Cryogenic Platforms for Quantum Computing

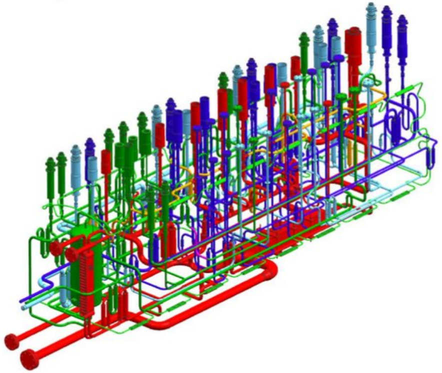
Greg Tatkowski, Matt Dubiel, Chris James

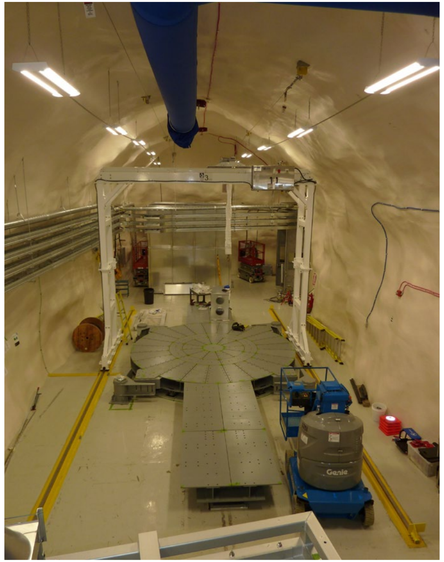
May 17th, 2025

Introductions

Greg Tatkowski

- Senior cryogenics engineer
  - Over 11 years experience at Fermilab working on:
    - Low temperature quantum systems at SQMS.
    - Liquid nitrogen and liquid helium systems for Mu2e.
    - A dark matter search one mile underground called SuperCDMS.
    - Cryogenic system review for a large liquid argon system called SBN-ND.
    - Miscellaneous cryogenics-related safety panels.
  - Education:
    - Illinois Institute of Technology: Bachelor of Science in Mechanical Engineering
    - Illinois Institute of Technology: Master of Mechanical and Aerospace Engineering
- Hobbies
    - Ice hockey

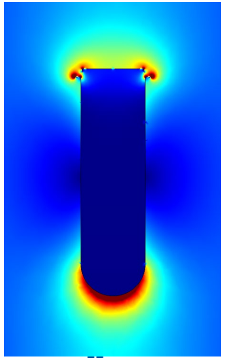




Introductions, cont.

Matt Dubiel

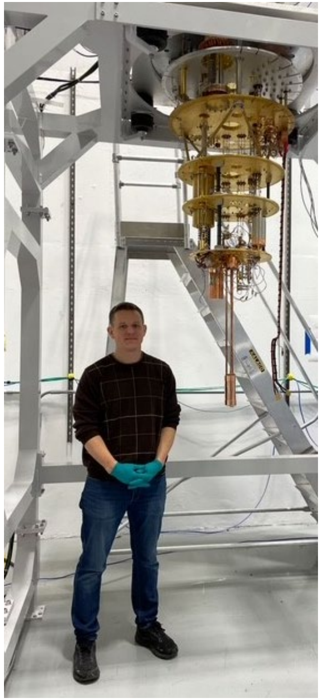
- Experience
  - Mechanical Engineer at Fermilab for 3+ years
  - Operation of SQMS Dilution Refrigerators
  - Design of Mechanical Hardware
  - Magnetic Shielding Design
- Education
  - Illinois Institute of Technology: Bachelor of Science degree in Mechanical Engineering
  - Lewis University: Bachelor of Science degree in Physics
- Hobbies
  - Ice Hockey



Introductions, cont.

Chris James

- Staff engineer at Fermilab:
  - 6 years at Fermilab
    - Short-Baseline Neutrino Far Detector (**SBN – FD**)
    - Short-Baseline Neutrino Near Detector (**SBN – ND**)
    - Gravity from Quantum Entanglement of Space Time (**GQuEST**)
    - Quantum Underground Instrumentation Experimental Testbed (**QUIET**)
    - Laboratory for Overground and Underground Devices (**LOUD**)
    - Cryogenic safety panels
    - Engineering Advisory Council
  - Education:
    - BS in Mechanical engineering from UIC
    - MS in Engineering Management from NIU



Ice Hockey: Additional Details

- Does anybody recognize this place?
- How does it work?

We Know That:

Note: Energy of water gets lower as it freezes

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Let's first note sources will be given here:

Image sources: pluspng.com, pngmart.com, storage.googleapis.com

We Also Know That:

$\neq$

Some Things we Might Not Know… Yet!

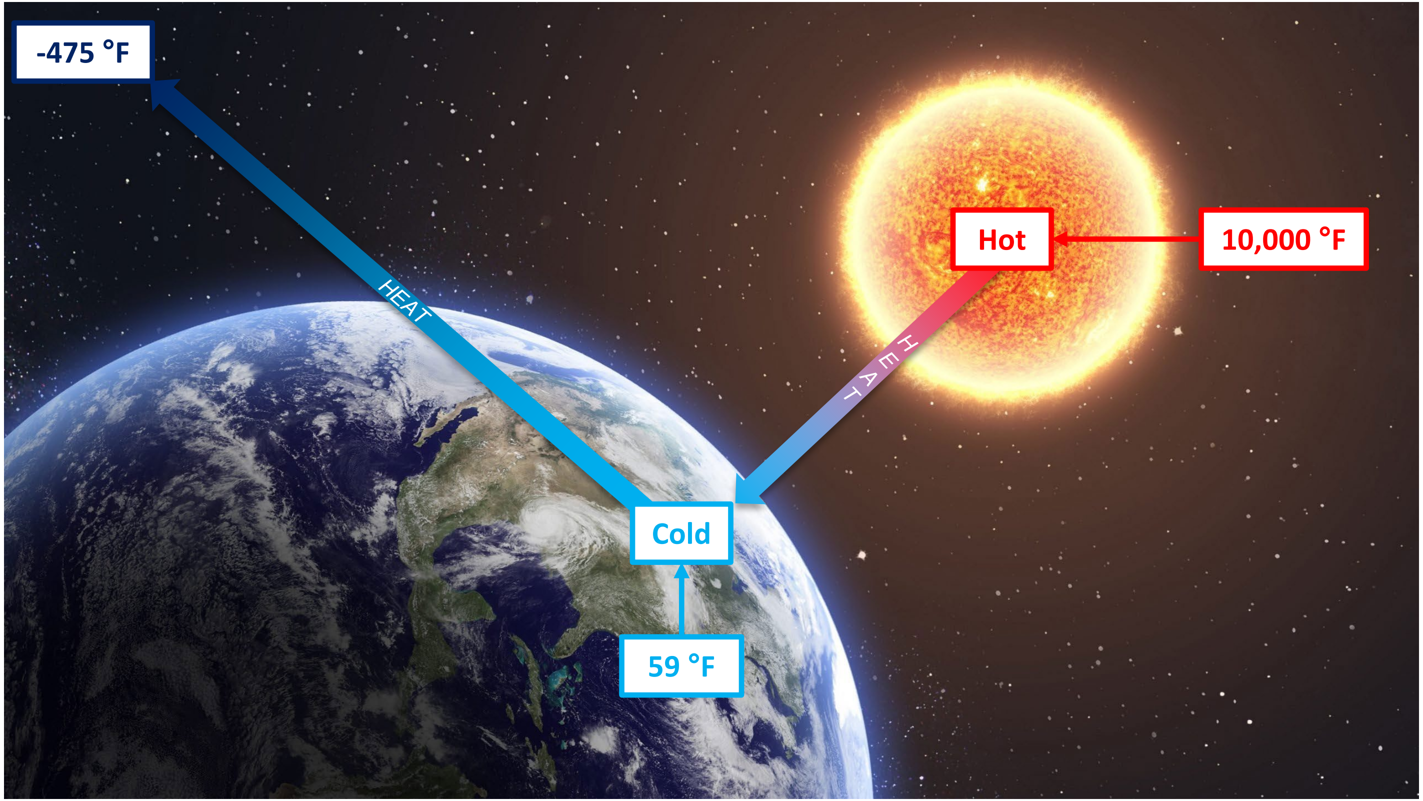

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Image sources: rd.com

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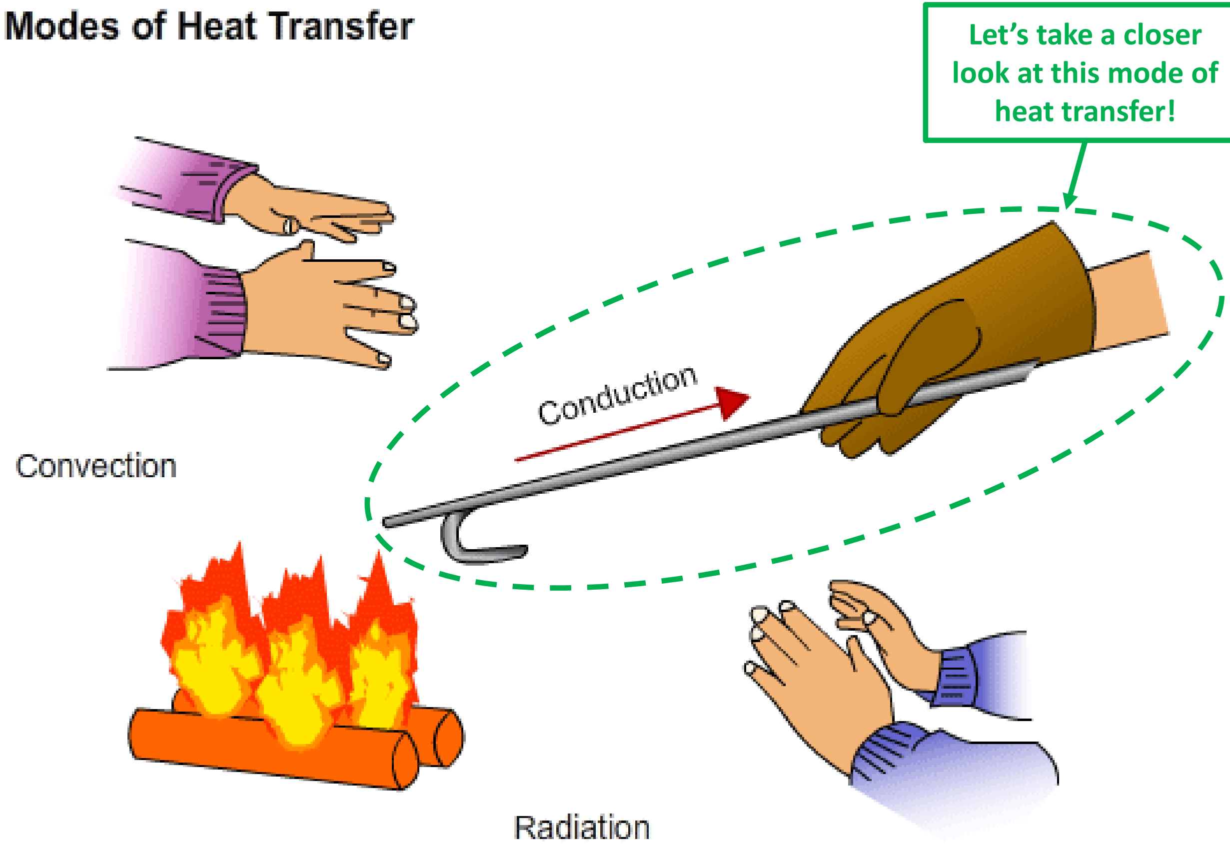
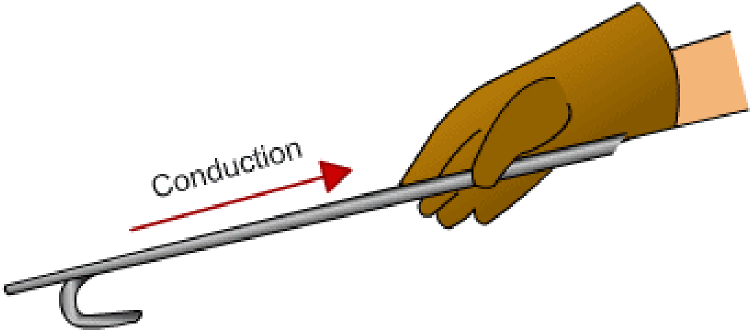


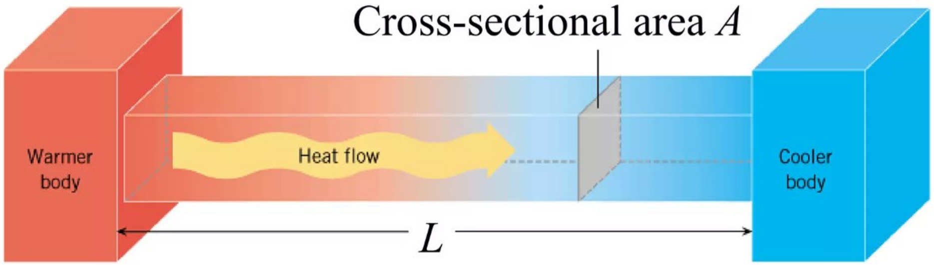
Let's take a closer look at this mode of heat transfer!

Image sources: ohsnapscience.blogspot.com

Some Things we Might Not Know… Yet (cont.)!



Conduction: Fourier's Law



$$Q = k\,A\left(\frac{\Delta T}{L}\right)$$

- Q = heat transfer
- k = thermal conductivity
- A = cross sectional area
- ΔT = temperature difference between two ends
- L = length

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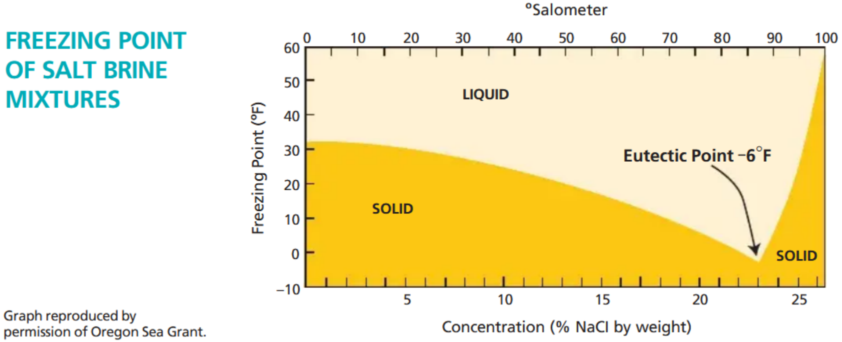
Image sources: slideshare.net/slideshow/heat-transfer-15633227/15633227

So How Do They Keep the Ice Cold at an Ice Rink?

- First, let's note that different substances have different freezing points.
  - For example, this is why salt is used on sidewalks in the winter.
    - Turns ice into liquid!
- Therefore, hypothetically speaking, you should be able to use 22% concentration salt water to freeze regular water.



Graph reproduced by permission of Oregon Sea Grant.
Additional information: http://seagrant.oregonstate.edu/sgpubs/onlinepubs/h99002.pdf

Image sources: gardenprofessors.com

Basic Thermodynamics of Hockey Rinks

Water

Wait! This doesn't work!

Why not?

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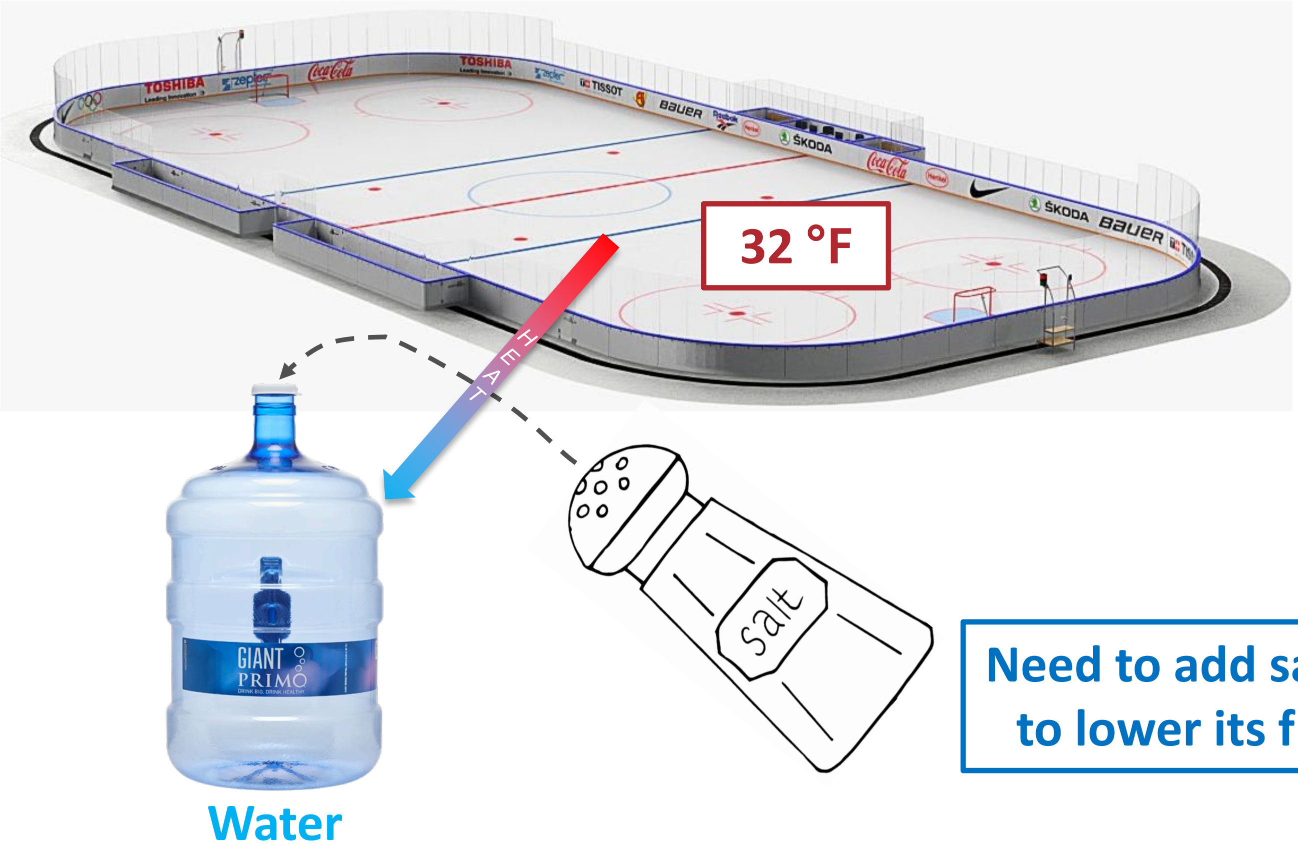
Image sources: free3d.com/3d-model/ice-hockey-rink-5436.html, store.primowater.com

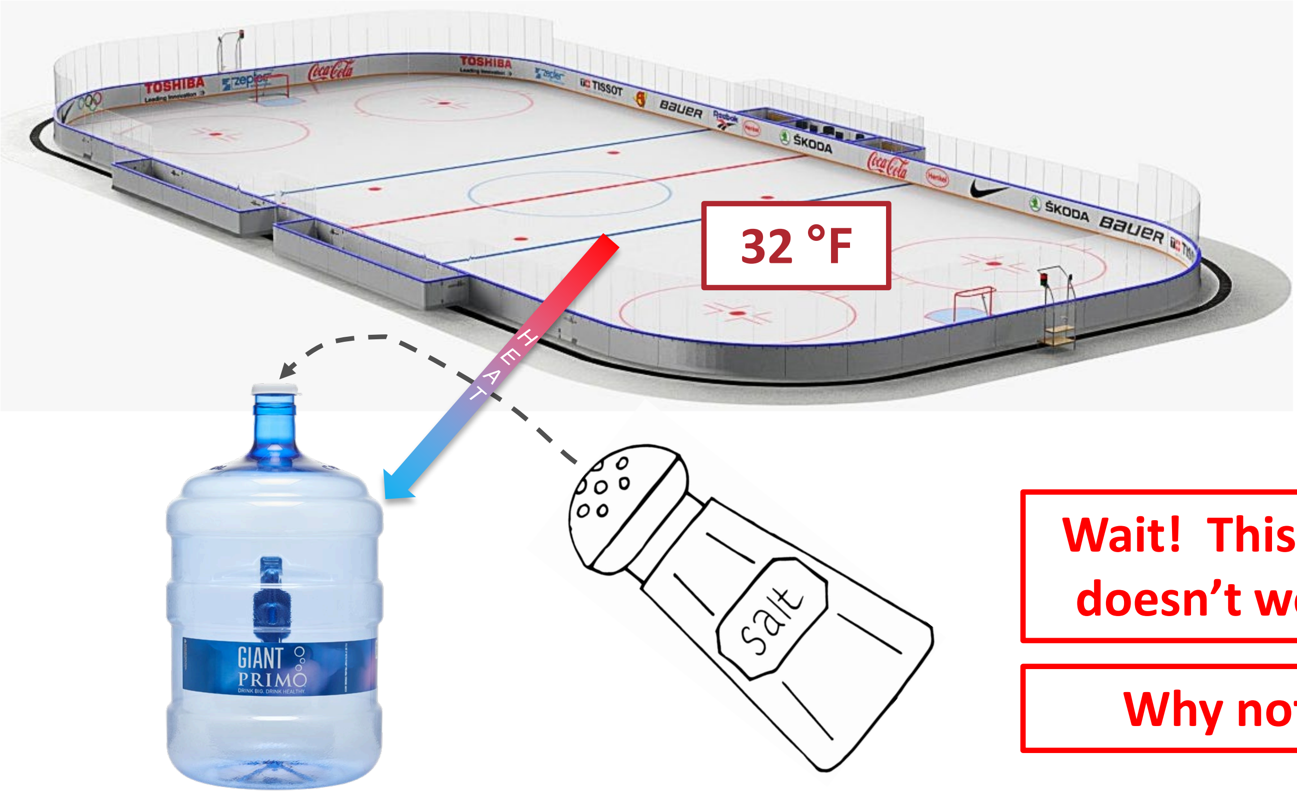
Basic Thermodynamics of Hockey Rinks, cont.



Need to add salt to the water to lower its freezing point!

Image sources: vecteezy.com/vector-art/8953503-salt-and-pepper-shaker-set-icon-sticker-sketch-hand-drawn-doodle-style-minimalism-monochrome-kitchen-seasonings-food

Basic Thermodynamics of Hockey Rinks, cont.



Water

Wait! This also doesn't work!

Why not?

Basic Thermodynamics of Hockey Rinks, cont.

