Thermal supercooling induced dendritic solidification

To show the formation of dendrites during the solidification of a supercooled melt (of a pure material)

Course Name: Phase transformations and heat treatment

Authors

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Learning Objectives

After interacting with this Learning Object, the learner will be able to:

- To show, schematically, the dendritic microstructure that develops during the directional solidification of a supercooled melt of a pure material
- To explain the temperature inversion that can occur during freezing of a supercooled melt (of a pure material)
- To explain the formation of primary and secondary arms of a dendrite
- To explain the formation of dendritic microstructure in terms of the competition between fast dissipation of latent heat through the liquid and the increase in interfacial energy

Definitions of the components/Keywords:

Temperature inversion: the formation of a temperature profile in which the temperature at the solid-melt interface is the highest (with temperature dropping on both the solid and melt sides)

Equilibrium freezing temperature: the temperature at which a solid and its melt have the same free energy and hence are in equilibrium with each other

Supercooling: the process of cooling a melt below its freezing point without allowing for the formation of solid

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Definitions of the components/Keywords:

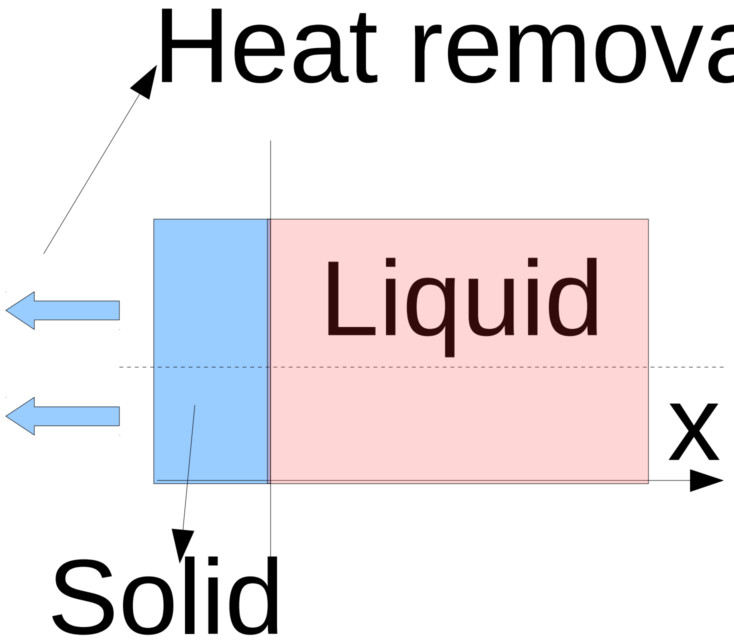
Dendrite: a crystal with branches – a crystal whose shape resembles that of a pine tree; the word is derived from the Greek word “dendrites” which means “of a tree”

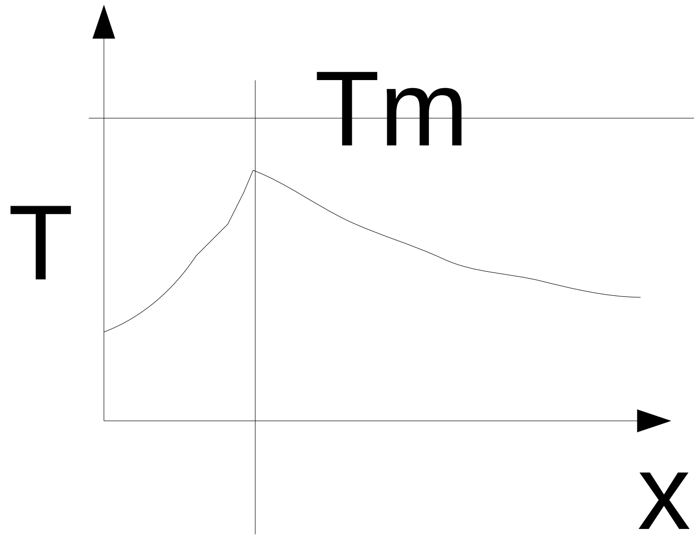
Primary dendritic arms: the first branches of a dendritic crystal

Secondary dendritic arms: the branches of a dendrite that form from the primary arms

Directional solidification: removing heat from a particular direction in a melt and hence moving the solid-liquid interface in a particular direction during solidification

