction of elongation per 300mm of length compared to a standard 300-mm scale.

3. A flat plate is to be cast in an open mold whose bottom has a square shape that is 200mm × 200mm. The mold is 40mm deep. A total of 1,000,000mm$^3$ of molten aluminum is poured into the mold. Solidification shrinkage is known to be 6.0%. Table 10.1 lists the linear shrinkage due to thermal contraction after solidification to be 1.3%. If the availability of molten metal in the mold allows the square shape of the cast plate to maintain its 200 mm × 200 mm dimensions until solidification is completed, determine the final dimensions of the plate.