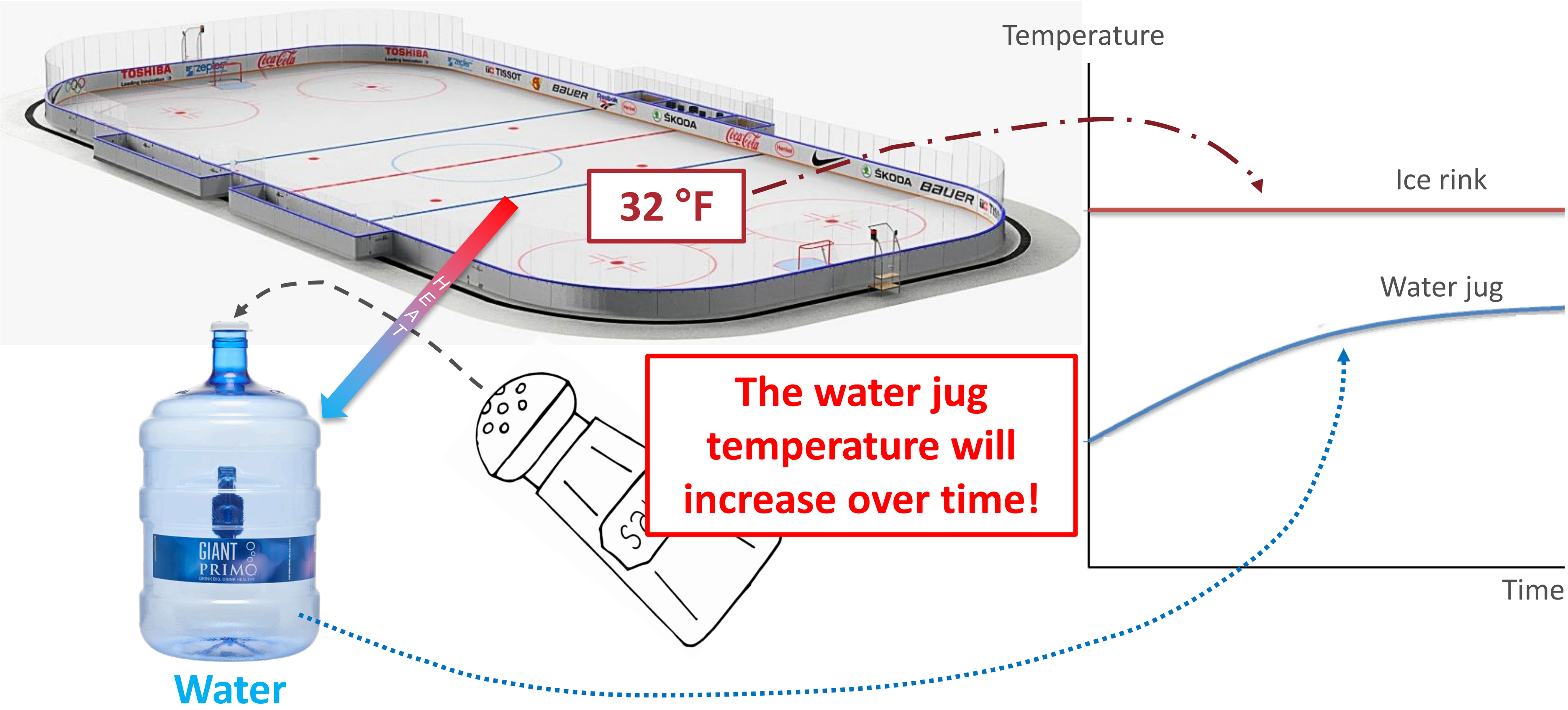


Image sources: nuclear-power.com/wp-content/uploads/logarithmic-mean-temperature-difference-example.png

Solution: The Refrigeration Unit

- A machine which uses energy to create a cooling effect, often utilizing special fluids called “refrigerants.”
  - In essence, it moves energy from one area to another.
- This unit needs a high temperature heat sink – why?
  - Let’s find out in the next slides!

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Image sources: carrier.com

High Temperature Heat Sink in a "Refrigeration Unit"

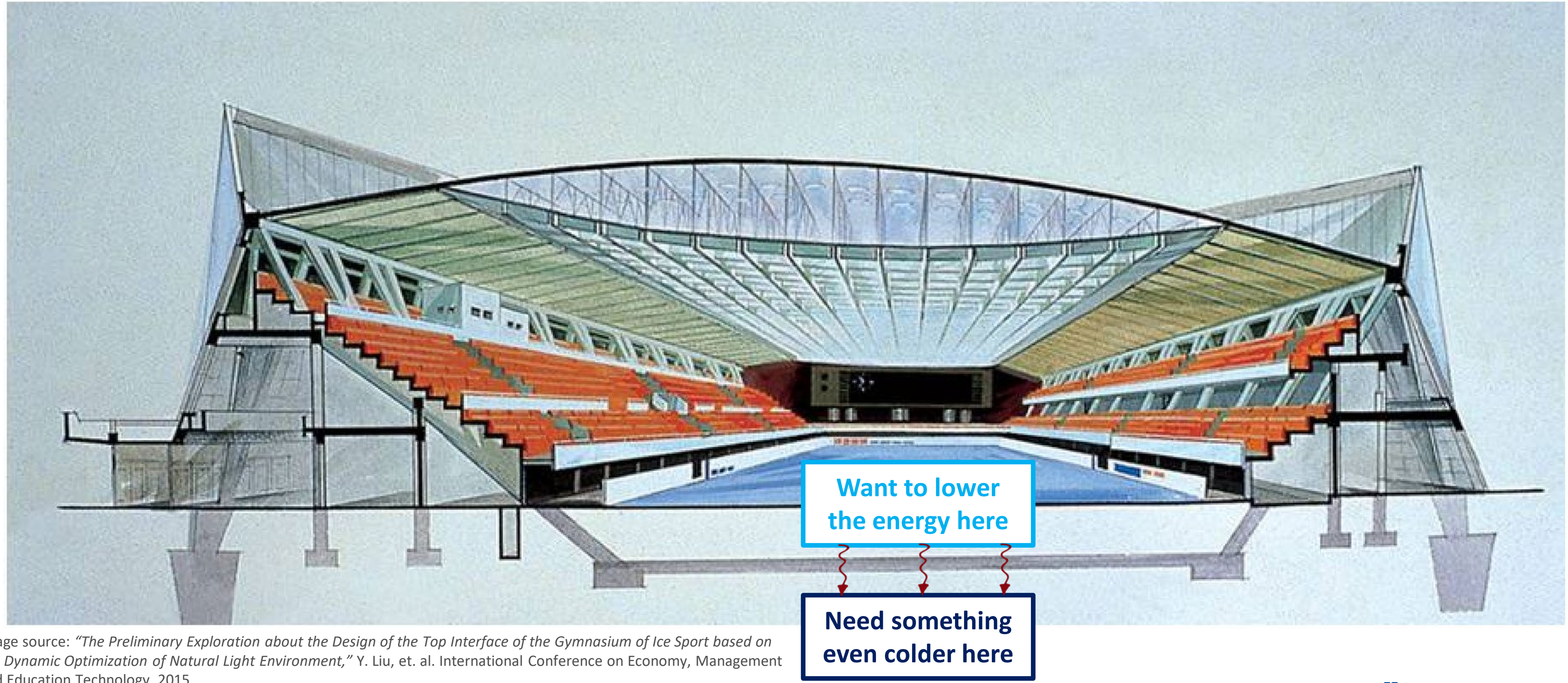

Image source: *"The Preliminary Exploration about the Design of the Top Interface of the Gymnasium of Ice Sport based on the Dynamic Optimization of Natural Light Environment,"* Y. Liu, et. al. International Conference on Economy, Management and Education Technology. 2015.

High Temperature Heat Sink in a “Refrigeration Unit” (cont.)

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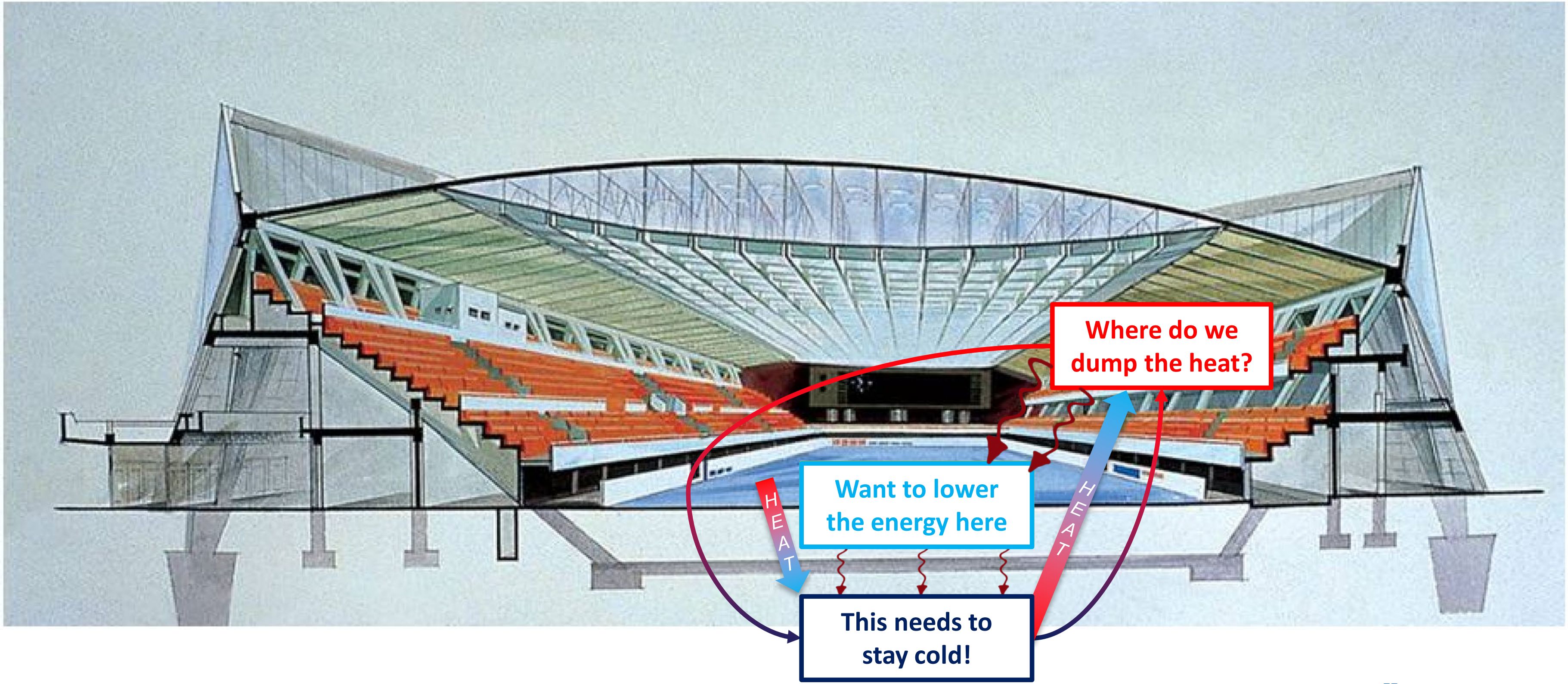
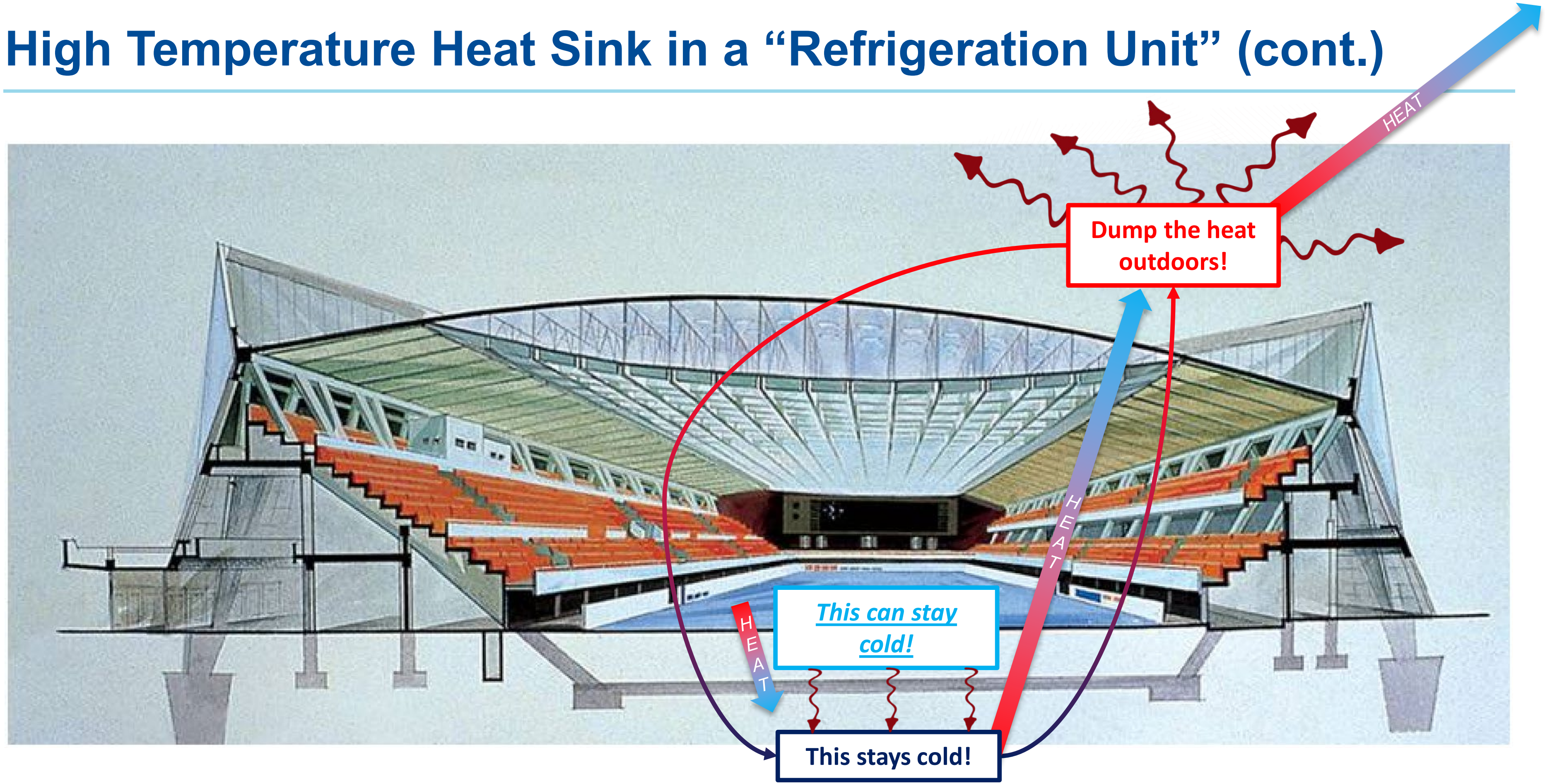
High Temperature Heat Sink in a "Refrigeration Unit" (cont.)



High Temperature Heat Sink in a "Refrigeration Unit" (cont.)



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High Temperature Heat Sink in a “Refrigeration Unit” (cont.)

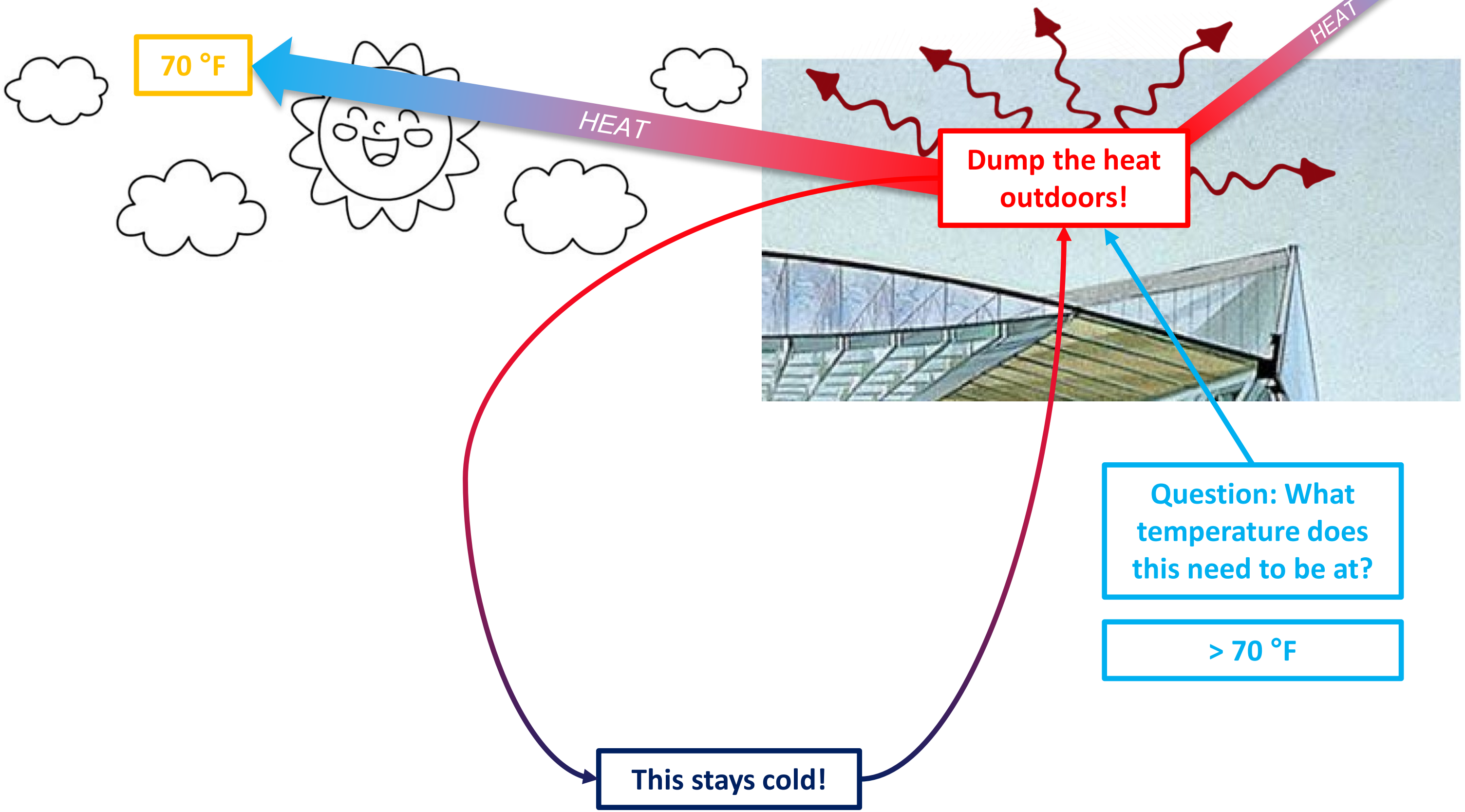

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Image sources: youtube.com

High Temperature Heat Sink in a "Refrigeration Unit" (cont.)

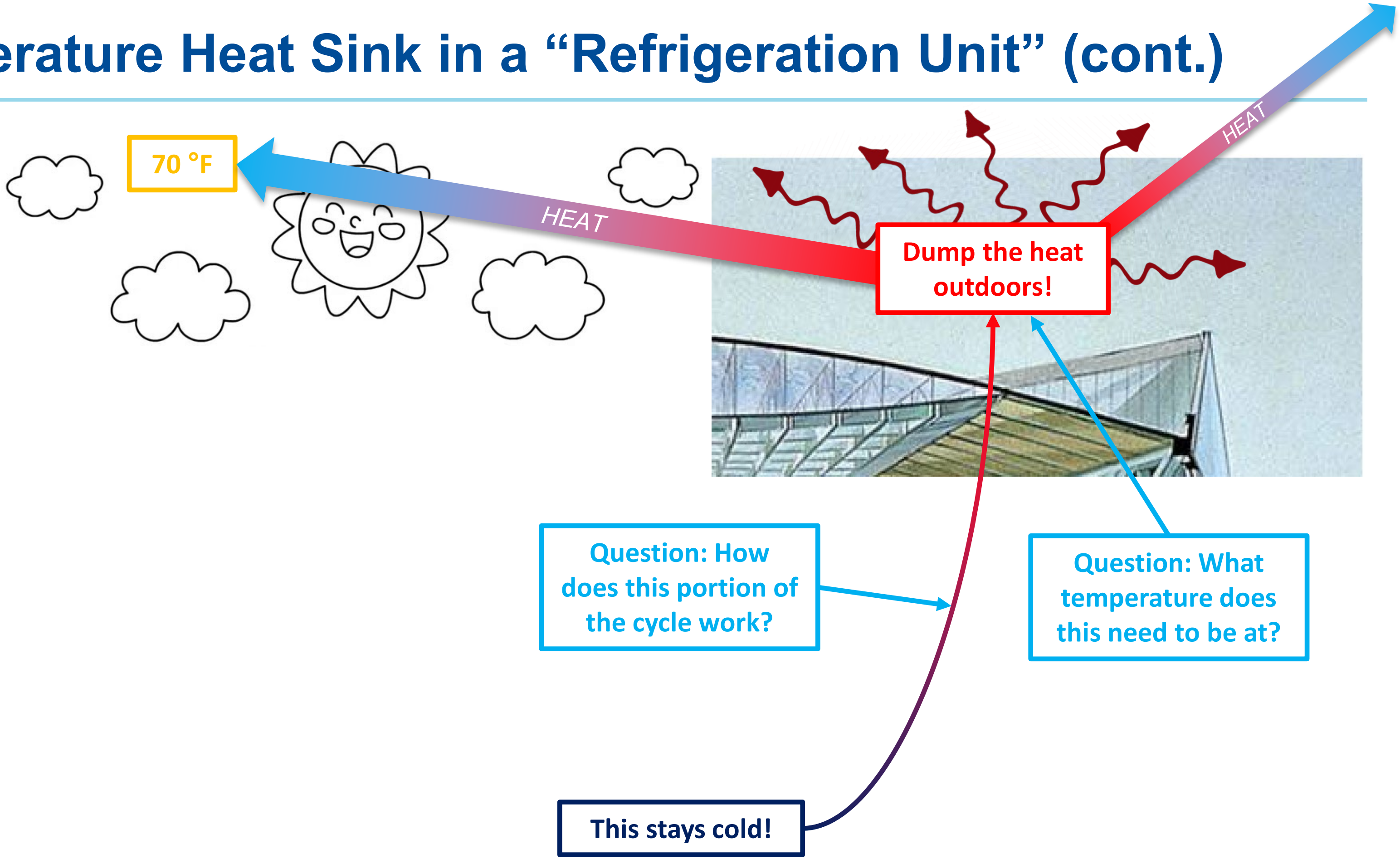
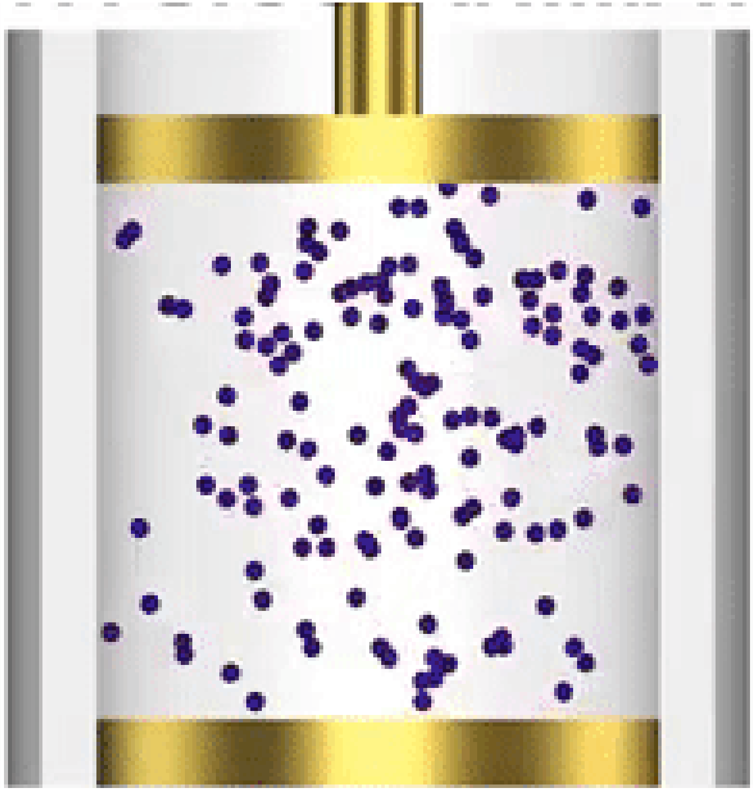


Image sources: youtube.com

Gas Compression

We will discuss this further in a little bit…



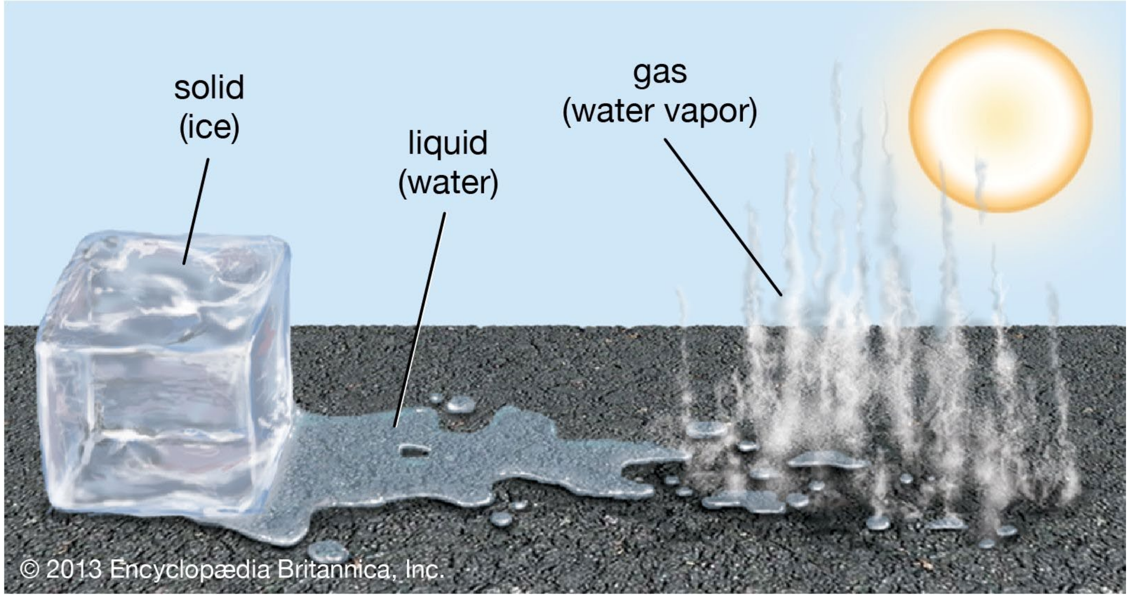
Cold temperature gas

Warm temperature gas

Image sources: physics-animations.com

How Much Energy is Required to Freeze Ice?