Concepts: Temperature inversion





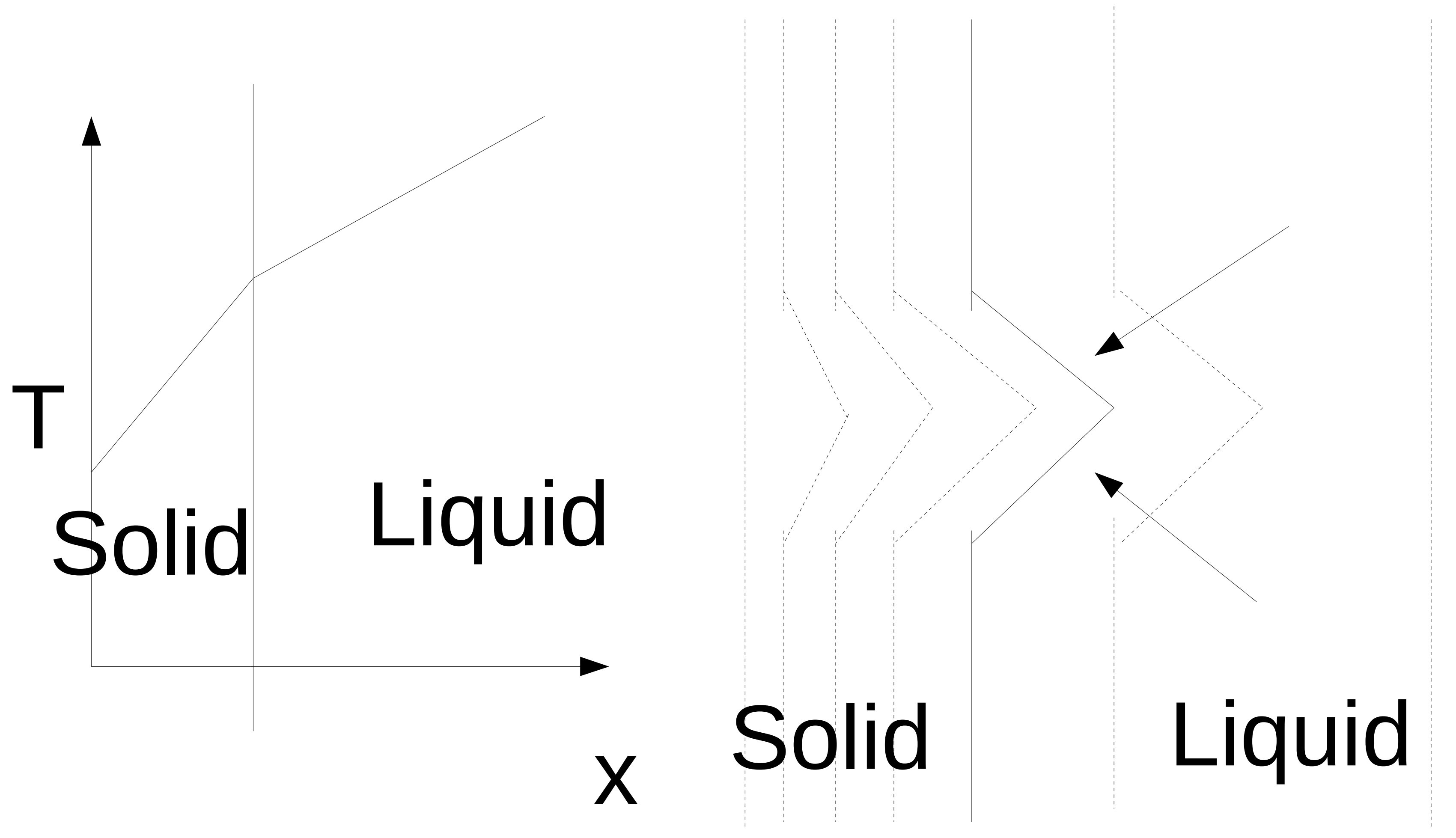
Let us consider a supercooled melt, from which, the heat is removed on one side. In such a case, sometimes, a temperature profile as shown can develop. This is known as temperature inversion.

Concepts: Temperature inversion

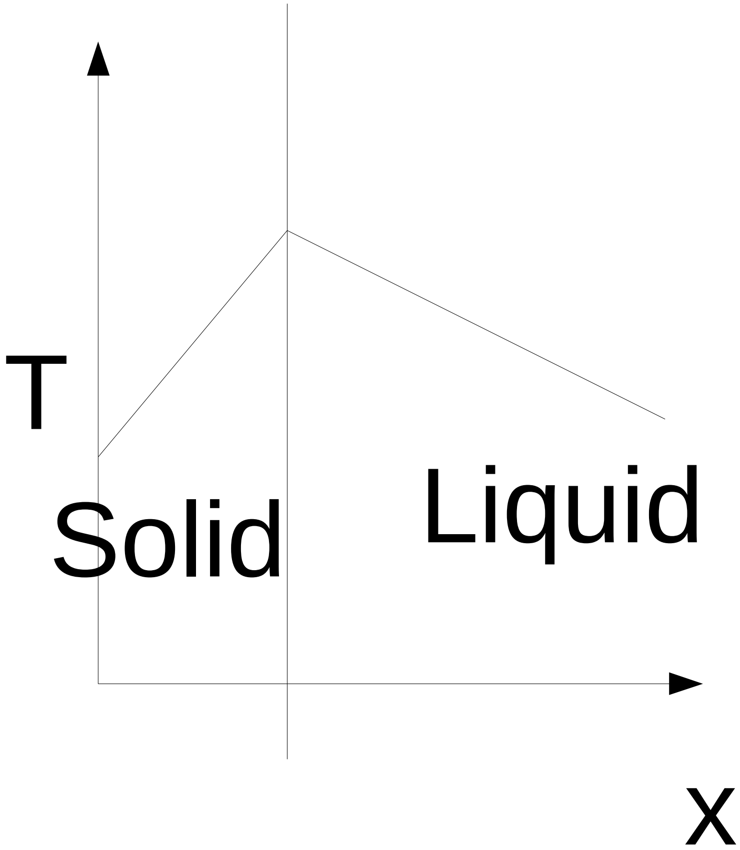
In temperature inversion, the temperature at the solid-melt interface is the highest with the temperature falling both in the solid and in the liquid. The temperature at the interface raises because of the release of latent heat associated with the phase transformation – the freezing of the melt into a solid. The temperature on the solid side drops because the heat is removed from the solid. The temperature on the liquid side drops because the liquid is supercooled.