- We first observe three states of water:
  - Solid
  - Liquid
  - Gas
- The energy required to convert between these states is well studied.



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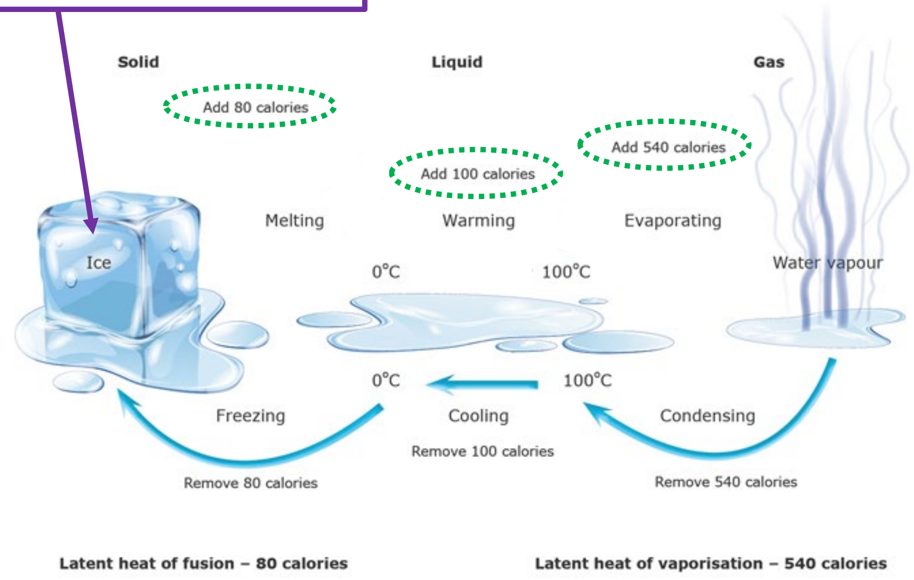
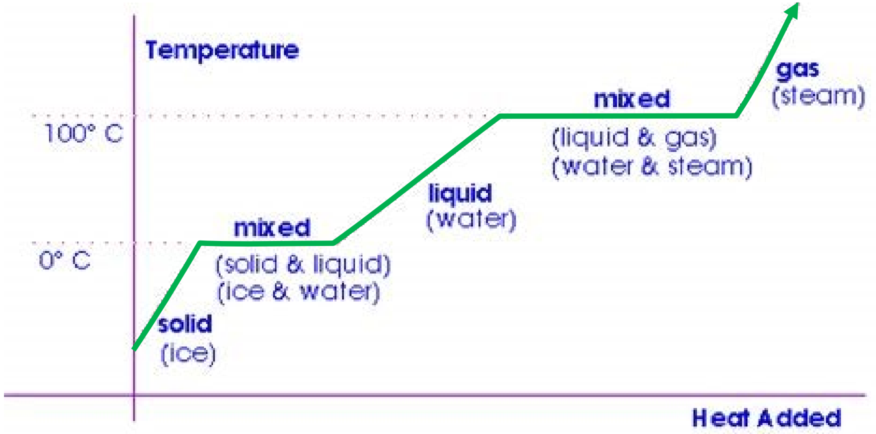
Changing States of Water and How Much Energy is Required

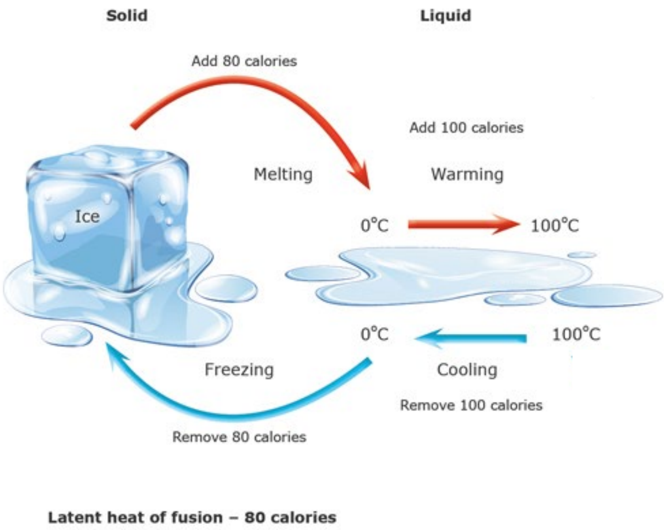
Assume weight = 1 gram

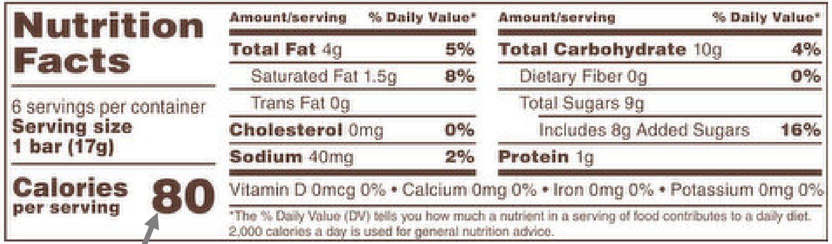




Source: https://www.ux1.eiu.edu/~cfadd/1360/20Heat/Latent.html

What is a Calorie?





Nutrition Facts

6 servings per container
Serving size 1 bar (17g)

Calories per serving 80

Amount/serving	% Daily Value*	Amount/serving	% Daily Value*
Total Fat 4g	5%	Total Carbohydrate 10g	4%
Saturated Fat 1.5g	8%	Dietary Fiber 0g	0%
Trans Fat 0g		Total Sugars 9g	
Cholesterol 0mg	0%	Includes 8g Added Sugars	16%
Sodium 40mg	2%	Protein 1g	

Vitamin D 0mcg 0% • Calcium 0mg 0% • Iron 0mg 0% • Potassium 0mg 0%

*The % Daily Value (DV) tells you how much a nutrient in a serving of food contributes to a daily diet. 2,000 calories a day is used for general nutrition advice.

1 Calorie = 1 kcal

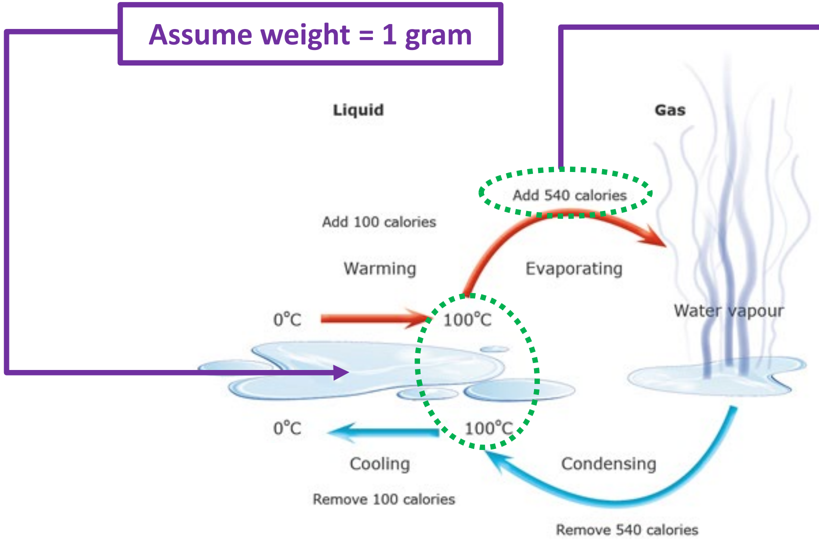
Conversion of KiloCalories into Other Units

From Kilocalories (kcal)	To Unit	Conversion Factor
1 kcal	calories (cal)	1 kcal = 1,000 cal
1 kcal	Kilojoules (kJ)	1 kcal ≈ 4.184 kJ
1 kcal	Watt-hours (Wh)	1 kcal ≈ 0.001162 Wh
1 kcal	British Thermal Units (BTU)	1 kcal ≈ 3.965 BTU
1 kcal	Electronvolts (eV)	1 kcal ≈ 2.613 x 10^{22} eV

Ex Examples.com

Image sources: peoi.org, animalia-life.club/qa/pictures/snickers-nutrition-facts, Walmart.com

What is a Calorie (cont.)?



540 cal to boil one gram of water is roughly the same amount of energy change which happens when you walk up one flight of stairs!

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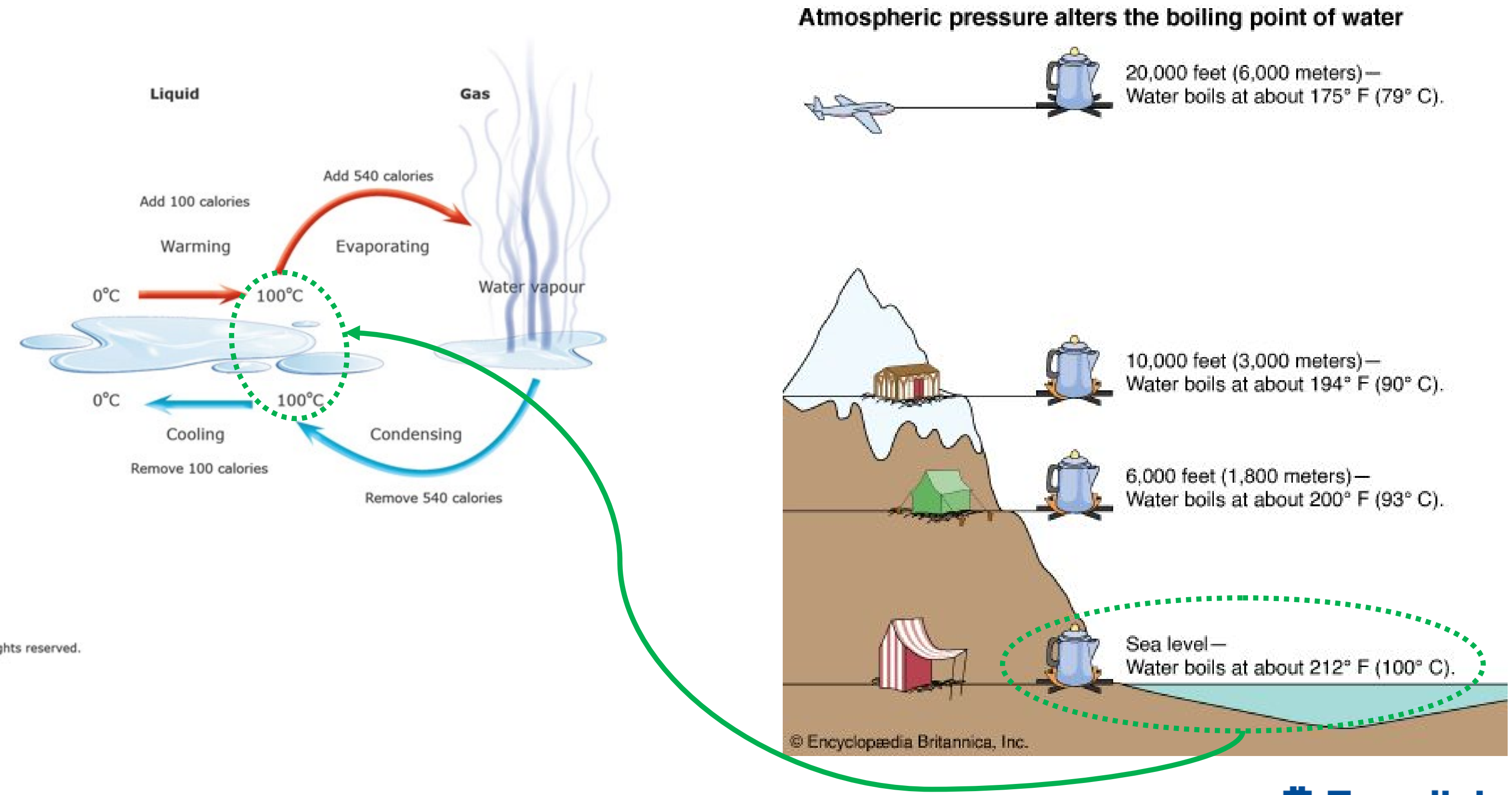
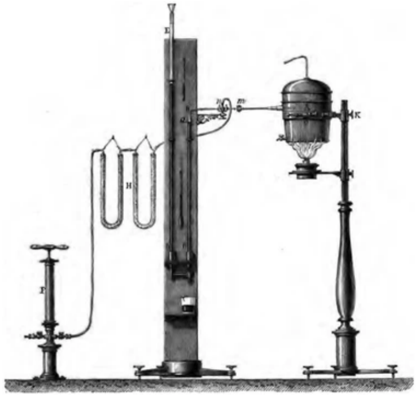
Image sources: vecteezy.com

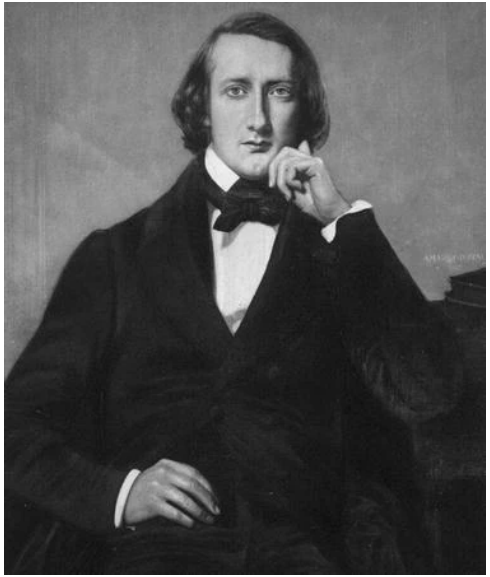
The Boiling Temperature of Water

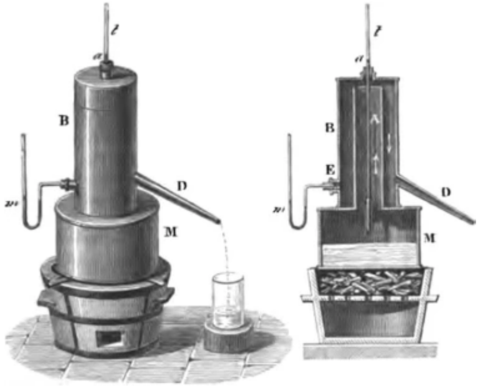


Critical Figures in Thermodynamics

- Scientists such as Henri Victor Regnault (1810-1878) spent their lifetime studying the properties of water, amongst other things.







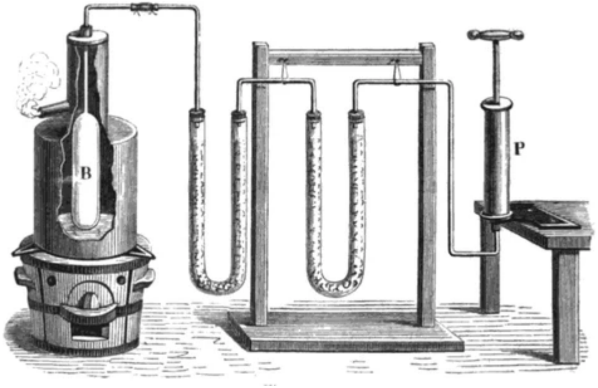


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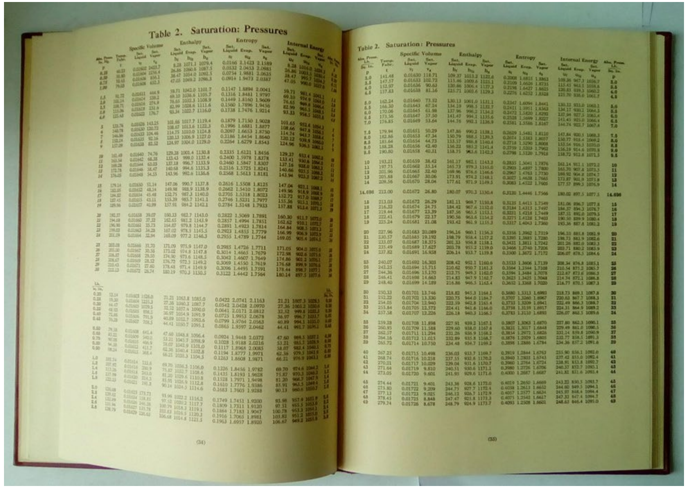
Image sources: https://link.springer.com/article/10.1007/s00016-010-0028-3

Critical Figures in Thermodynamics, cont.

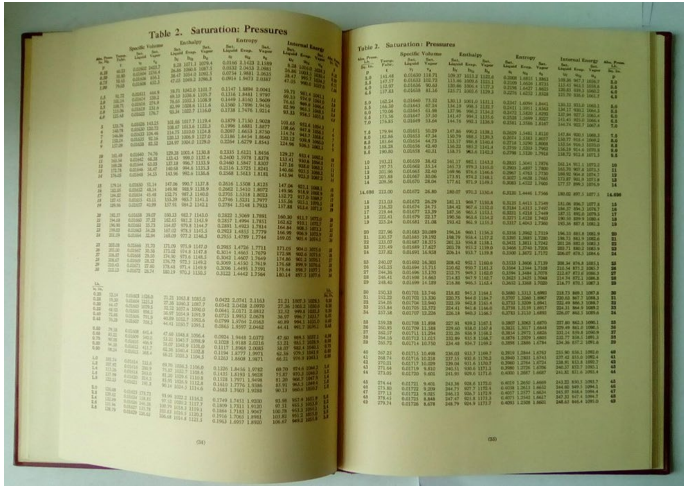


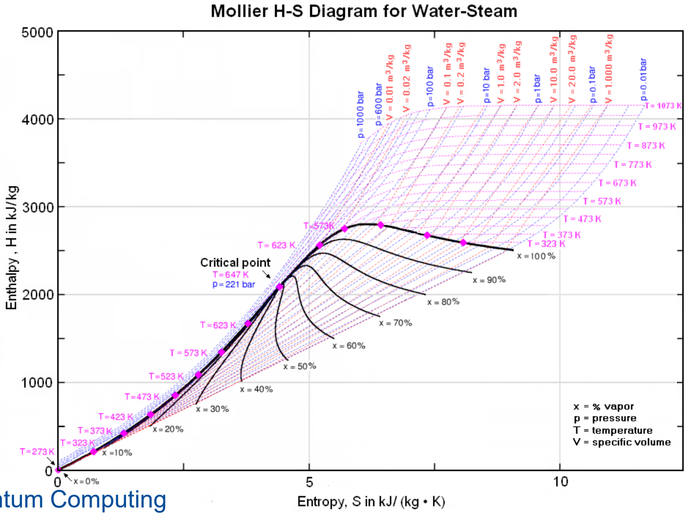
- Others such as Joseph H. Keenan and Frederick G. Keyes compiled this data into books known as “steam tables.”

Image sources: amazon.com, en.citizendium.org

Critical Figures in Thermodynamics, cont.

- Others such as Joseph H. Keenan and Frederick G. Keyes compiled this data into books known as "steam tables."
- The data of these "steam tables" is also available graphically thanks to the work of people such as Richard Mollier (1863-1935).