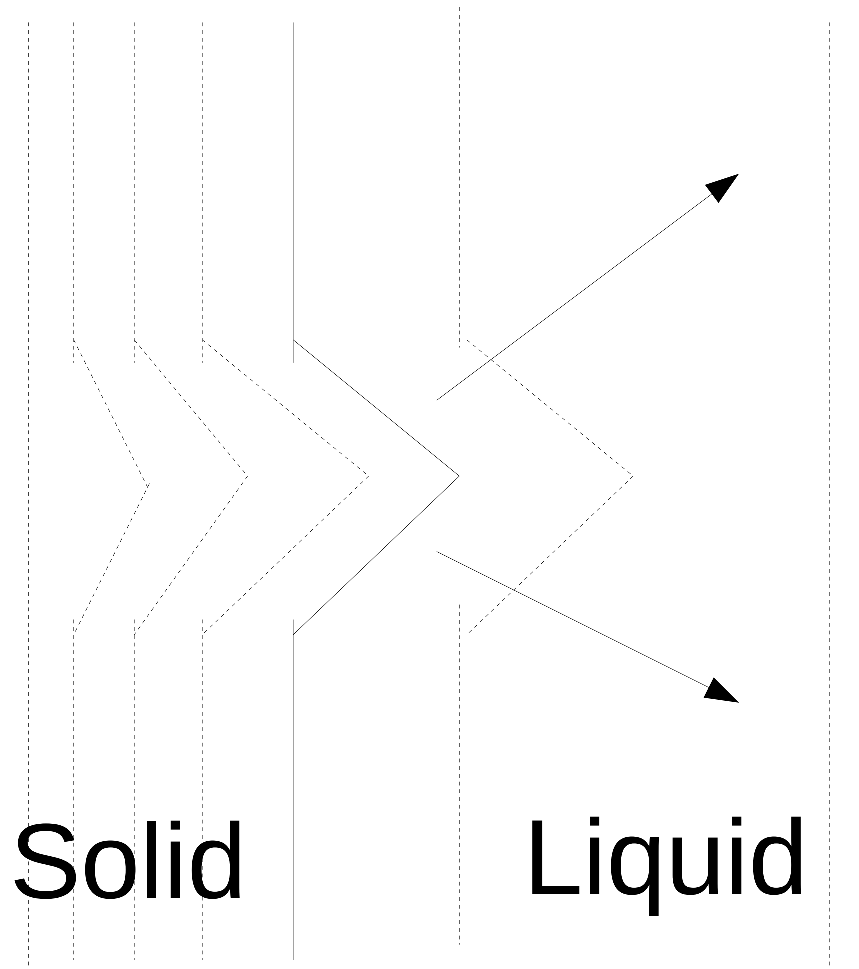
Concepts: Point effect of diffusion

By looking at the temperature gradient ahead of a solid liquid interface with a bump, one can see if any bumps that form will grow or will get suppressed. More specifically, in case of temperature inversion, the bumps will grow and if the temperature increases into the (pure) melt from the interface, the bumps will get suppressed. This is shown schematically in the following figures.



Broken lines: isothermal (lines of same temperature); arrows: direction of heat flow

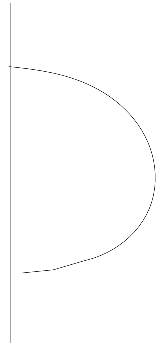


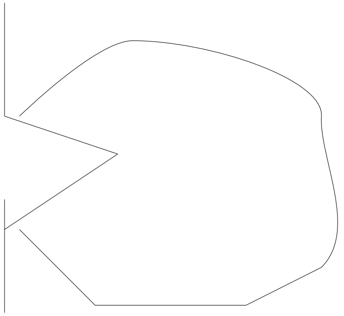


Broken lines: isothermal (lines of same temperature); arrows: direction of heat flow

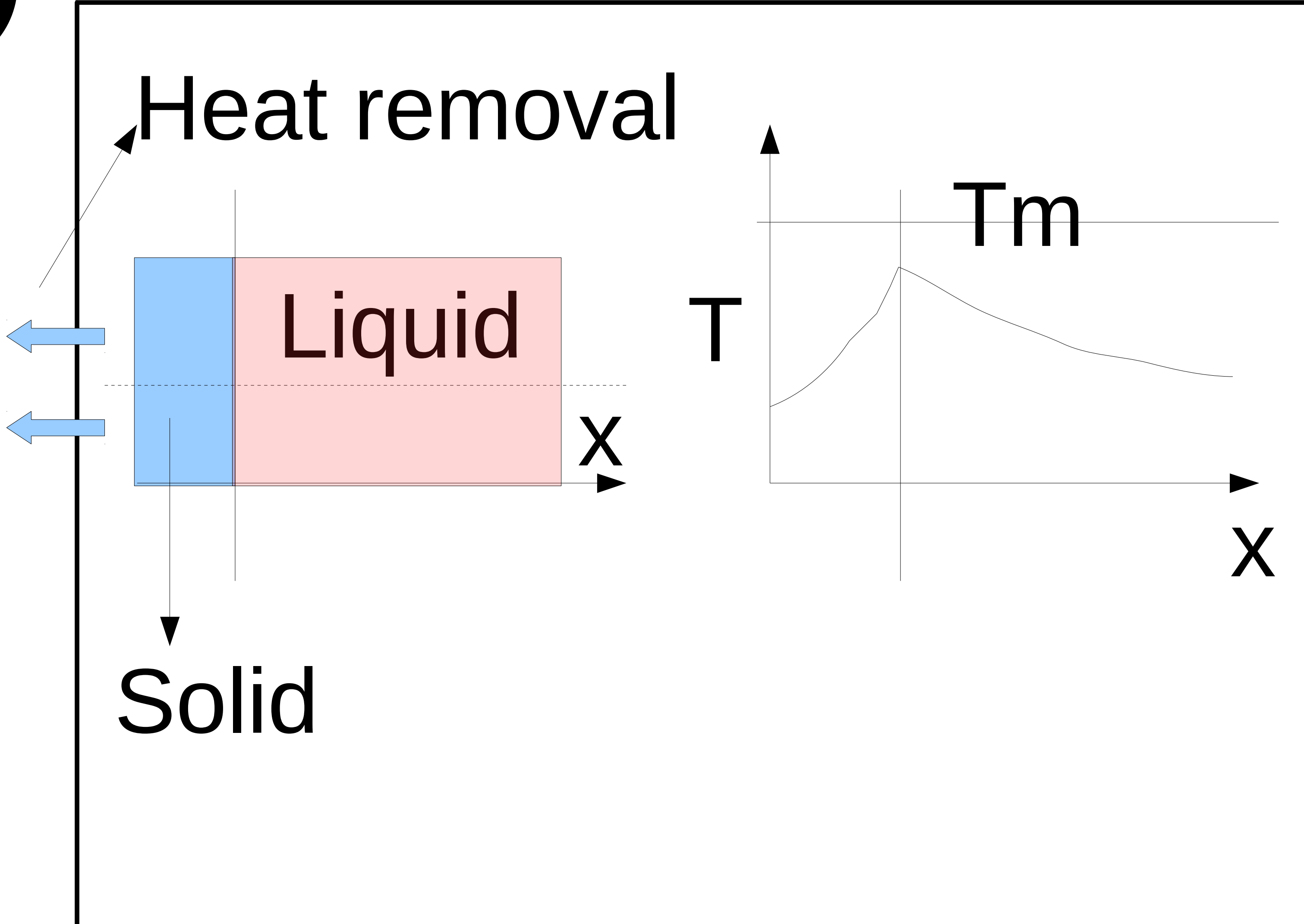
Concepts: Point effect of diffusion

The efficient removal of heat through liquid in the case of temperature inversion in also known as point effect of diffusion. For heat to be removed from a plane, as shown below, there is only a half-sphere volume of liquid is available; however, for a spike the available volume is more. In case the spike ends in a sharp point, for that point one full sphere is available (hence the name – point effect of diffusion)





Master Layout: Part 1



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Master Layout: Part 1

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In this step, we want to show how temperature inversion can occur during the freezing of a pure material if the melt is supercooled. In pure materials, producing supercooling is difficult but is not impossible; such supercooling that one produces in a pure material is called thermal supercooling

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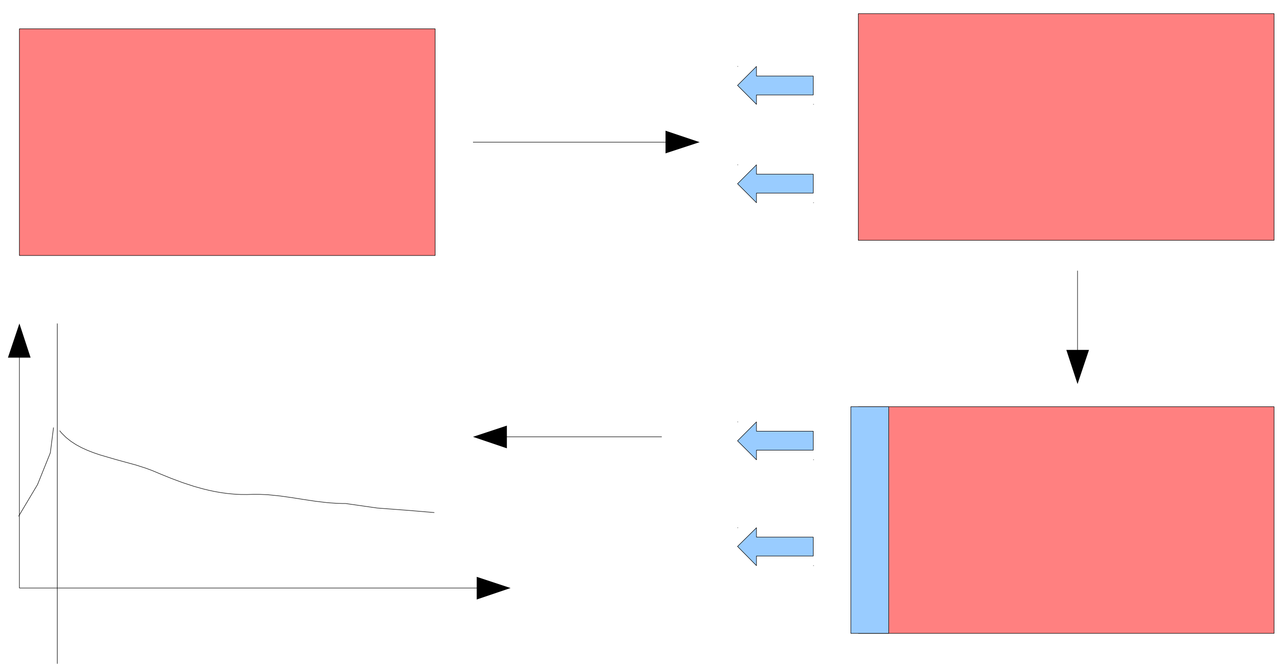
Analogy / Scenario / Action

In this part, the action we want to show is as follows:

- Show a supercooled melt
- Show the removal of heat from one side
- Show the solid-melt interface
- Show the temperature profile that develops – specifically, the inverted profile



Step 1:

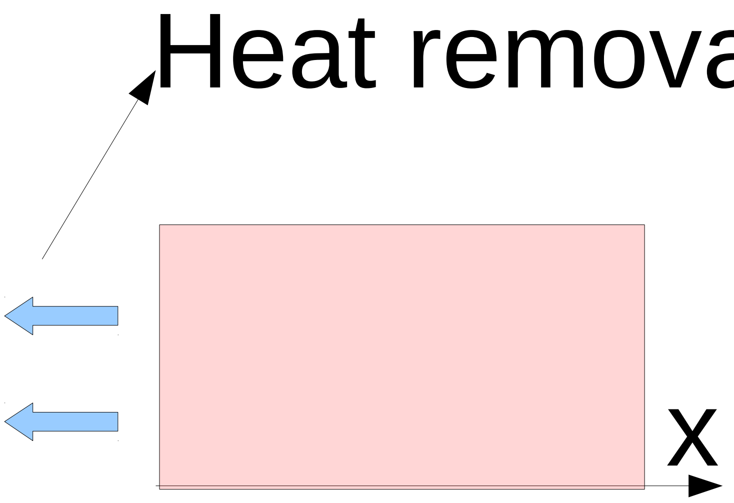
T1: Supercooled melt

Supercooled melt

Step 1

Description of the activity	Audio narration	Text to be displayed
First show a rectangular box filled with colour pink in the left side half of the animation area. Mark the pink region as supercooled liquid. Mark the horizontal axis and label it as x.	Consider the supercooled melt pure material – that is a pure liquid which is kept at a temperature lower than its freezing point without allowing it to freeze.	