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Ice Rink Revisited

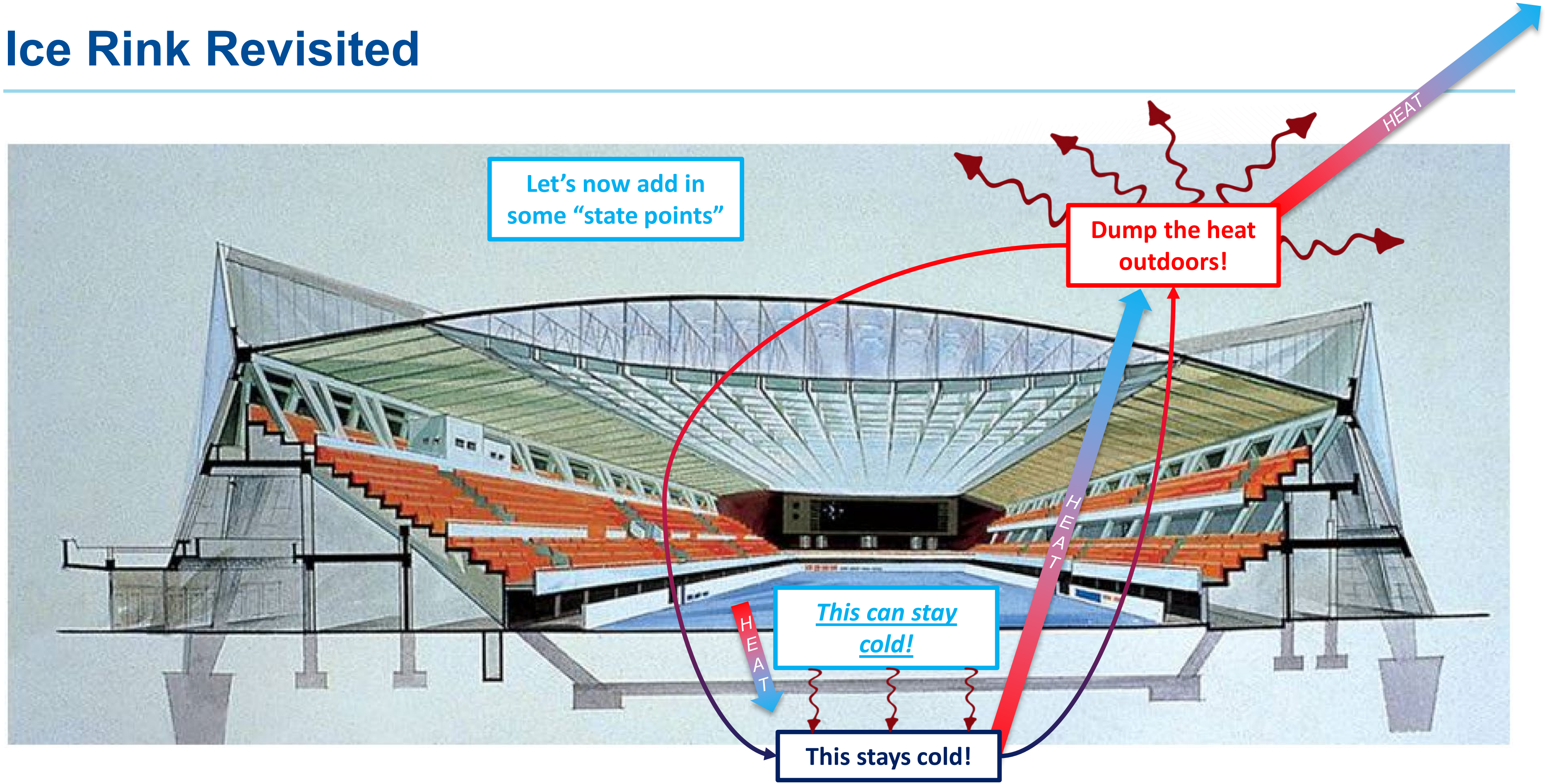
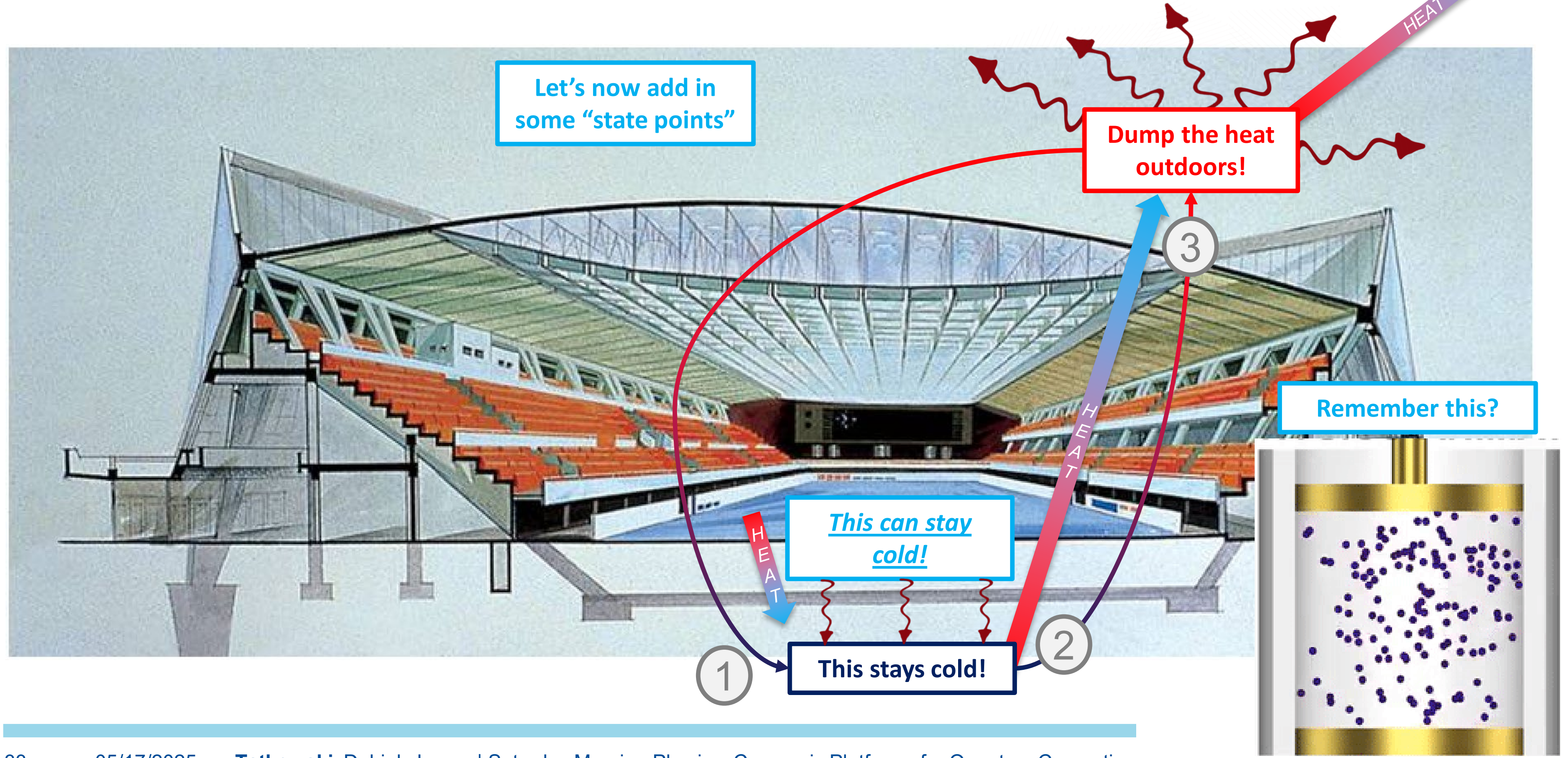


Image sources: docs.codecalculation.com

Ice Rink Revisited, cont.



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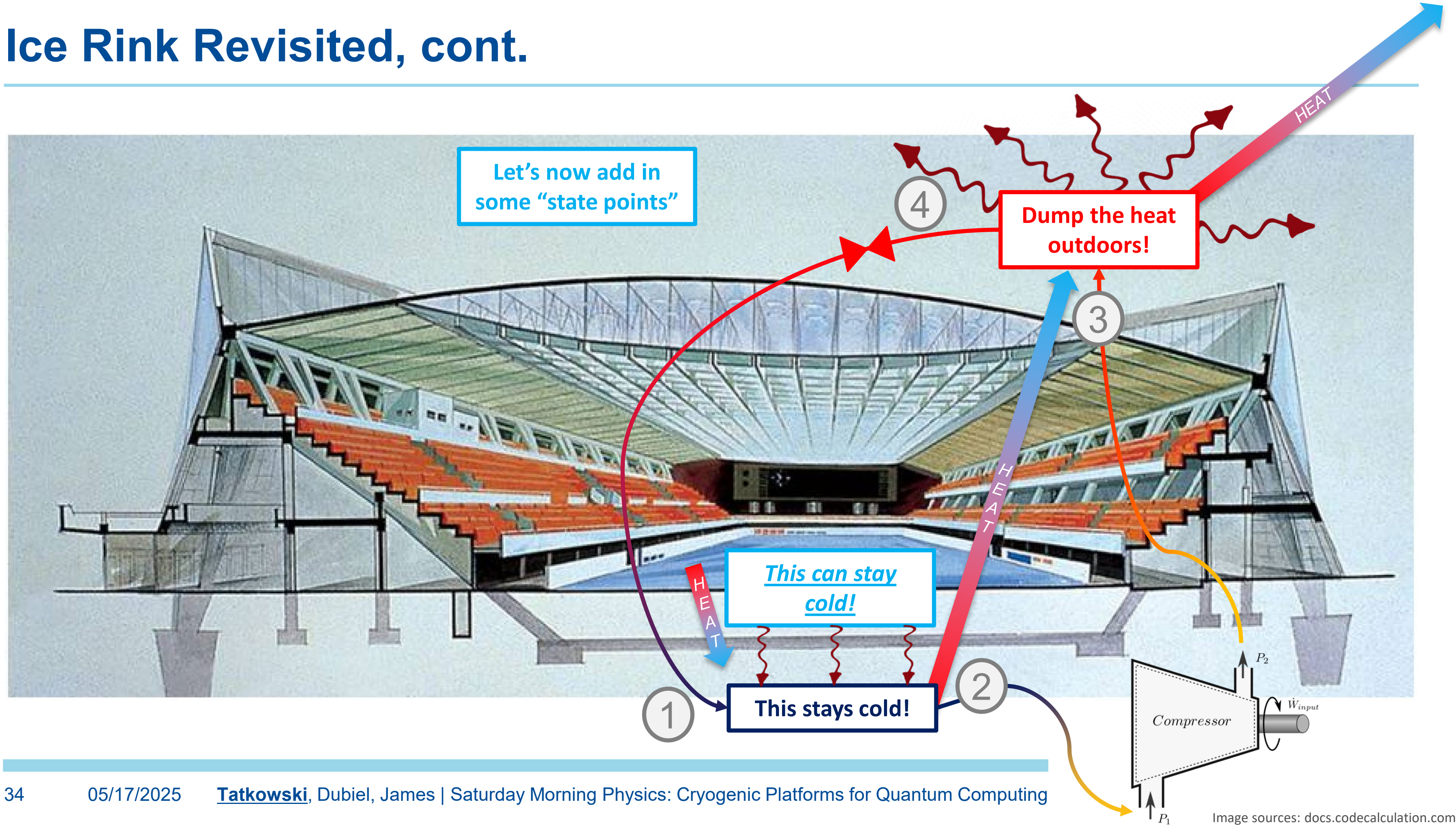

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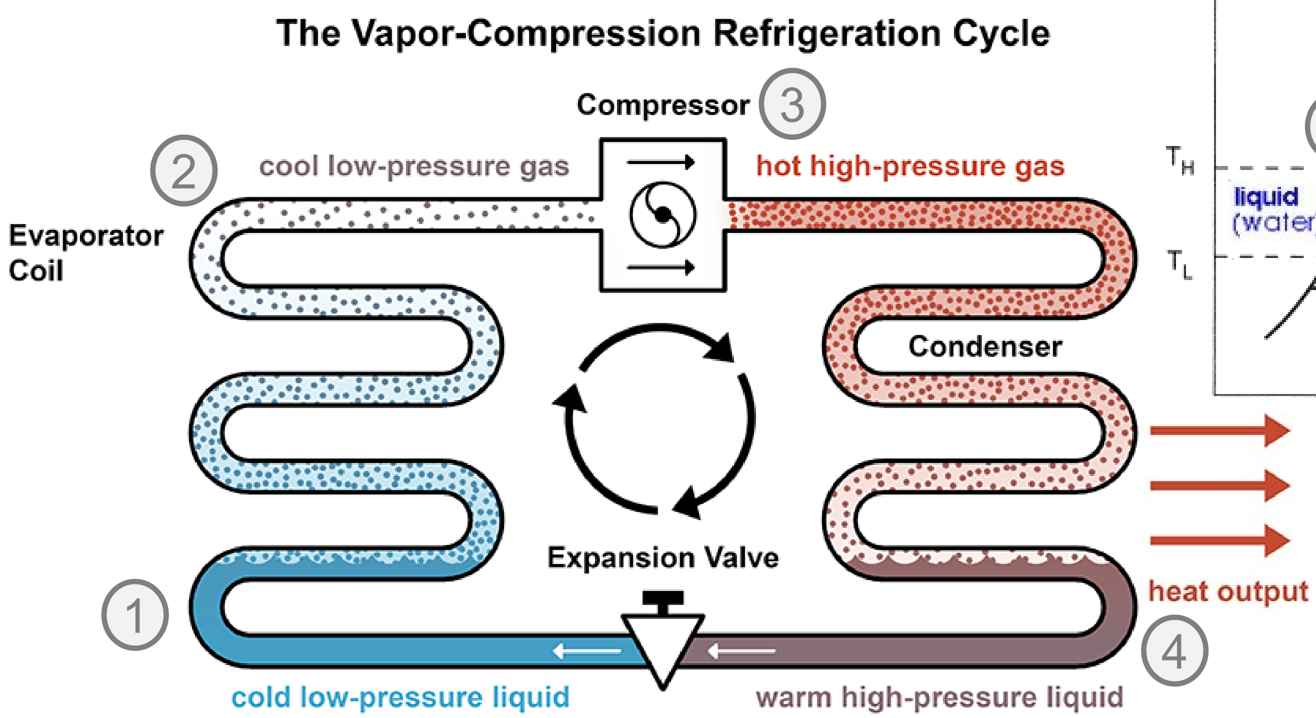

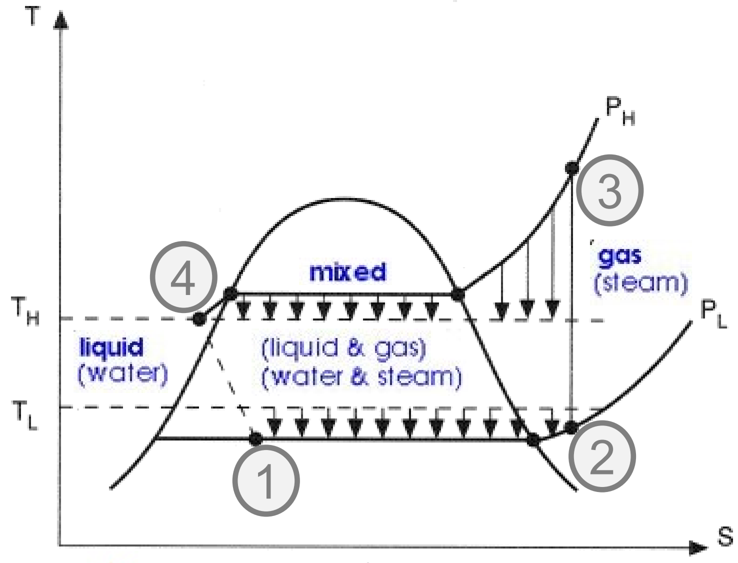

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Image sources: ifixit.com, thermopedia.com

Other Key Concepts in Thermodynamics

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- Reversibility and irreversibility
- Open and closed systems

Reversibility and Irreversibility

- Reversibility: A theoretical process in which the state of a system is changed in a series of infinitesimally small steps while the system maintains equilibrium with its surroundings during every step.
  - At every step, the changes can be “undone” to restore the system to its prior state.
- In other words, a reversible process is one where a system’s final state can be reversed to its initial state without leaving any trace on the surroundings.
- In the context of refrigeration/cryogenics, a reversible process
  - consumes the least amount of mechanical power (work) for compression
  - produces maximum mechanical power (work) during expansion

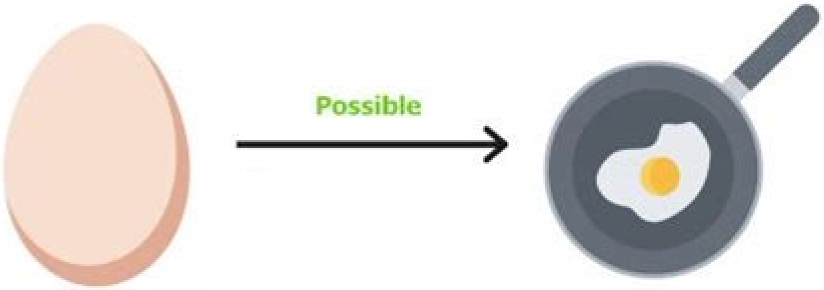

Image and slide sources: John Weisend II, Ram Dhuley, USPAS Cryogenic Engineering Course, 2025, lawofthermodynamicsinfo.com

Reversibility and Irreversibility

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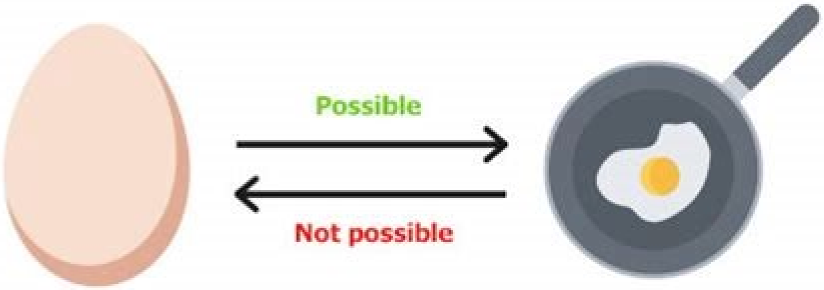

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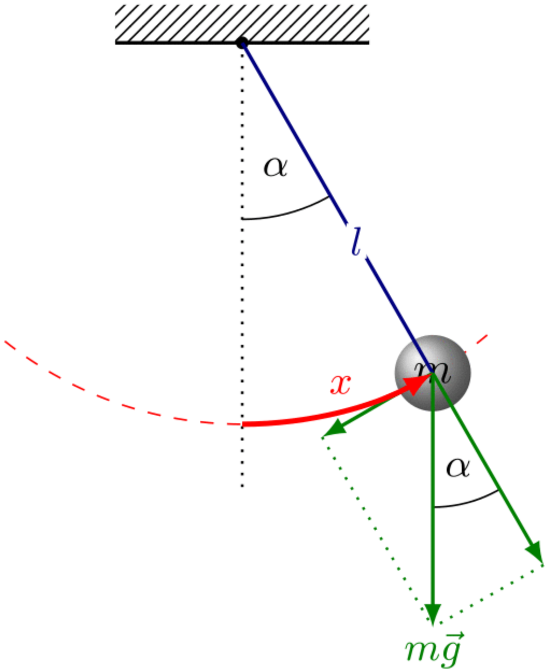


Image and slide sources: John Weisend II, Ram Dhuley, USPAS Cryogenic Engineering Course, 2025, lawofthermodynamicsinfo.com, skill-lync.com/student-projects/week-3-solving-second-order-odes-595

Open System vs. Closed System

- Let's pretend we have an empty bathtub.

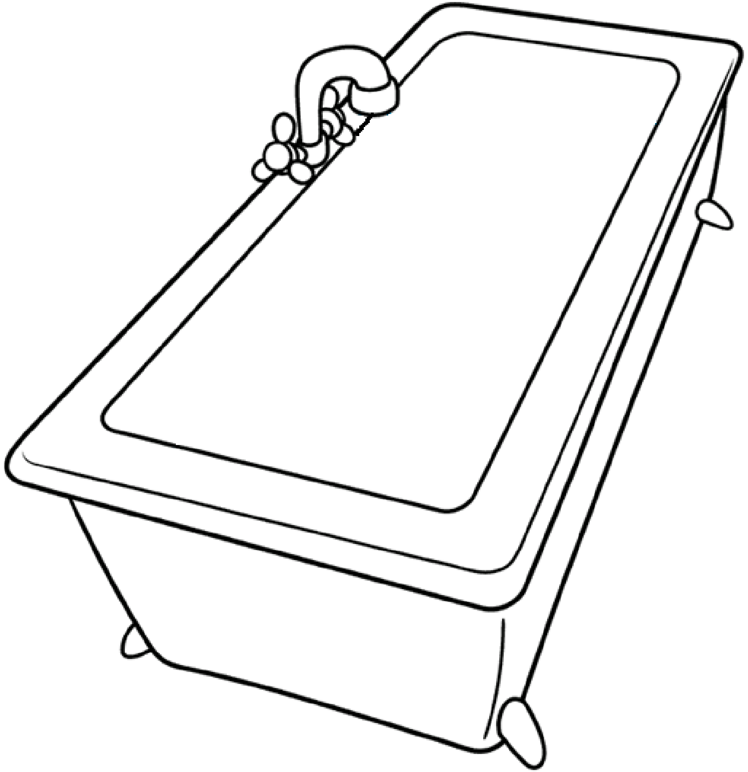
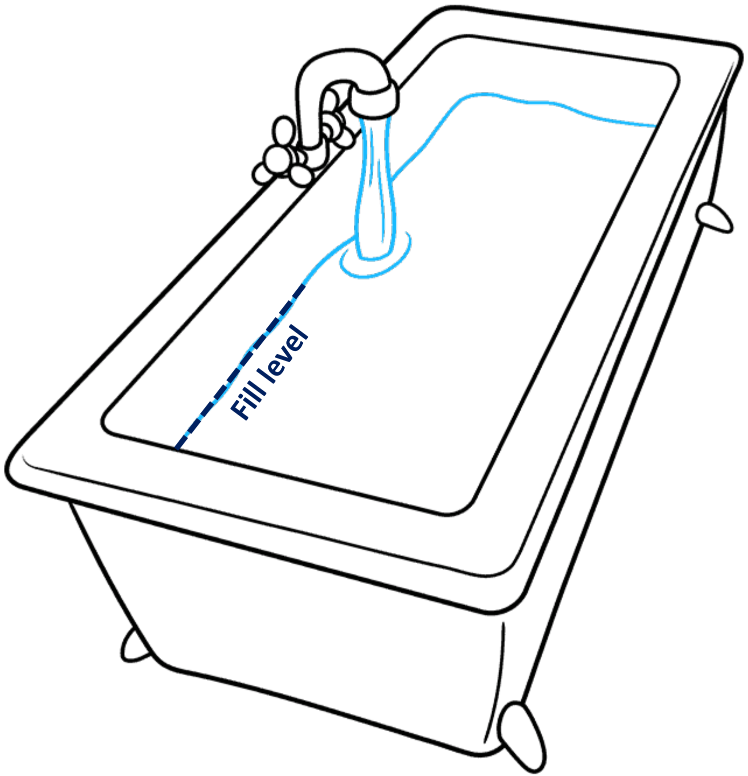


Image sources: easydrawingguides.com/how-to-draw-a-bathtub/

Open System vs. Closed System (cont.)

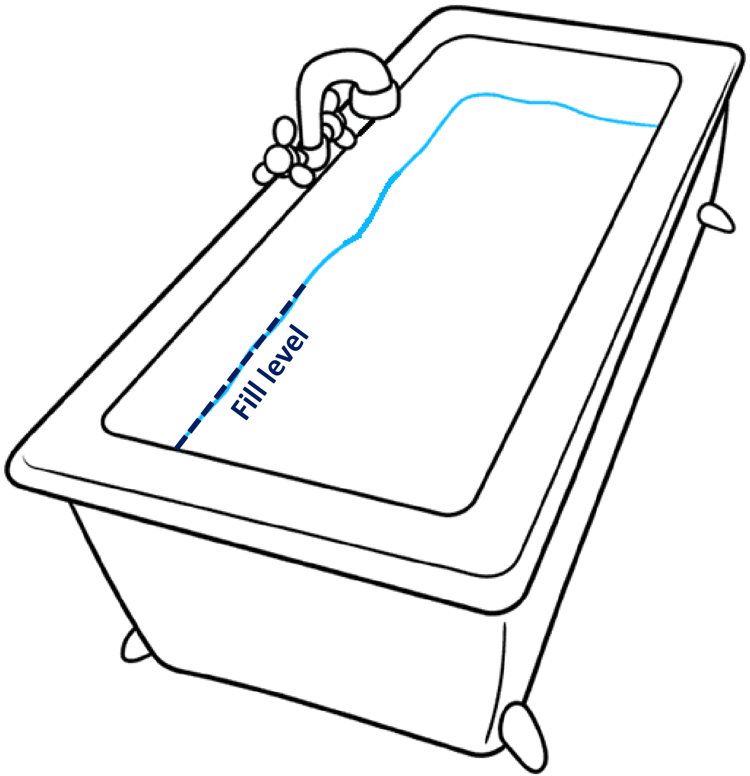
- We're now going to fill it up to some predetermined level.



Closed System

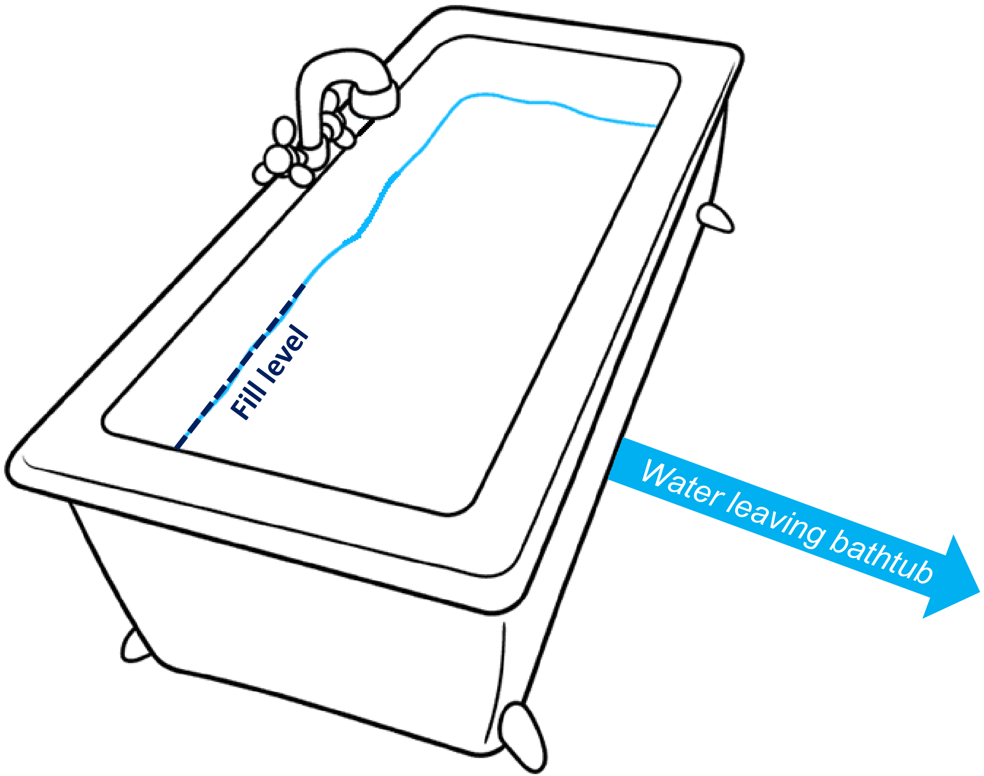
- We now shut off the water.