Step 2: T1: Heat removal

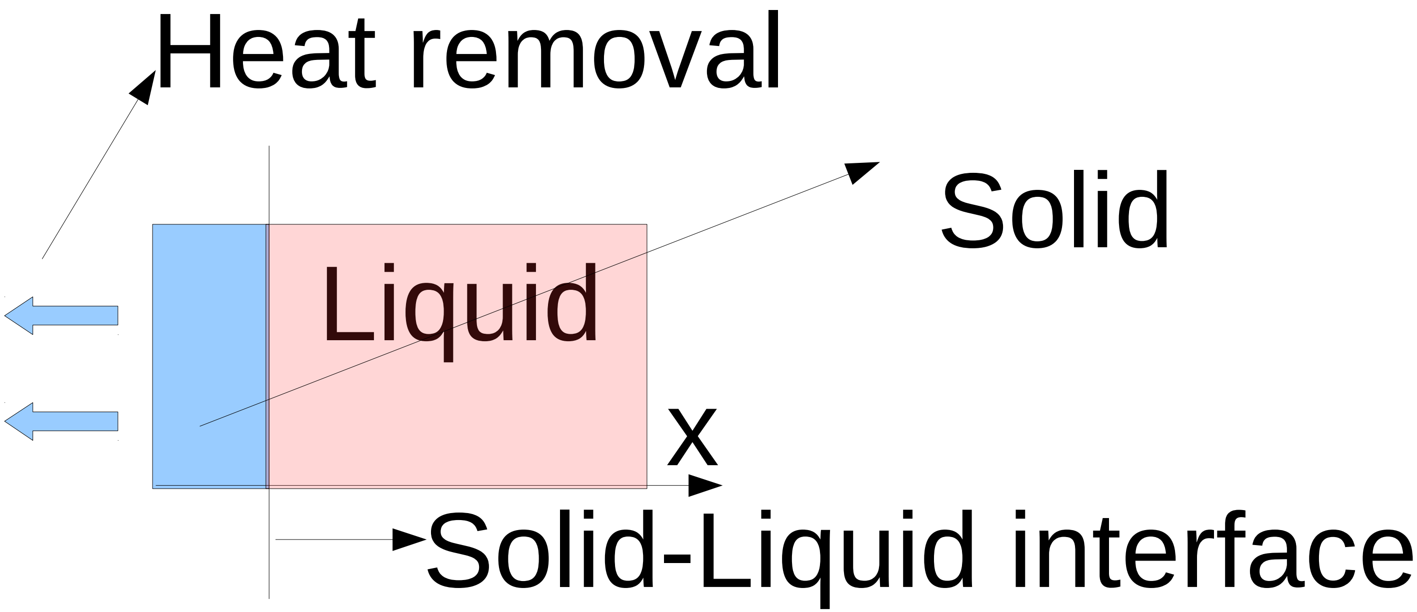


Step 2

Description of the activity	Audio narration	Text to be displayed
Introduce two big arrows at the left hand corner and write heat removal.	Let the three sides of the melt, namely, right, top and bottom be insulated. Let heat be removed from the left side of the melt.	

Step 3:

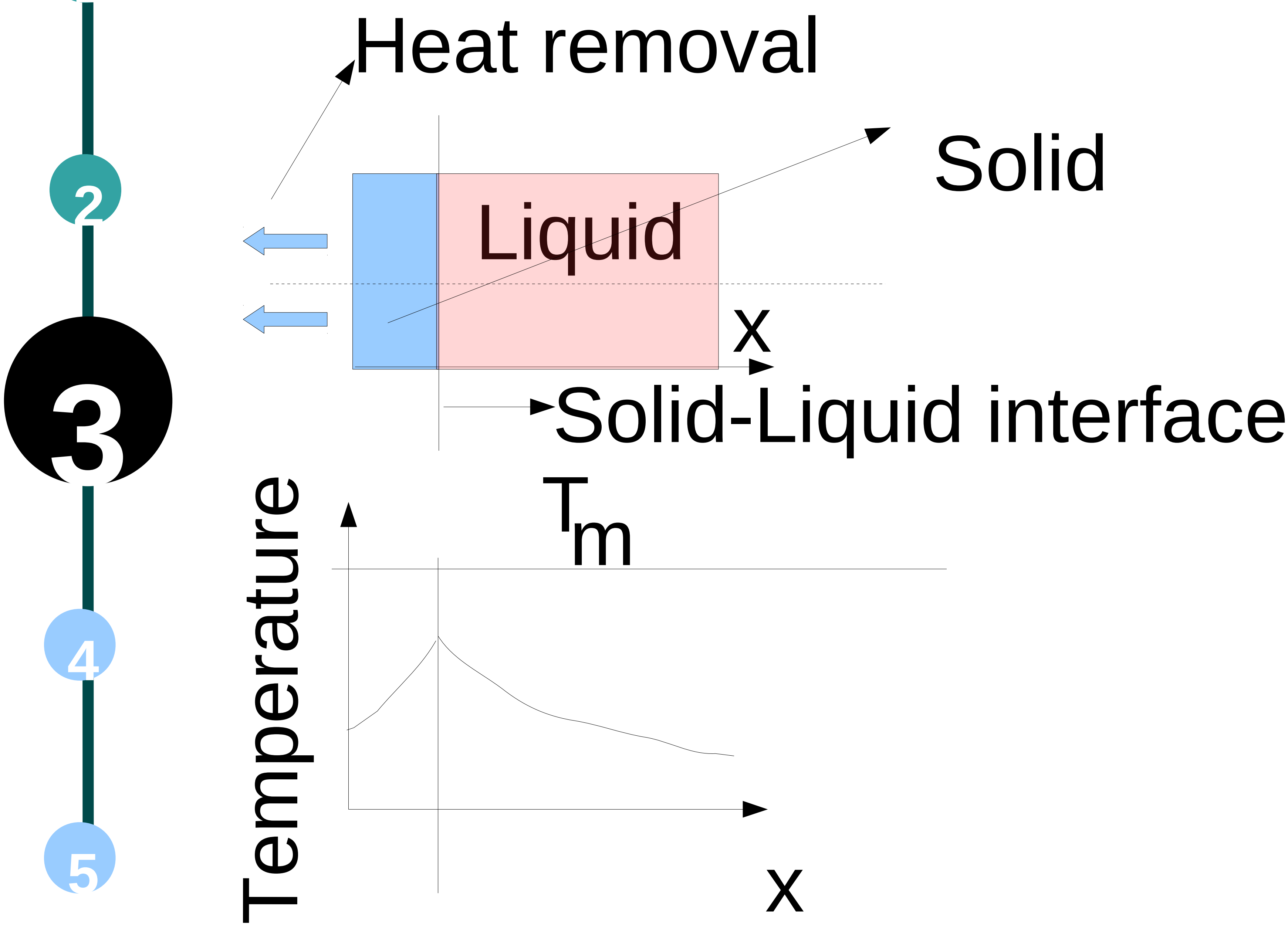
T1: Formation of temperature inversion



Step 3

Description of the activity	Audio narration	Text to be displayed
Form a thin layer of blue box next to the heat removal arrows inside the rectangular box. Draw a vertical line separating the blue-pink regions in the figure and mark it as solid-liquid interface.	Let us consider the formation of a small amount of solid at the left side. Let the interface between the formed solid and the melt be planar as shown. Since heat is getting removed from the left, the solid-liquid interface will move into the melt (that is, towards the right).	

Step 4: T1: Formation of temperature inversion



Step 4

Description of the activity	Audio narration	Text to be displayed
On the right half of the animation area, draw the x-and y-axes of a plot. Label the x-axis as x. Label the y-axis as Temperature. Now show a dotted line across the solid-melt sytem. As the dotted line is being drawn, show the temperature profile – which increases from left, reaches the highest value at the interface and then keeps decreasing as we move to the right.	Let us consider a horizontal line from the left to the right across the solid-melt interface. The temperature is the highest at the interface due to the release of latent heat. On both sides of the interface, temperature drops -- on the solid side because heat is getting removed from the solid and on the liquid side because the melt is supercooled. The formation of such a temperature profile is known as temperature inversion. Note that inversion is possible only in a heavily supercooled liquid. Such supercooling is hard if not impossible to achieve.	

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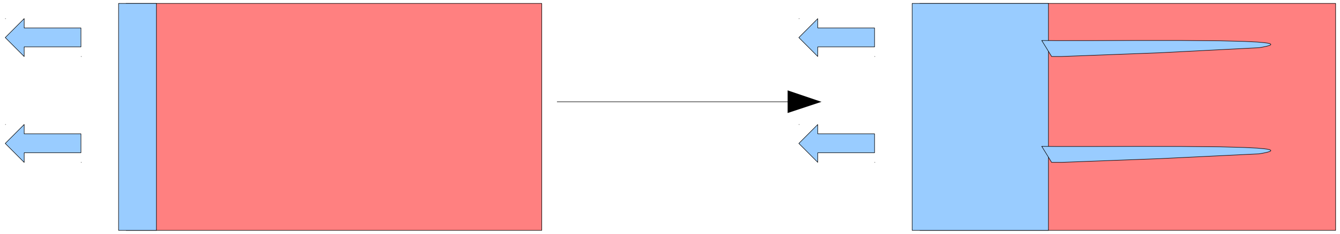
Master Layout: Part 2

In this step, we want to show how temperature inversion can lead to the formation of spikes in the planar interface between the solid and the melt.

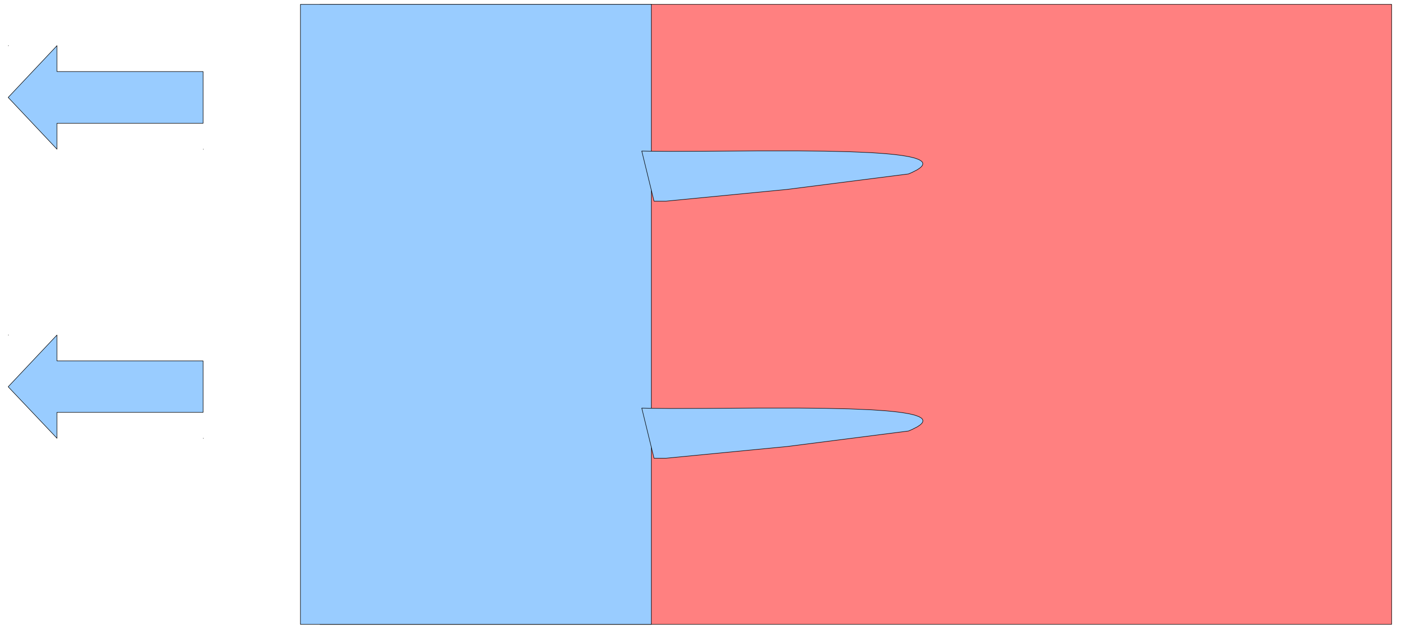
Analogy / Scenario / Action

In this part, the action we want to show is as follows:

- Show a planar interface between solid and melt.
- Impose a perturbation on the interface.
- Show that it leads to break-up of the planar interface.