Closed system: Water level stays the same because no water enters or exits bathtub!



Open System

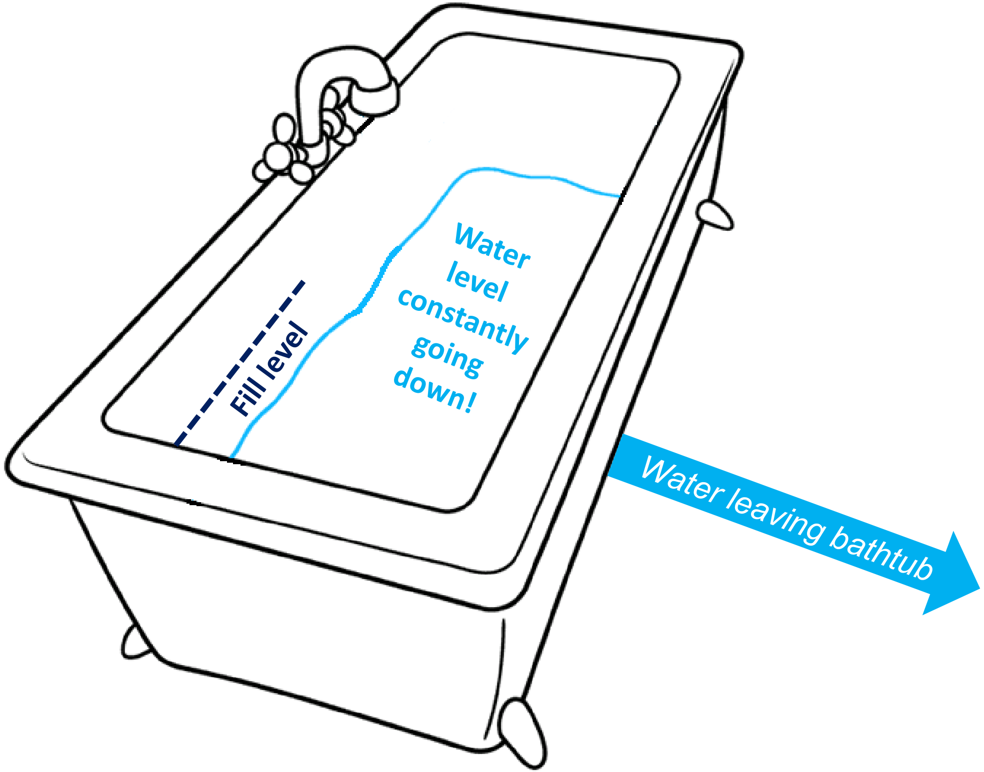
- Let’s open the drain valve.



Open System (cont.)

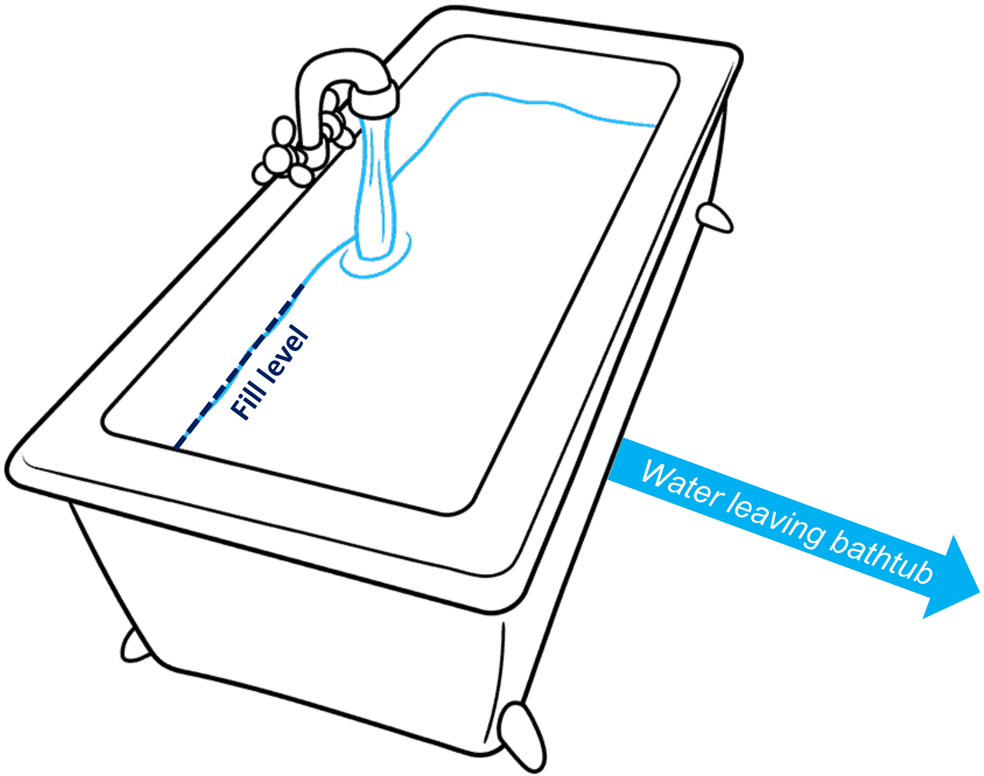
- Drain valve open.

Open system: Water always leaving bathtub!



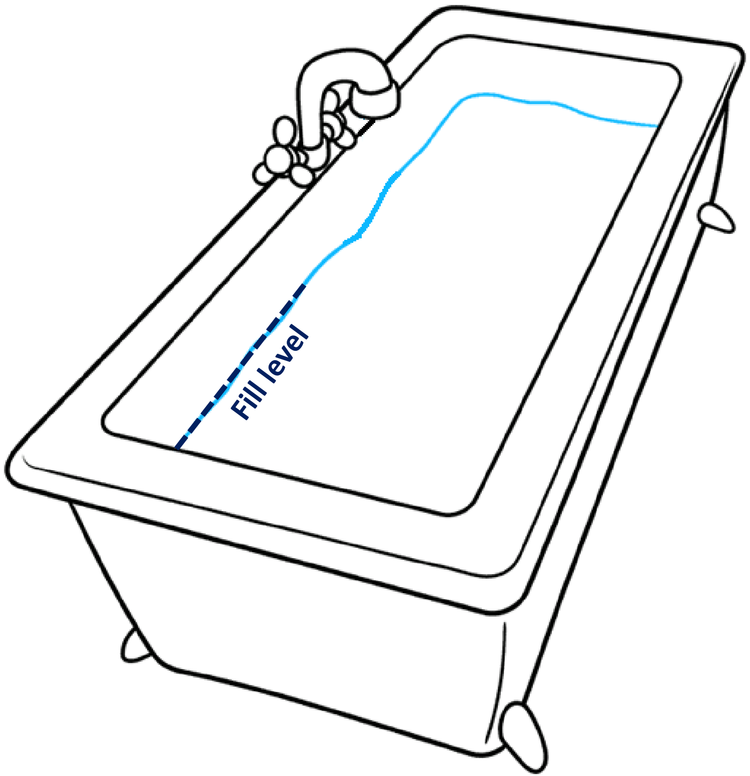
Open System vs. Closed System (cont.)

- Let's fill the bathtub back to the previous level!



Open System vs. Closed System (cont.)

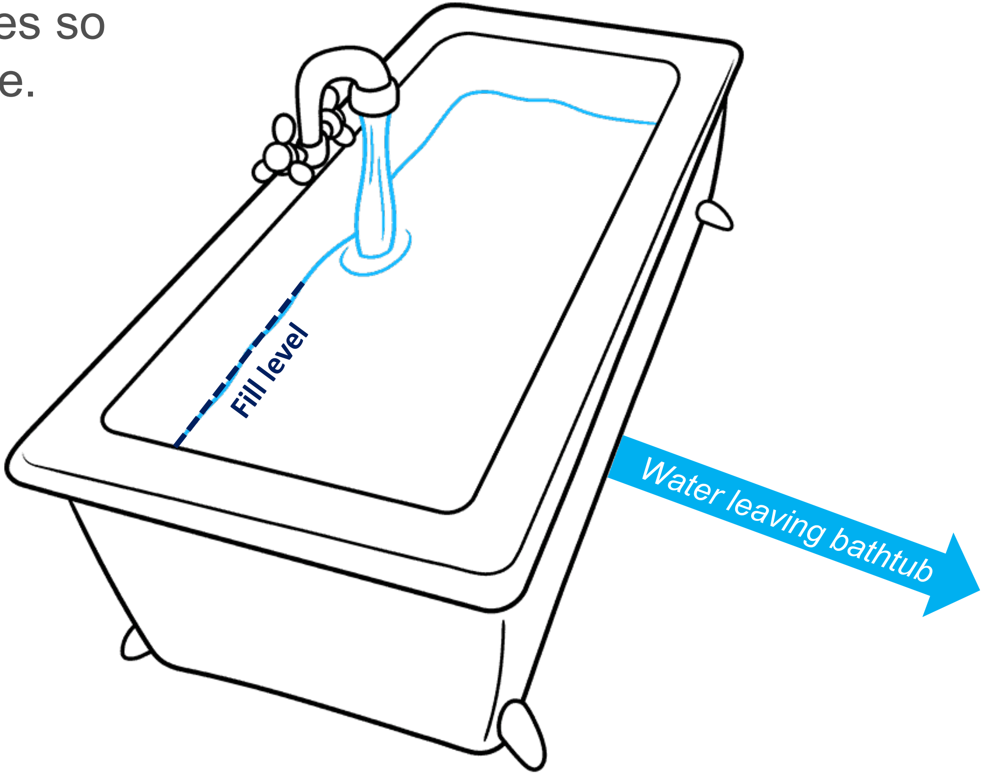
- Once at the fill level, let's shut off the water supply.



Open System vs. Closed System (cont.)

- Now, let's open both fill and drain valves so that the flow rates are exactly the same.
- What kind of system is this?

Open system: Water always entering and leaving bathtub!



Open System vs. Closed System (cont.)

- Another example: Let's say we installed a fountain in the bathtub.
  - All of the water stays within the bathtub; no splashing
- What kind of system is this?

Closed system: Water does not ever leave the bathtub!

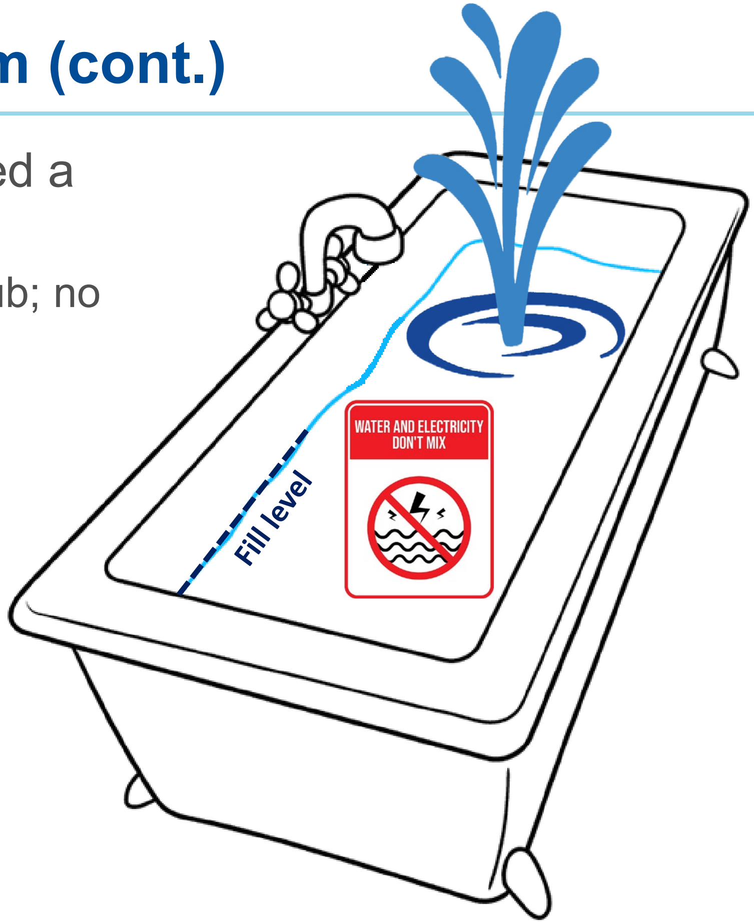
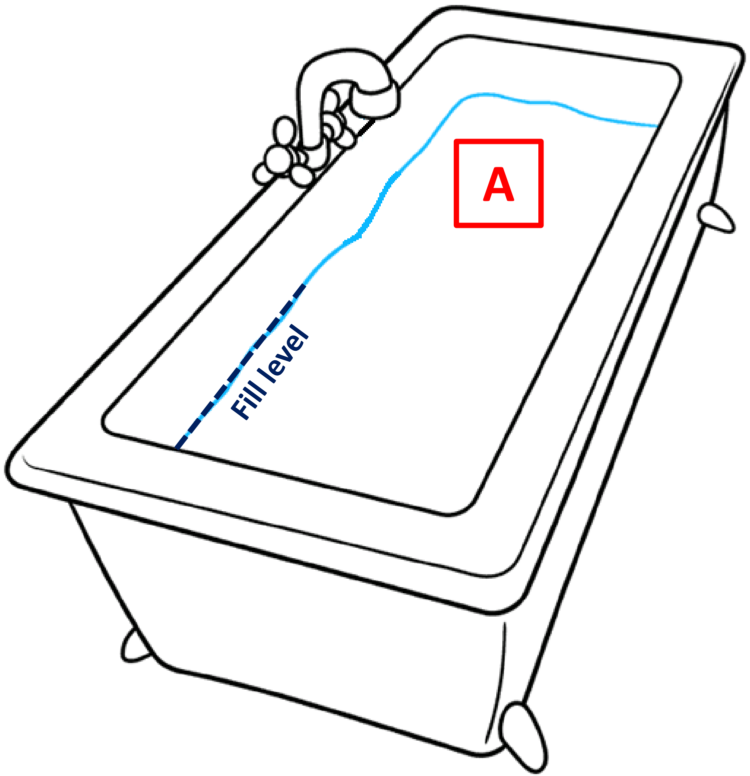
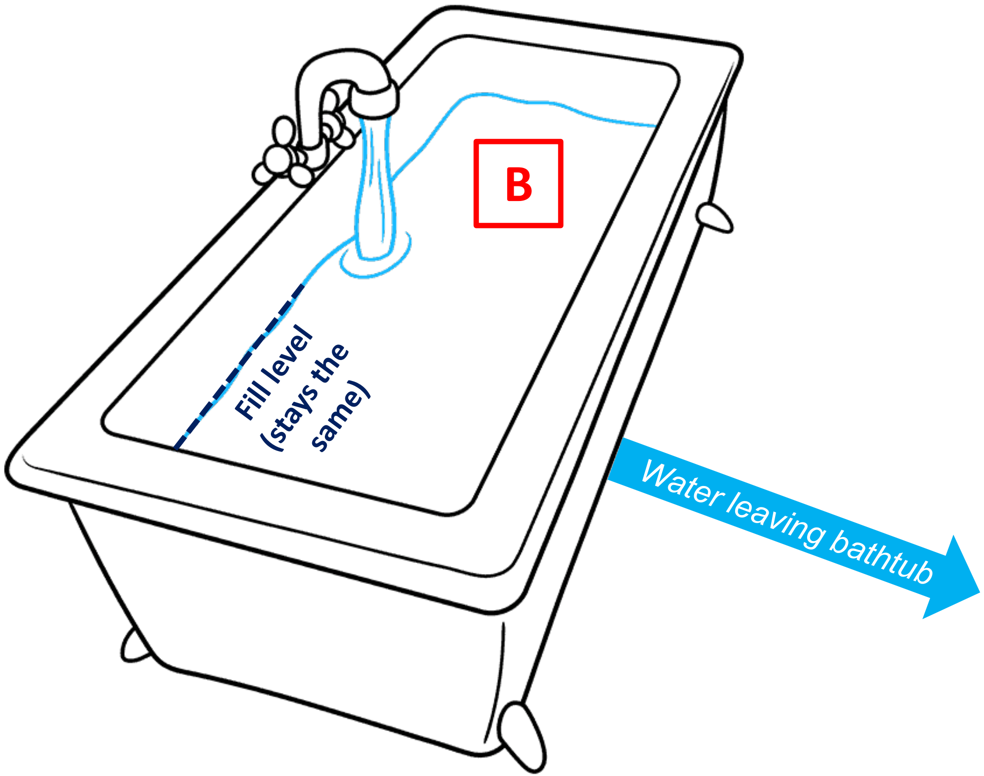


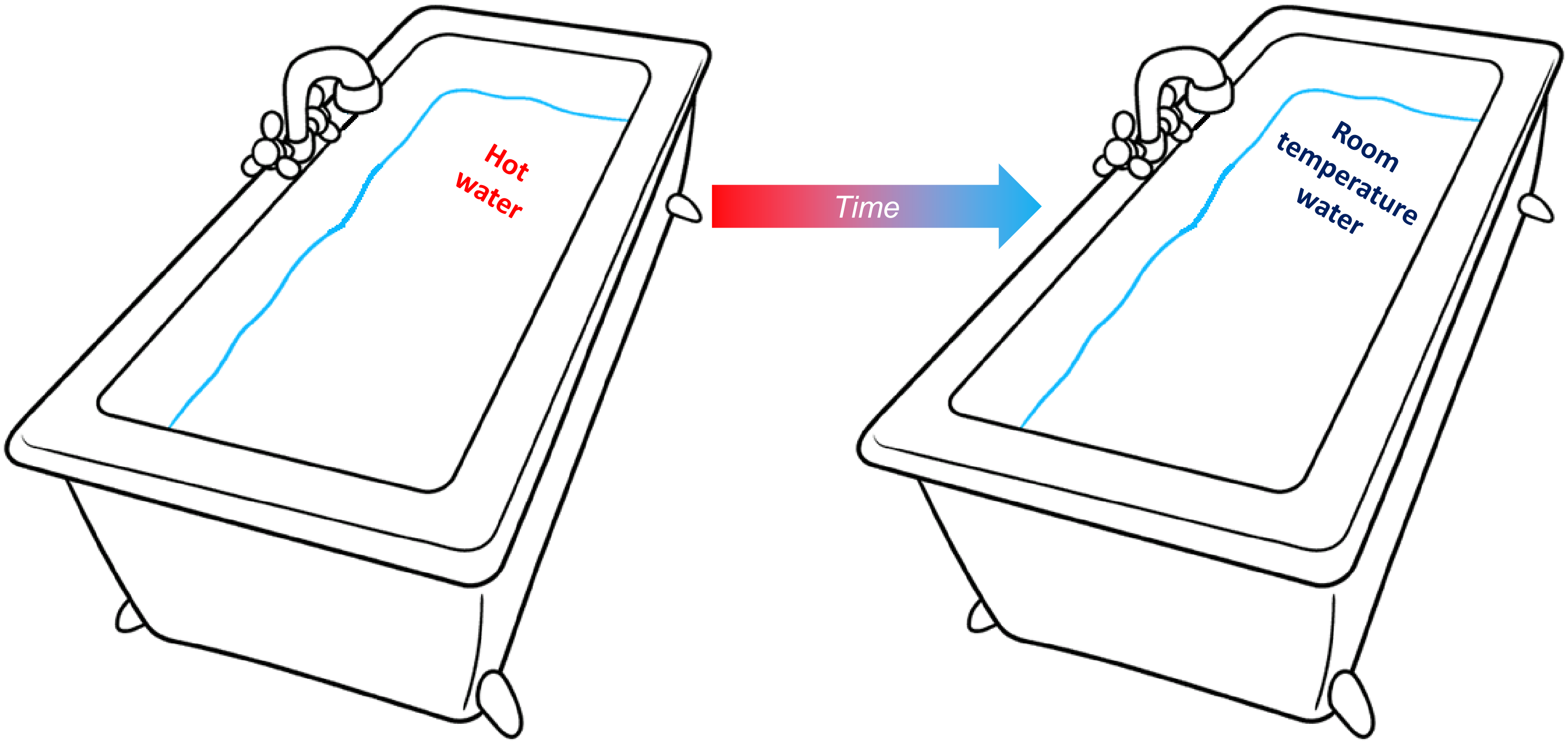
Image sources: fountains2go.com, walmart.com

Which System is Better at Conserving Water?

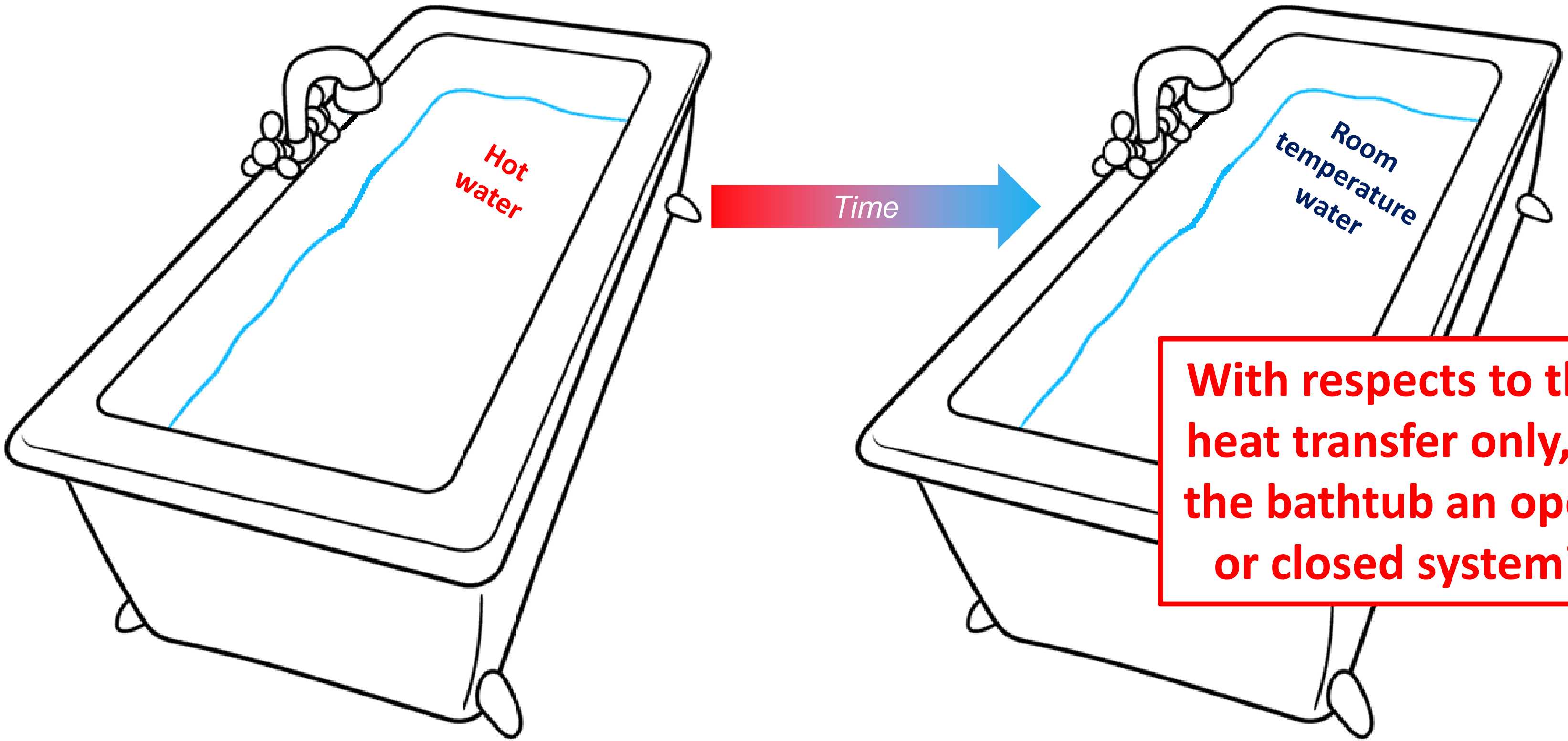




Heat is Being Transferred Too!