Step 1



Step 1

Description of the activity	Audio narration	Text to be displayed
Introduce two small spikes. Make them grow horizontally towards right.	The soldification of pure melt is constrained only by the removal of latent heat from the interface. If the temperature profile shows temperature inversion, then, any small spikes that are produced, will have a tendency to grow as spikes into the melt; by doing so, the latent heat will be taken by the supercooled liquid. If there be no temperature inversion spikes will be suppressed because they can not release the latent heat into the melt.. Because of the heating of the melt next to the spikes, very close to a spike any other spike will be suppressed. Thus, the spikes have a tendency to form at uniform distance.	

Step 1

Description of the activity	Audio narration	Text to be displayed
	The spikes that form from the planar interface are called the primary dendritic arms. As noted earlier, the spikes tend to be uniformly spaced. This spacing is called the primary dendritic arm spacing. Also, in different crystals, the dendritic arms grow preferentially along specific crystallographic directions. For examples, in a fcc and bcc crystals, the dendritic arms tend to develop along the 100 direction of the crystal. Similarly, in a body centered tetragonal crystal, the dendritic arms tend to develop along 110 direction and in a hcp crystal, they develop along the 10{bar 1}0 direction.	

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Master Layout: Part 3

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In this step, we want to show the formation of secondary and tertiary spikes leading to a full blown dendrite.

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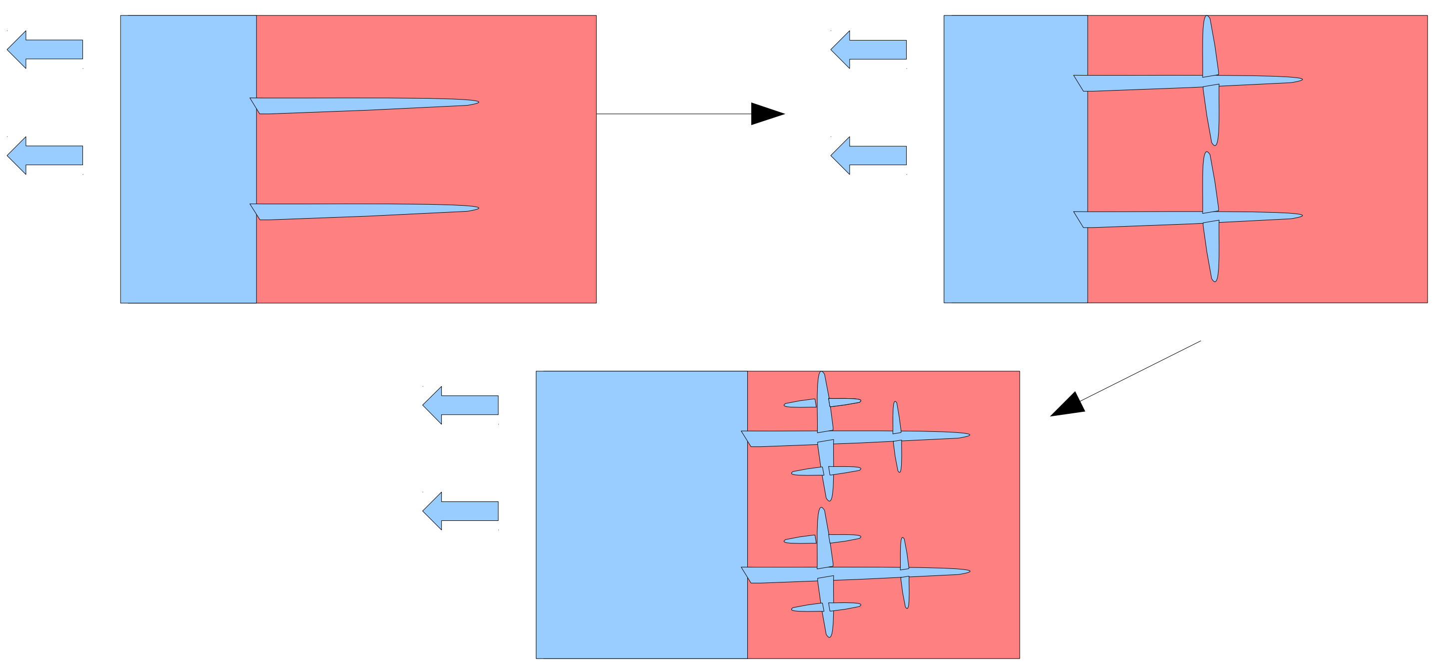
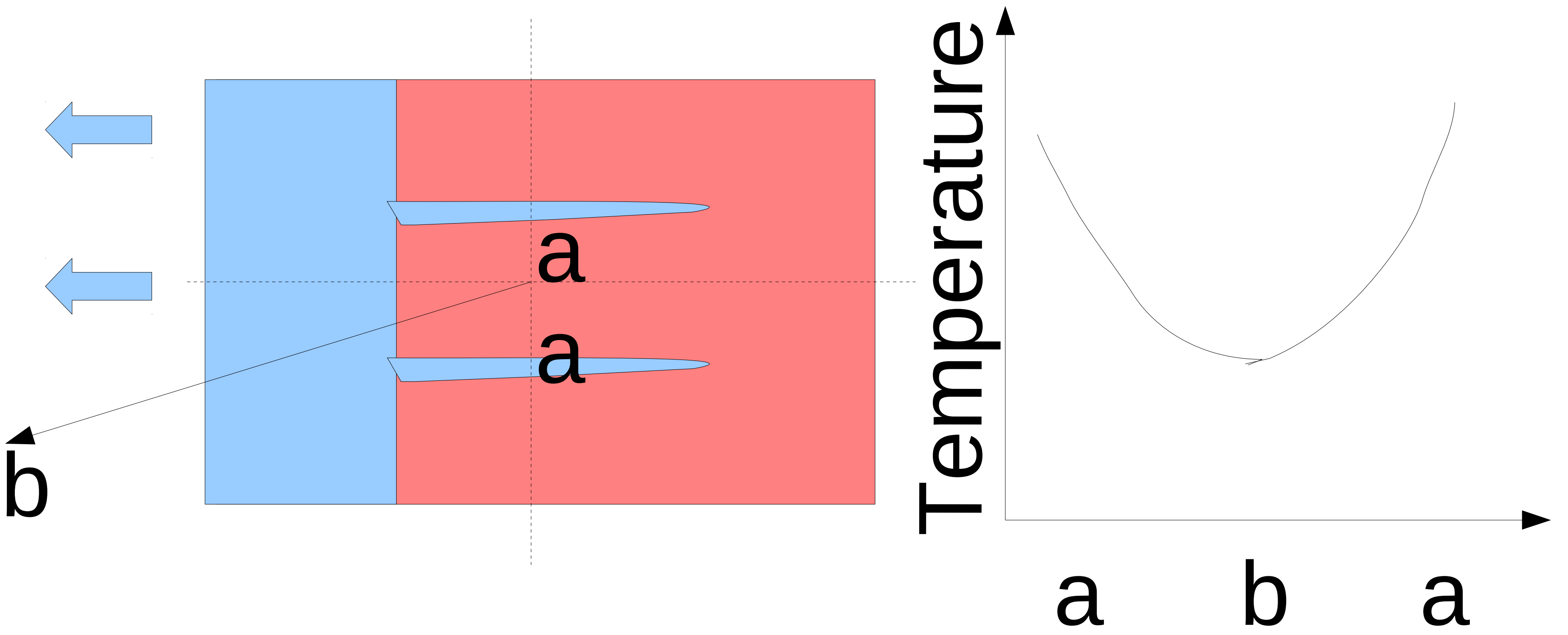
Analogy / Scenario / Action

In this part, the action we want to show is as follows:

- Explain the thermal profiles that lead to the formation of secondary arms
- Show the secondary arms
- Show the formation of tertiary arms



Step 1



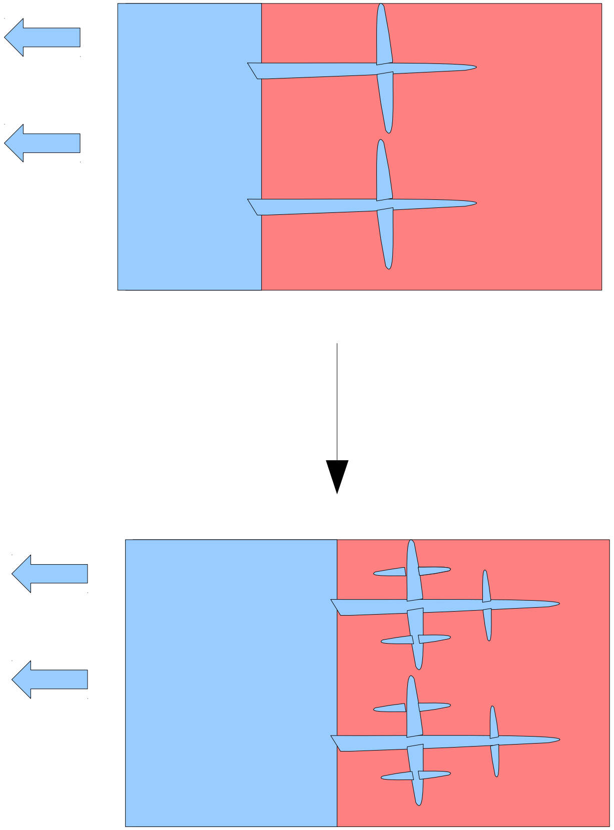
Step 1

Description of the activity	Audio narration	Text to be displayed
Show the picture with two spikes. Draw a line as shown. Mark two points at which the line cuts the spikes and mark them both as 'a'. Mark a point at the centre between these two point and mark it as “b”. On the right half of the animation area, draw the x-and y axes. Along the x-axes, mark the points plot as shown – marking points a, b, and a, b and a. Label the y-axis as temperature.	Consider the region between the primary arms. Just next to the arms (points marked a in the figure), the temperature is high due to the latent heat released. However, towards the centre between the two points (point marked b), the temperature could be low. If such a temperature inversion is set-up, then again, the primary arm will branch into secondary arms.	

Step 1

Description of the activity	Audio narration	Text to be displayed
Show a schematic plot on the figure which has the shape of a well with the minima at b.		

Step 2



Step 2

Description of the activity	Audio narration	Text to be displayed
Draw spikes on the side to the primary spike. Ass spikes to those spikes.	As is clear from the animation, this process of branching can continue; secondary branches can give rise to tertiary branches and so on. However, the interfacial area between the solid and the melt increases with increasing branching, in turn, resulting in an increase of the interfacial energy. Hence, the dendrite formation can be understood as a competition between two opposing tendencies – interfacial energy which would prefer more planar growth and release of latent heat which would prefer a branched interface (if the melt is supercooled enough to accept the released latent heat).	

Animation Area

Region to Show dendrite formation

Area to Show the plots

A P P E N D I X

Questionnaire *for users to test their understanding*

- During the directional solidification of a pure material, for the dendritic microstructure to form

  [a] Supercooling of the melt is necessary. True or False?

  [b] Temperature inversion should take place. True or False?

  [c] The crystal structure of the solid should be fcc or bcc. True or False?

  [d] The temperature of the interface can be above that of the equilibrium freezing temperature. True or False?

  [e] The interfacial energy associated with a dendritic crystal-melt interface is high as compared to a planar crystal-melt interface. True or False?

Questionnaire

1.

Answer: True

2.

Answer: True

3.

Answer: False

4.

Answer: False

5.

Answer: True

Links for further reading

Books:

Physical metallurgy principles, Second edition, R R Reed-Hill, Affiliated East-West Press Pvt. Ltd., 2008.

Phase transformations in metals and alloys, D A Porter and K E Easterling, Second edition, Chapman and Hall, 1991.

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Summary

- Temperature inversion is essential for dendritic microstructure to develop during the directional solidification of a pure melt
- Temperature inversion is a result of the directional removal of heat and the supercooling in the melt
- The increase in interfacial energy during dendritic branching opposes the tendency of dendritic branching