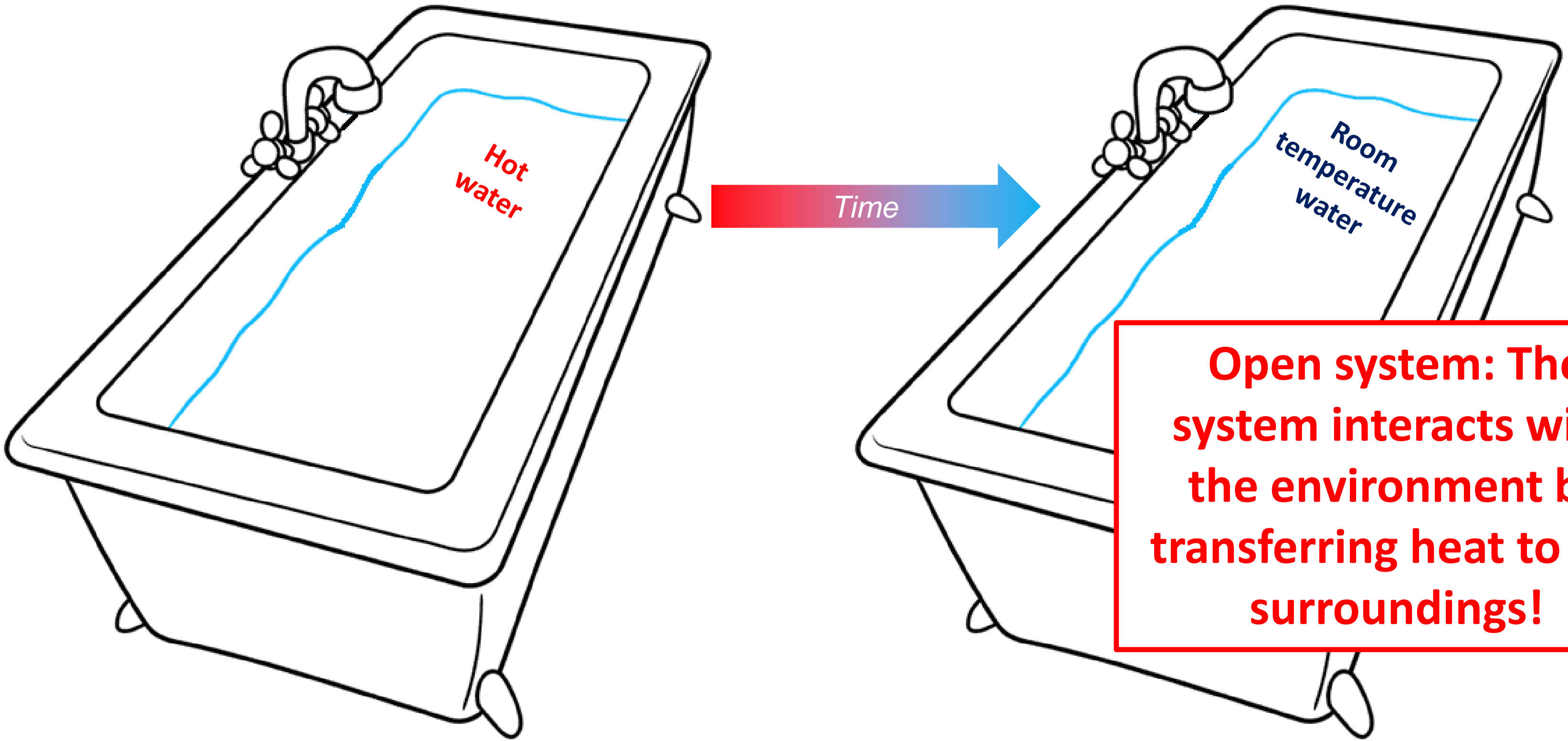


Heat is Being Transferred Too (cont.)!



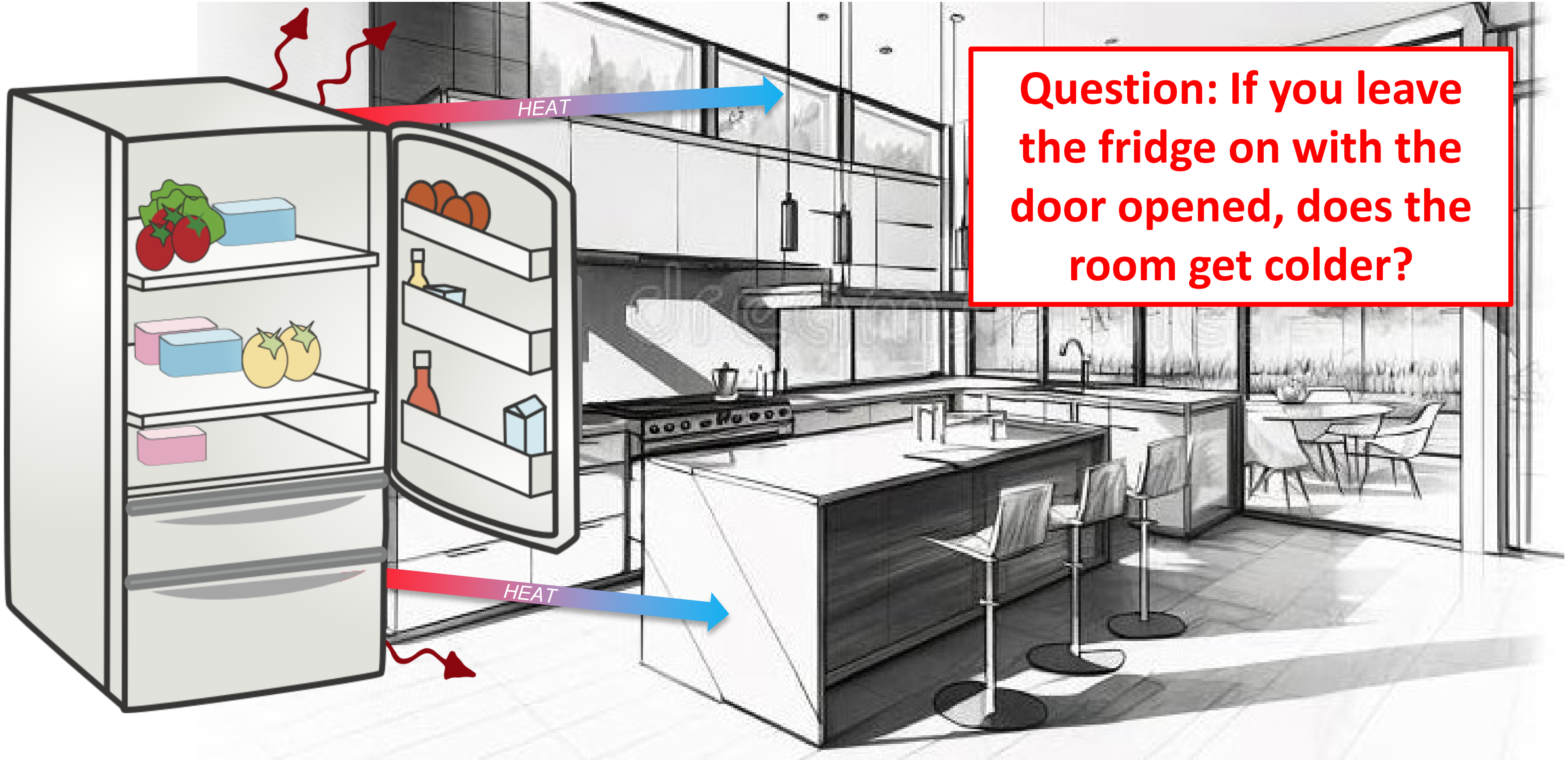
With respects to the heat transfer only, is the bathtub an open or closed system?

Heat is Being Transferred Too (cont.)!



Open system: The system interacts with the environment by transferring heat to the surroundings!

Trick Question



Question: If you leave the fridge on with the door opened, does the room get colder?

Image sources: dreamstime.com, freesvg.org

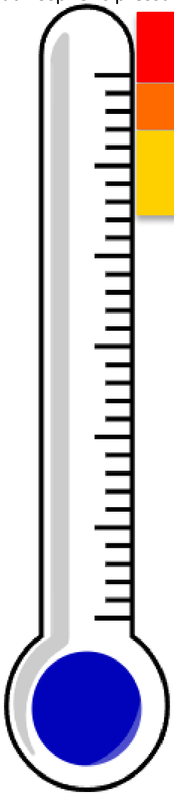
What Is Cryogenics?

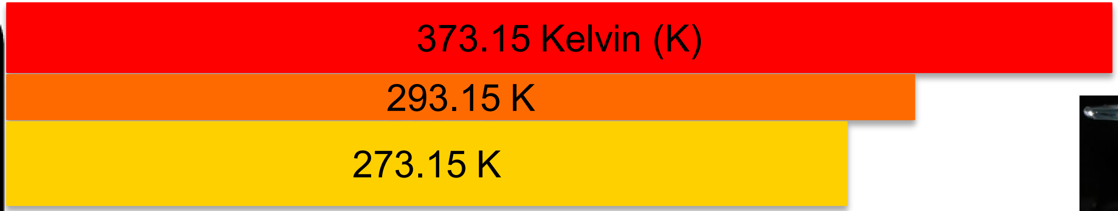
At atmospheric pressure

Boiling water

Room temperature

Water becomes solid (freezing)





Boiling water: 212 °F

Room temperature: 68 °F

Water becomes solid (freezing): 32°F

Image sources:.wired.com/story/yes-you-can-boil-water-at-room-temperature-heres-how/, easyartstart.com/how-to-draw-a-house-step-by-step/, bigriverambulance.com/post/beware-of-ice

What Is Cryogenics?

At atmospheric pressure

Boiling water	373.15 Kelvin (K)
Room temperature	293.15 K
Water becomes solid (freezing)	273.15 K
Oxygen becomes liquid	90 K
Nitrogen becomes liquid	77 K
Oxygen becomes Solid	54 K

Cryogenics = 120 K or -153 C

Oxygen becomes liquid: -297.33 °F

Nitrogen becomes liquid: -320 °F

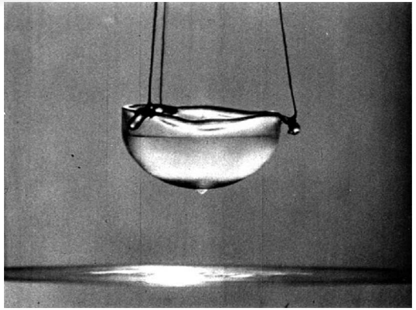
Oxygen becomes solid: -361.82 °F

Image sources:. en.wikipedia.org/wiki/Liquid_oxygen, food-contact-surfaces.com/2018/09/perils-of-liquid-nitrogen-in-food/, assignmentpoint.com/solid-oxygen/

What Is Cryogenics?

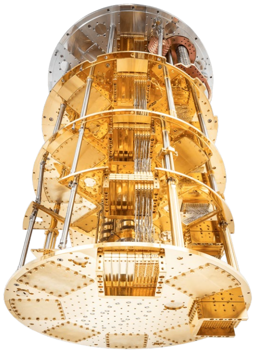
At atmospheric pressure

Boiling water	373.15 Kelvin (K)
Room temperature	293.15 K
Water becomes solid (freezing)	273.15 K
Oxygen becomes liquid	90 K
Nitrogen becomes liquid	77 K
Oxygen becomes Solid	54 K
Helium becomes liquid	4.2 K
The background temp. of space	2.7 K
Dilution refrigeration	0.007 K



Helium becomes liquid: -452.20°F

The background Temperature of outer space: -454.80°F



Dilution refrigeration: < -459.658 °F

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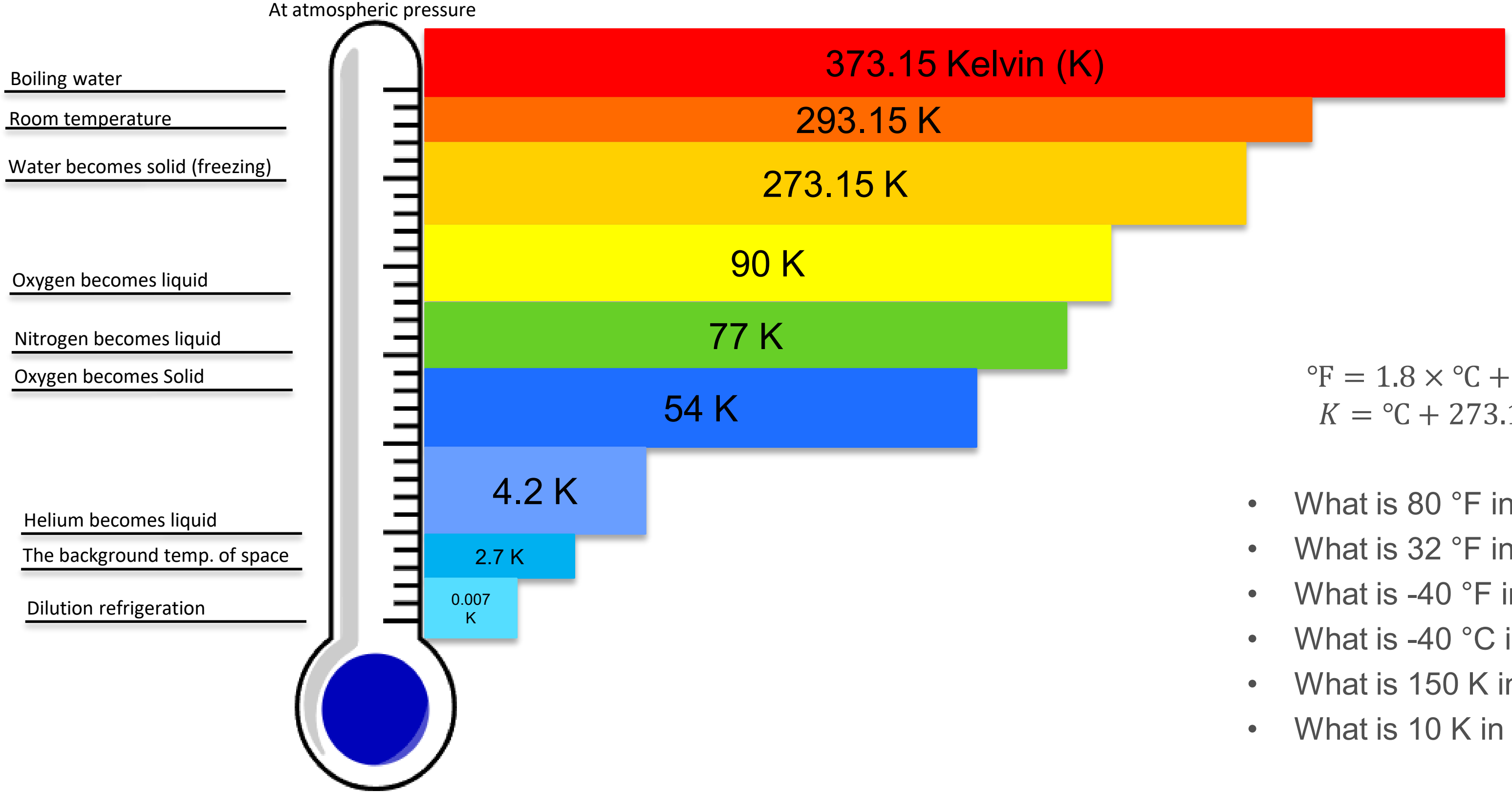
Image sources:. studiousguy.com/helium-uses, space.com/how-cold-is-space, bluefors.com/products/dilution-refrigerator-measurement-systems

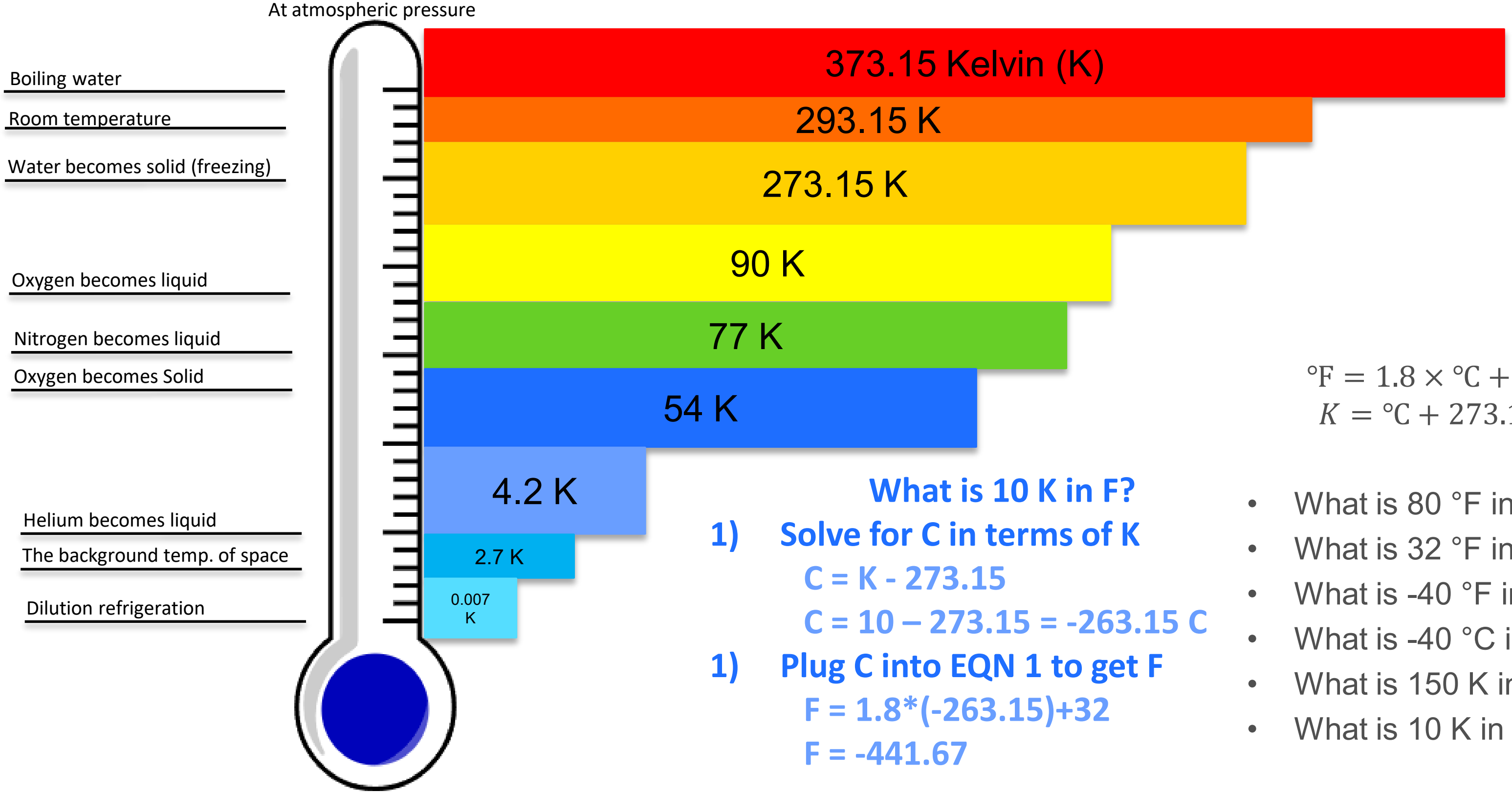
What Is Cryogenics?



$$°F = 1.8 \times °C + 32$$
$$K = °C + 273.15$$

- What is 80 °F in °C?
- What is 32 °F in °C?
- What is -40 °F in °C?
- What is -40 °C in K?
- What is 150 K in °F?
- What is 10 K in °F?

What Is Cryogenics?



$$°F = 1.8 \times °C + 32$$
$$K = °C + 273.15$$

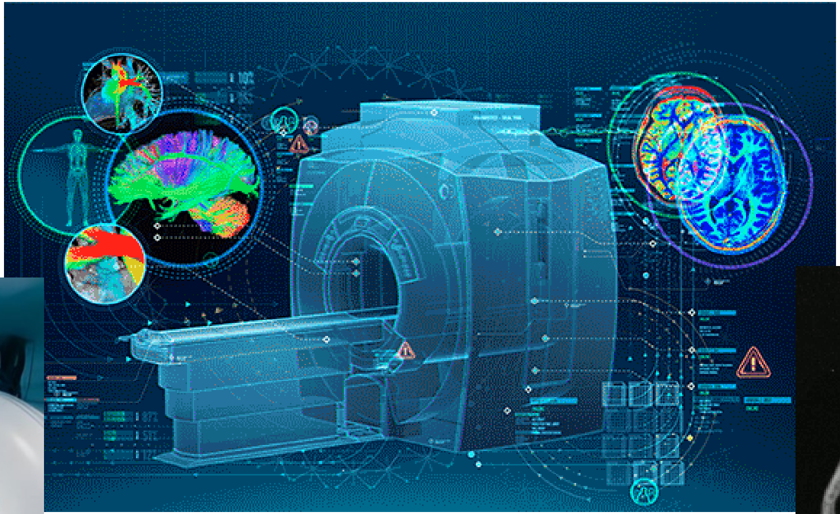
What is 10 K in F?

1) **Solve for C in terms of K**
   C = K - 273.15
   C = 10 – 273.15 = -263.15 C
1) **Plug C into EQN 1 to get F**
   F = 1.8*(-263.15)+32
   F = -441.67

- What is 80 °F in °C? **Ans: 26.67 C**
- What is 32 °F in °C? **Ans: 0 C**
- What is -40 °F in °C? **Ans: -40 C**
- What is -40 °C in K? **Ans: 233.15 K**
- What is 150 K in °F? **Ans: -189.67 F**
- What is 10 K in °F? **Ans:-441.67 F**

Fermilab

Why is Cryogenics Important?



MRI machines

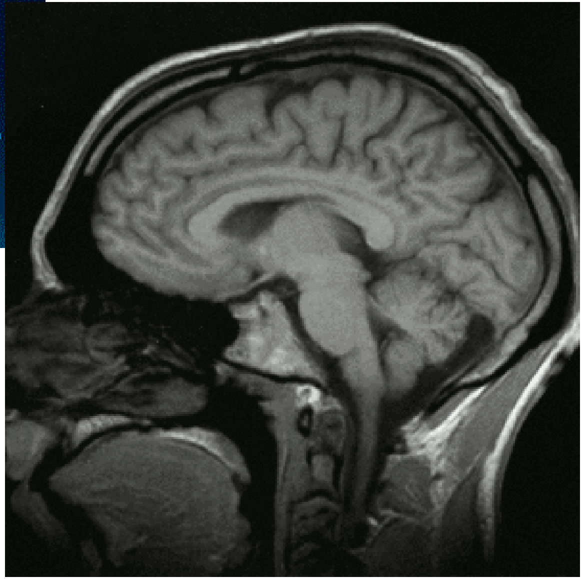
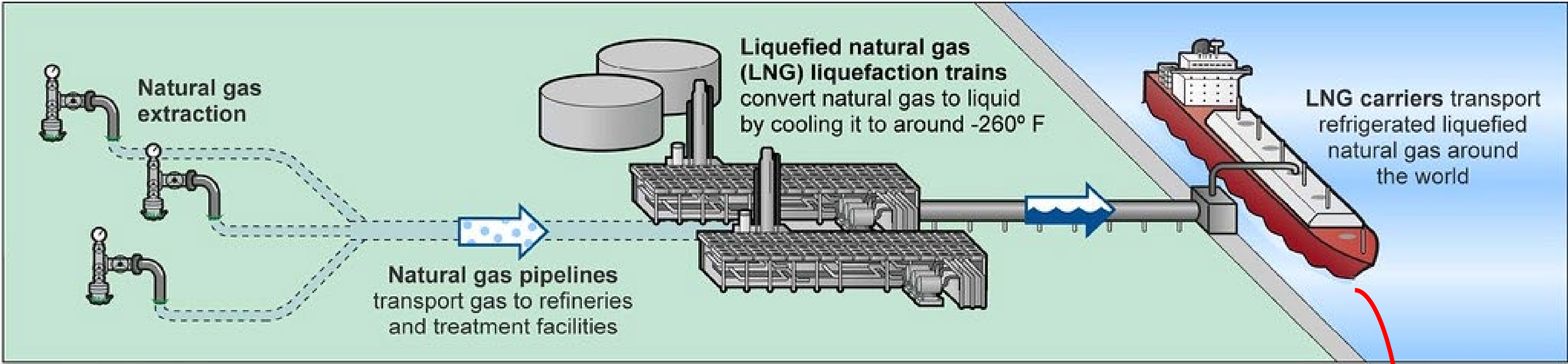


Image sources: newsroom.gehealthcare.com, kiddle.co, csm-cryogenic.com

Why is Cryogenics Important (cont.)?

Image sources: wired.com, fpscorp.ca, pricechopper.com

Why is Cryogenics Important (cont.)?

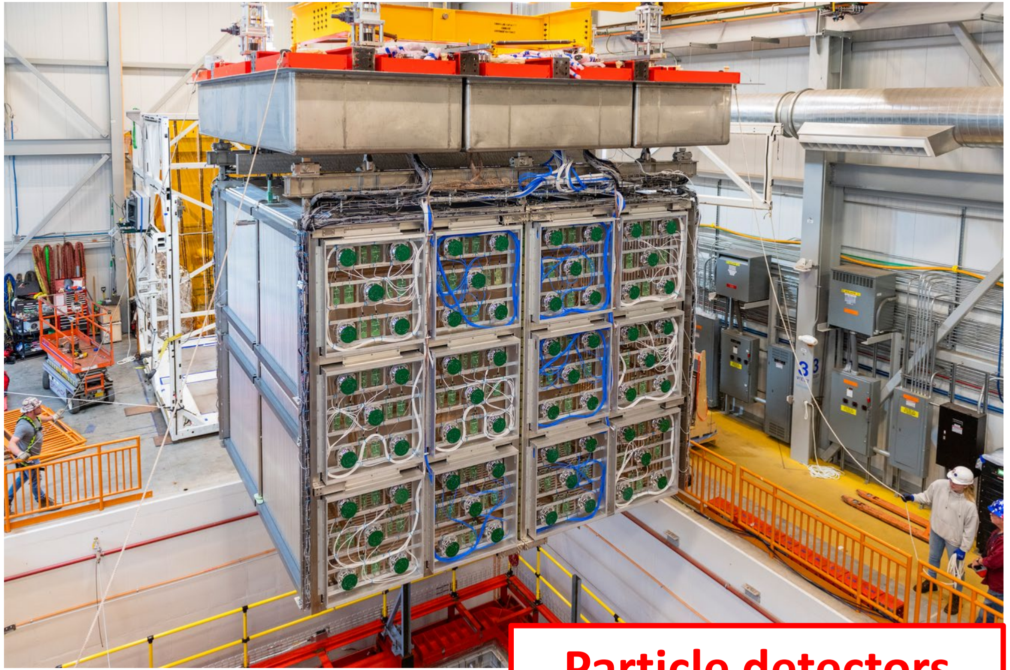


Source: GAO. | GAO-16-104

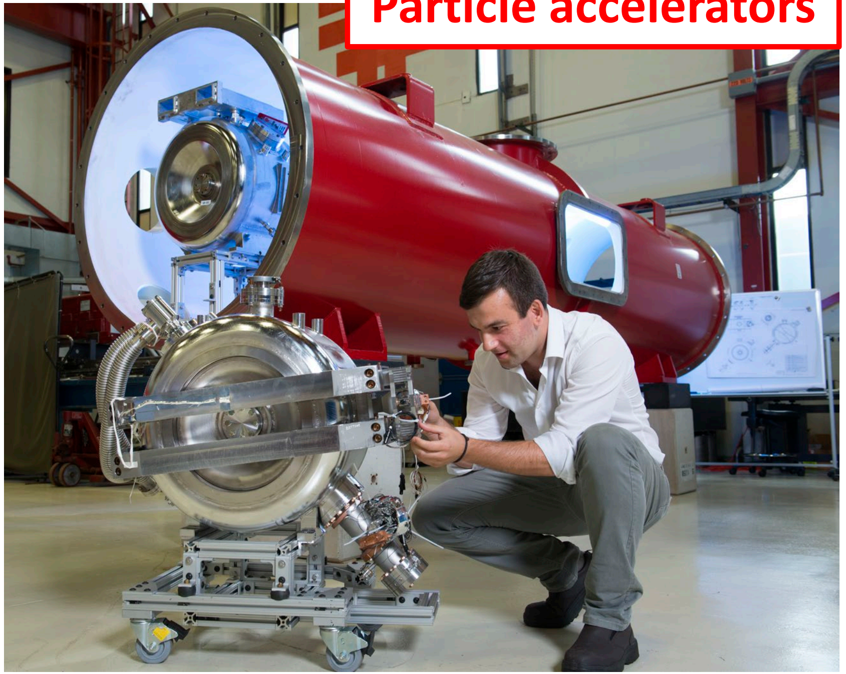
Liquified Natural Gas: Can be shipped all over the world!

Image sources: getgasla.com

Why is Cryogenics Important (cont.)?



Particle detectors



Particle accelerators

Image sources: fnal.gov

Why is Cryogenics Important (cont.)?

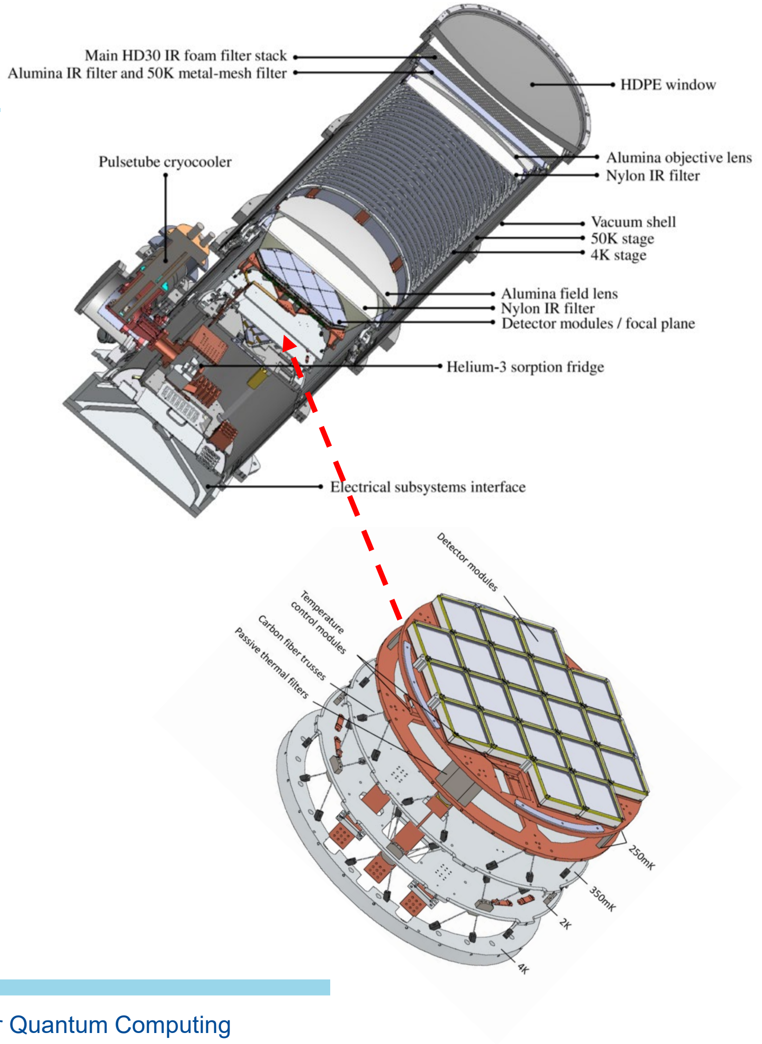


Image sources: photolibrary.usap.gov, bicepkeck.org

5-minute break

Cold History of Chicago, cont.

- In the 1800's, if something needed to be cold:
  1. Workers would spend winters cutting out ice from frozen rivers and lakes in Illinois and Wisconsin, for example.
  2. Ice would be transported in big blocks to "storehouses" to be sold throughout the year.
     - Shown to the right is such a storehouse in Blue Island, Illinois.

Image sources: https://www.shorpy.com/node/27180

Cold History of Chicago, cont.

- In the 1800's, if something needed to be cold:
  1. Workers would spend winters cutting out ice from frozen rivers and lakes in Illinois and Wisconsin, for example.
  2. Ice would be transported in big blocks to "storehouses" to be sold throughout the year.
     - Here's a storehouse in Yorkville, Illinois right on the Fox River.

Image sources: historyonthefox.wordpress.com

Cold History of Chicago, cont.

- In the 1800's, if something needed to be cold:
    1. Workers would spend winters cutting out ice from frozen rivers and lakes in Illinois and Wisconsin, for example.
    2. Ice would be transported in big blocks to "storehouses" to be sold throughout the year.
    3. Ice was critical to the success of Chicago's Union Stockyards, as inventions such as ice-cooled "reefer" railroad cars allowed for already processed meats to be shipped all over the country.

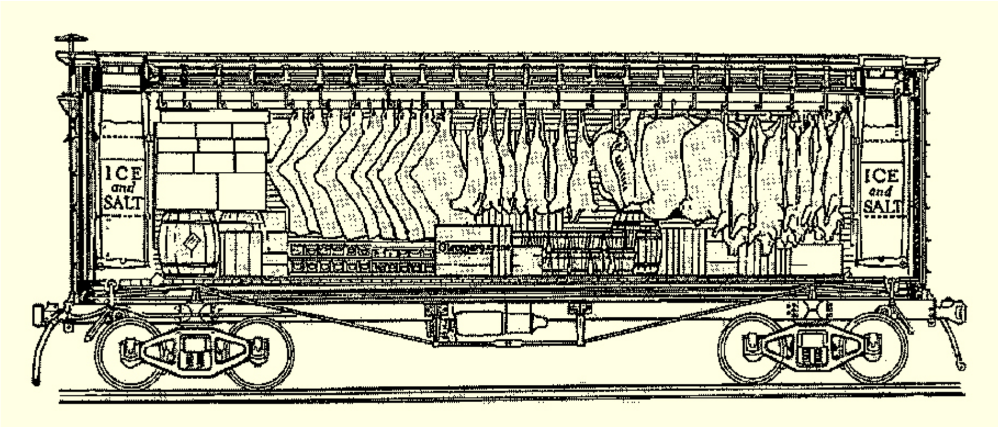
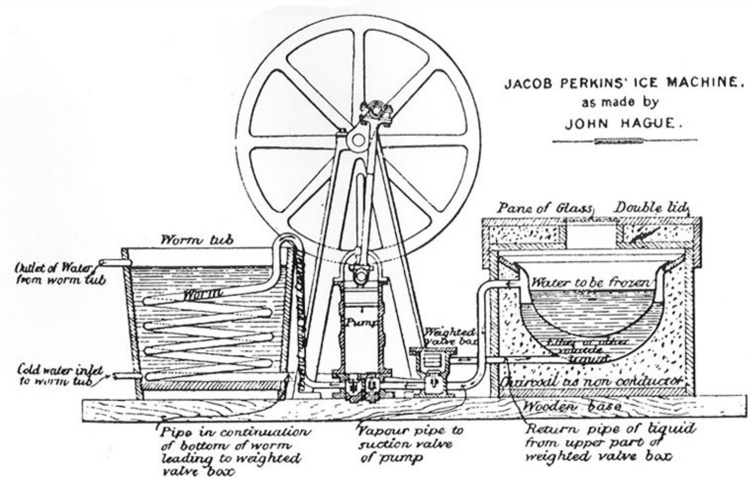


Image sources: historyonthefox.wordpress.com

History of Cryogenics – Early Thermodynamics

- **1755**: Ice is artificially produced in a lab for the first time by William Cullen
  - Cullen evaporated diethyl ether by creating a partial vacuum around the liquid which absorbed heat
- **1807:** Thomas Young first uses the word 'energy' in a scientific context
- **1823**: **Michael Faraday** begins liquefying various non cryogenic gasses using a single shot process
- **1824**: **Sadi Carnot** publishes *Reflections on the Motive Power of Fire*
  - Laid the foundation for modern thermodynamics despite being based on an incorrect theory (caloric theory)

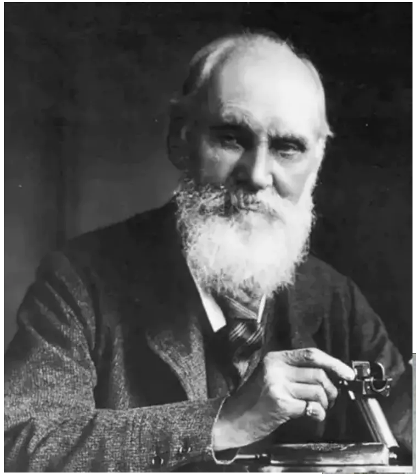


First practical ice making machine from 1834

Image sources: www.scienceandsociety.co.uk

History of Cryogenics – Early Thermodynamics

- **1829**: Coriolis defines ‘work’ in a scientific context and proposes the kinetic energy formula
- **1840s:** Development of the 1st and 2nd Laws of Thermodynamics
- **1848-1852: Lord Kelvin** recognizes there is an absolute zero and an absolute temperature scale is proposed (Kelvin)
- **1870:** First ice rink by William Newton using ammonia gas and carbonic acid
- **1897:** Rudolf Diesel, a student of **Carl von Linde**, demonstrates his diesel engine.
- **1913:** Introduction of first electric appliance style household refrigerators



William Thomson aka Lord Kelvin

1876, Glaciarium in London

Image sources: https://www.gla.ac.uk/explore/lordkelvin200/about/
https://www.smithsonianmag.com/smart-news/first-artificial-skating-rinks-looked-pretty-smelled-terrible-180963486/

History of Cryogenics – Dawn of Cryogenics

- **1873**: **James Dewar** invents the use of a vacuum for thermal insulation
    - Namesake for ‘Dewars’, vacuum insulated vessels for storage of cryogenic liquids
- **1877**: Oxygen is first liquified as a mist (90K or -181.5°F) separately by Pictet and Cailletet
- **1883**: Wroblewski and Olszewski are the first to study properties of liquid O_2 and liquid N_2 (dry ice, 77K or -321°F)
- **1898**: Dewar liquifies Hydrogen (20K or -423°F)
- **1894**: **Kamerlingh Onnes** (University of Leiden) coins the term ‘cryogenic’ in a paper
- **1908**: Onnes liquifies Helium (4.2K or -452°F)
- **1911**: Onnes discovers superconductivity

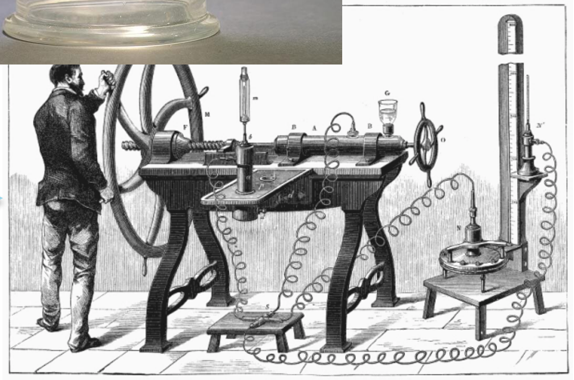


Fig. 1.—CAILLETET'S APPARATUS FOR LIQUEFYING GASES.

Source: Scientific American

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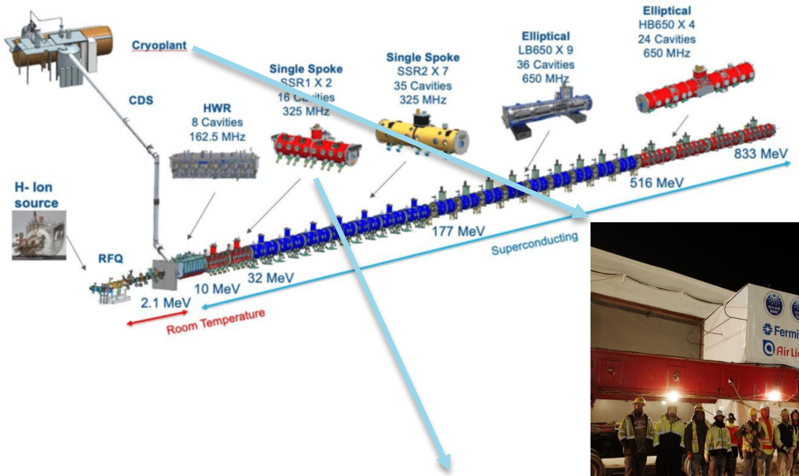
Image sources: https://www.rigb.org/explore-science/explore/blog/six-amazing-objects-ris-faraday-museum

History of Cryogenics – Modern Cryogenics

- Large scale cryogenics achieved via cryogenic plants and flooding devices with cryogenic liquids
- Below 1K we must use more obscure methods:
  - He-3/He-4 mixing (Dilution Refrigerators, **popular in Quantum Computing**) (~7mK)
  - Laser Cooling (<1mK, no practical cooling power)
  - Adiabatic Demagnetization Refrigerators (~30mK)
  - Nuclear Demagnetization Refrigerators (<1μK, pK range)
- Coldest temperature ever achieved is 38pK (0.000000000038 K).

These are temperatures well below that of outer space! (2.7K)



History of Cryogenics – Dilution Refrigerators

- **1951**: Cooling mechanism for Dilution Refrigerators first proposed by Heinz London (Oxford University)
- **1965**: First DR is built at University of Leiden and reaches 220mK (Das, de Bruyn & Taconis)
- **1966**: DRs reach 80mK (Hall, Ford and Thompson) and 25mK (Neganov, Borisov & Liburg)
- Today DRs can routinely reach below 10mK

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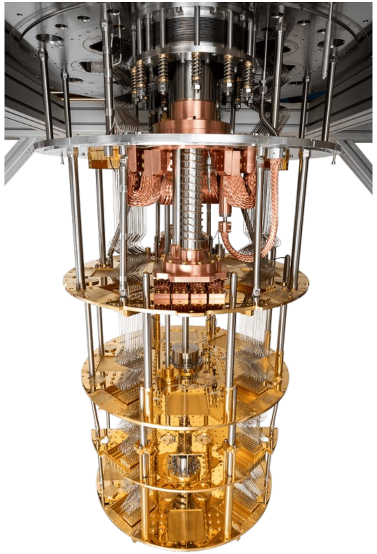
History of Cryogenics – Dilution Refrigerators cont.

- Oxford Instruments (UK) first commercialized DRs in the 1960s
- Other industry players now include Leiden Cryogenics (Netherlands) and Bluefors (Finland)
  - SQMS currently has 8 Bluefors DRs
  - Fermilab also has Leiden, Oxford and CryoConcept DR’s
- Growing industry with new startups:
  - Zero Point Cryogenics (Canada)
  - Maybell Quantum (US, new SQMS partner)
- Variety of DRs now available in different sizes and various cooling powers



Bluefors XLD1000

Zero Point Cryogenics Model I

Maybell Quantum Big Fridge

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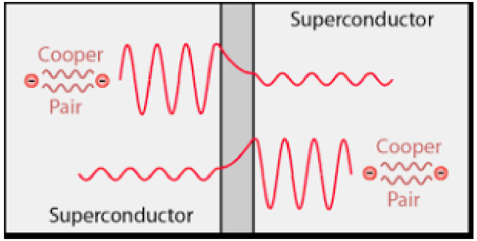
Why Do We Need Cryogenics in Quantum?

- Superconductivity
  - Different materials superconduct at various cryogenic temperatures
  - No electrical resistance
  - Creates phenomena applicable to quantum research (Meissner Effect, Cooper Pairs)
- Reduced thermal noise allows for ‘cleaner’ electrical signals
  - Quantum computing devices generally operate at low powers
  - Devices are very sensitive to external disturbances
- Due in large part to the reliance on cryogenics, large scale quantum computing may rely on data centers

1.3 GHz SRF Cavity



Josephson Junction

Image sources: SQMS

Quantum Data Centers - What is a Conventional Data Center?

- Room(s) or building(s) used to house a large volume of computing components
- Provide external users additional resources (computing power, data storage) beyond their local device
- Typically optimized for:
  - Condensed footprint
  - Energy efficiency
  - Modularity/ease of maintenance
- How do we utilize data centers?
  - Cloud storage (OneDrive, iCloud)
  - AI software (ChatGPT)
  - Server farms (website hosting, online games)
- Due to their complexity, the wider adoption of Quantum Computing will likely rely on data centers

Google Data Center in Iowa

Fermilab

Image sources: Google

Quantum Data Centers – New Challenges for Cryogenics

- How do we integrate large cryogenic systems into familiar data center layouts?
- Requires a different approach from research
  - Reliable long term cryogenic temperatures
  - Move from individual isolated systems to interconnected
  - Integration into cryogenic plants, leverage greater cooling power at 4K and above of cryo plants
  - ‘Condensed’ cryogenic footprint

QCL3 (“The Quantum Garage”) is a ***small*** step towards what a quantum data center could look like

Image sources: SQMS

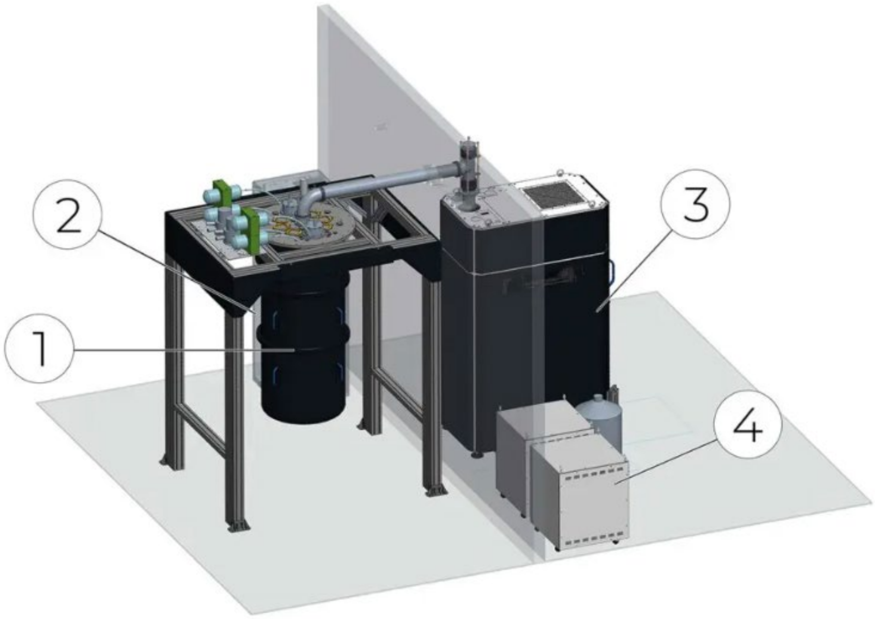
Quantum Data Centers – New Challenges for Cryogenics, cont.

Pros:

- Nearly ‘Plug and Play’ Setup
- Relatively compact footprint for individual units

Cons:

- Isolated systems
- Pulse Tubes require supply of cooling water
- Become space consuming when installing multiple units
- Electrical efficiency concerns when scaling to 10s and 100s of units
- Limited cooling power available



1. Cryostat and its support frame, 2. Thermometry Unit, 3. Gas Handling System, 4. Pulse Tube Cryocooler compressors.

Common Layout for Bluefors and other DRs

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Image sources: Bluefors

Cryogenics Plants

- Remember our old friend, the "refrigeration unit?"
- Can we change its design so that it produces even colder temperatures?

Image sources: carrier.com

Cryogenics Plants, cont.

- First, let's remind ourselves of the thermodynamic cycle of the "refrigeration unit."

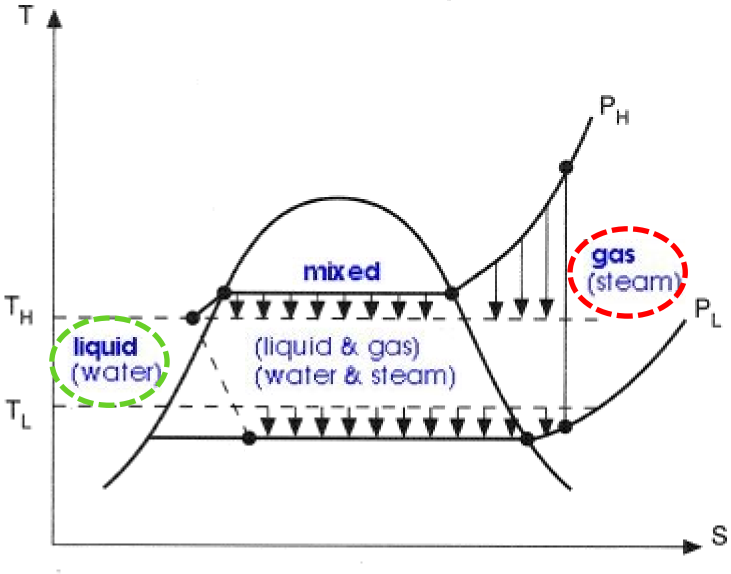
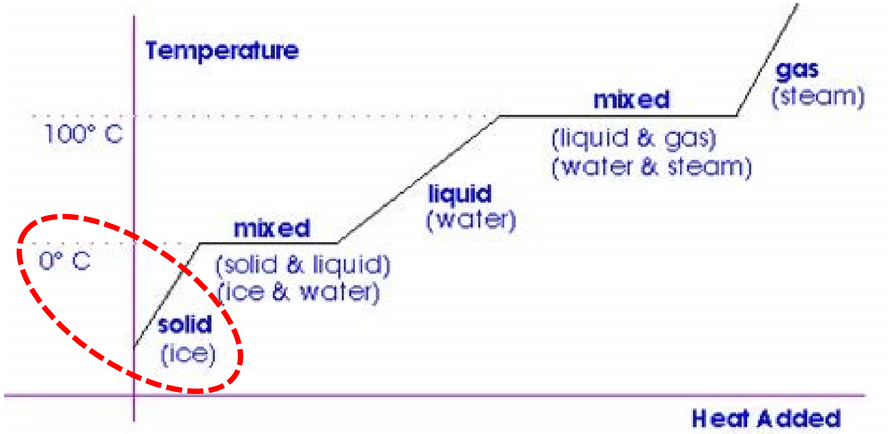


Image sources: thermopedia.com

Cryogenics Plants, cont.

Question: Why can't we use water to get to very low temperatures?



Source: https://www.ux1.eiu.edu/~cfadd/1360/20Heat/Latent.html

Cryogenics Plants, cont.

- How do we get around this problem?

Let's use this → Helium-4 (4.214)

Fluid	Boiling point (K)	Boiling point (°C)
Helium-3	3.19	−269.96
Helium-4	4.214	−268.936
Hydrogen	20.27	−252.88
Neon	27.09	−246.06
Nitrogen	77.09	−196.06
Air	78.8	−194.35
Fluorine	85.24	−187.91
Argon	87.24	−185.91
Oxygen	90.18	−182.97
Methane	111.7	−161.45
Krypton	119.93	−153.415

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Image sources: wikipedia.org

Thermodynamic properties of helium

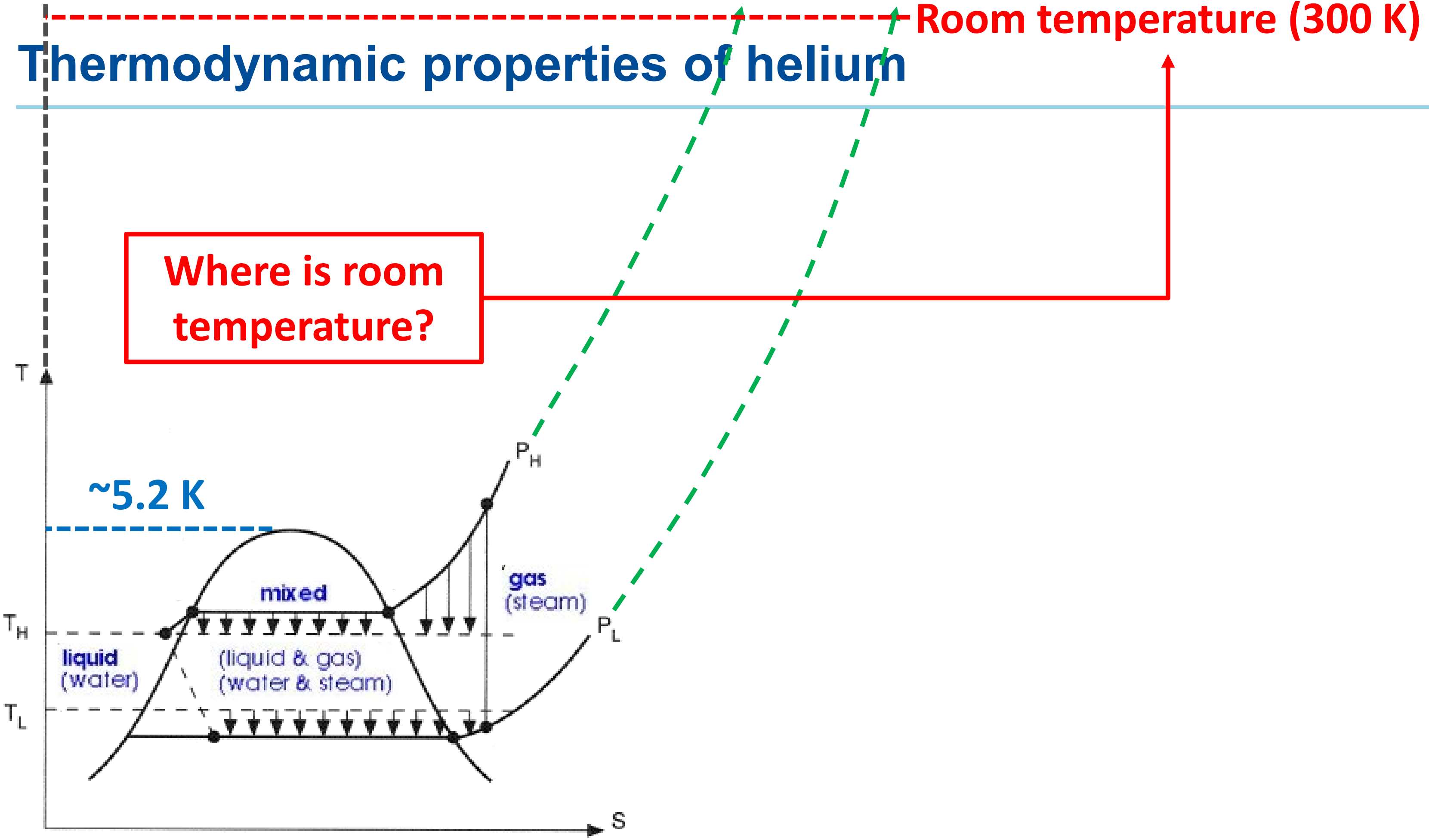
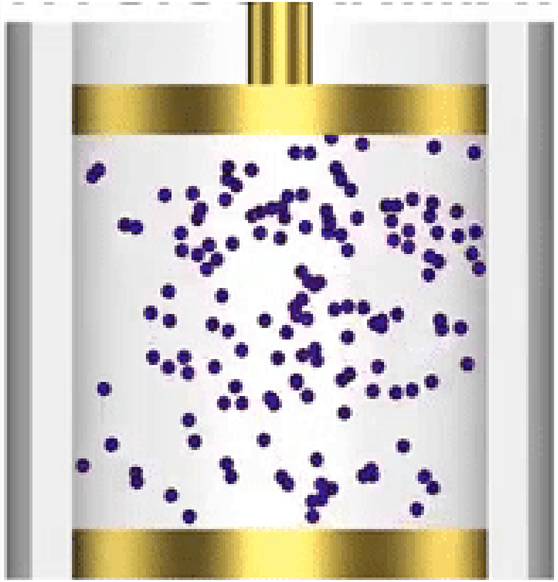


Image sources: thermopedia.com

Thermodynamic properties of helium



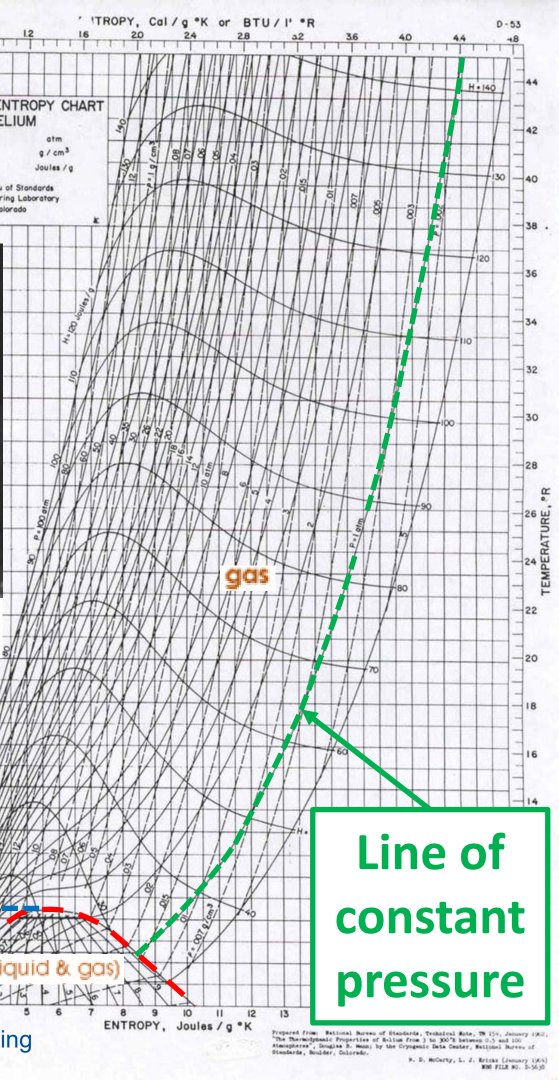
Compression heats the gas

Expansion cools the gas

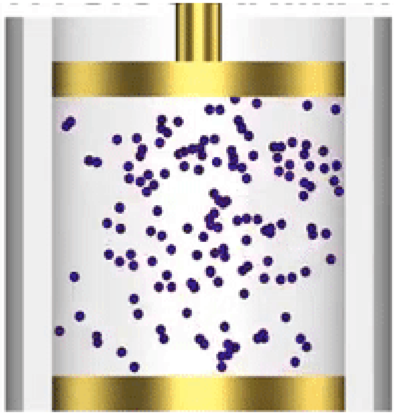
Richard Mollier

25 K !

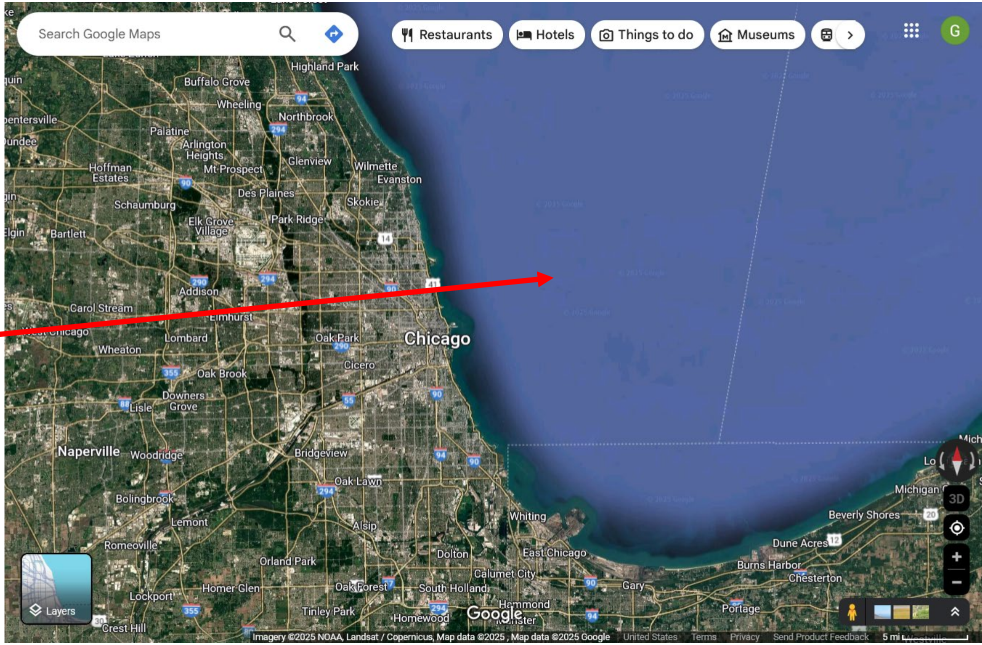
~5.2 K



Cryogenic Cycle Basics



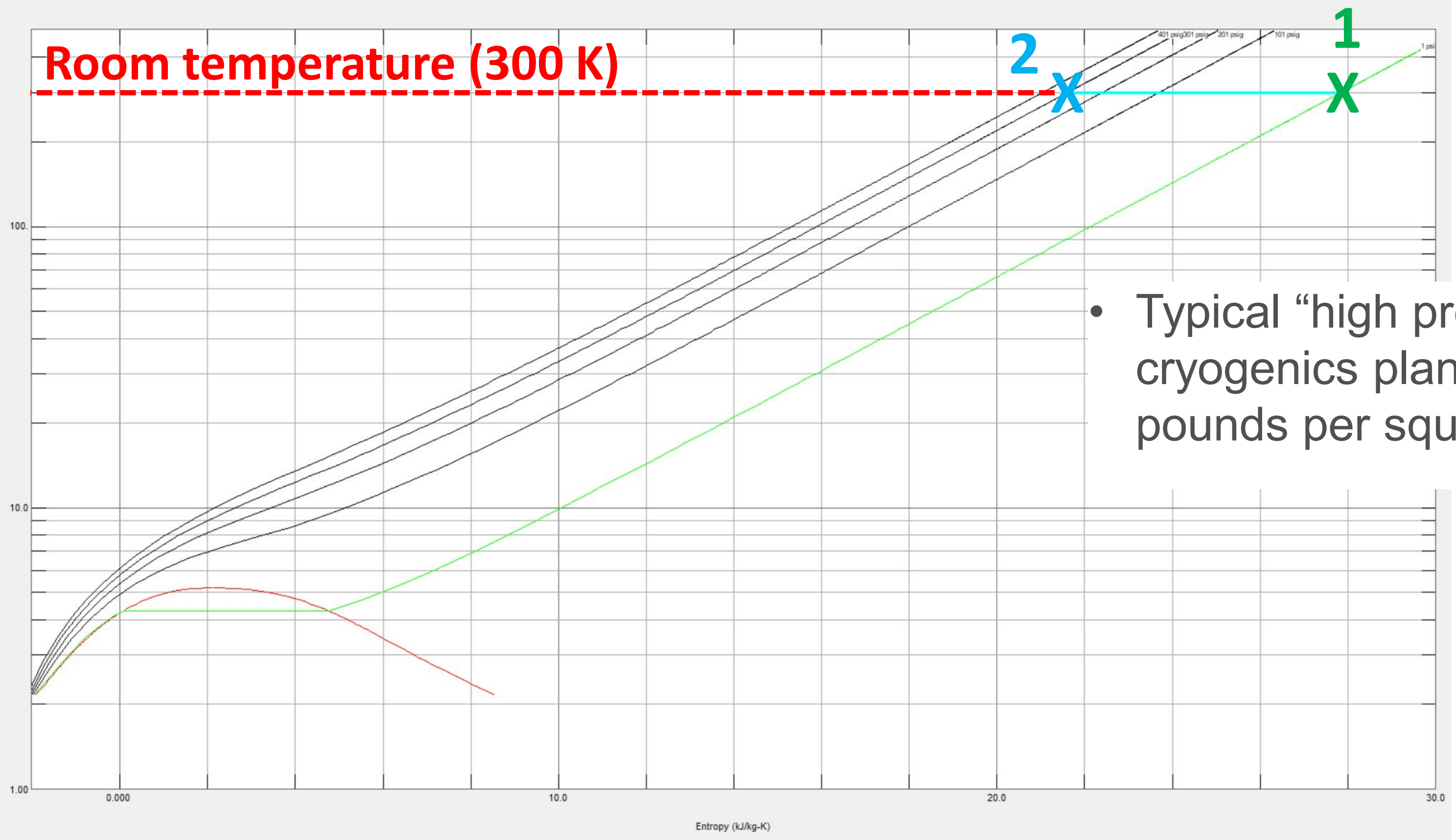
Where to dump the heat of compression?



Cryogenic Cycle Basics

- State 1: Room temperature, atmospheric pressure
- State 1a: Increased the pressure (with a compressor) – so, temperature goes up ↑
- State 2: Removed the heat of compression (Lake Michigan), so now you have state 1 temperature but much higher pressure!

Cryogenic Cycle Basics, cont.



- Typical "high pressures" in cryogenics plants are ~300 pounds per square inch (psi).

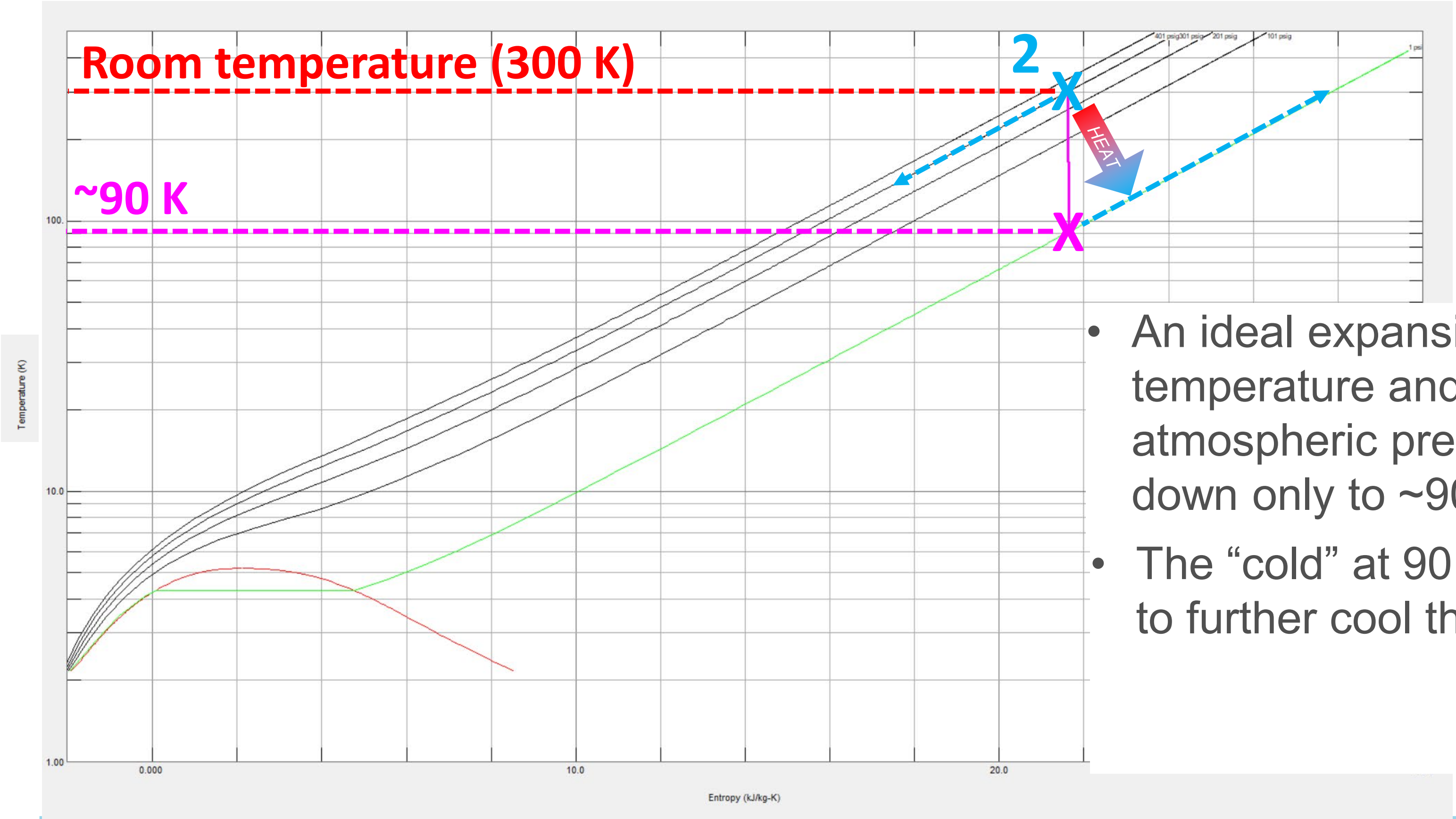
Image sources: REFPROP

Cryogenic Cycle Basics

- State 1: Room temperature, atmospheric pressure
- State 1a: Increased the pressure (with a compressor) – so, temperature goes up ↑
- State 2: Removed the heat of compression (Lake Michigan), so now you have state 1 temperature but much higher pressure!
- State 3: Need to lower the temperature.

How do we do this?

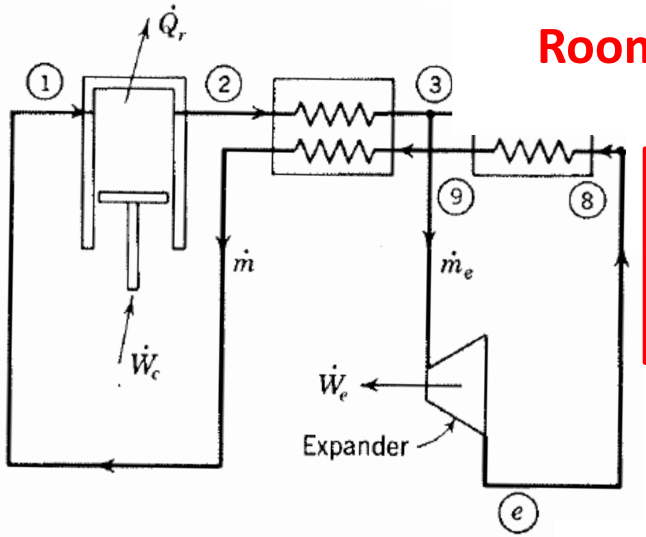
Cryogenic Cycle Basics, cont.



- An ideal expansion from room temperature and 300 psi to atmospheric pressure gets you down only to ~90 K.
- The “cold” at 90 K can be used to further cool the gas at 2.

Cryogenic Cycle Basics, cont.

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



How do we complete the cycle from 90 K to 4 K?

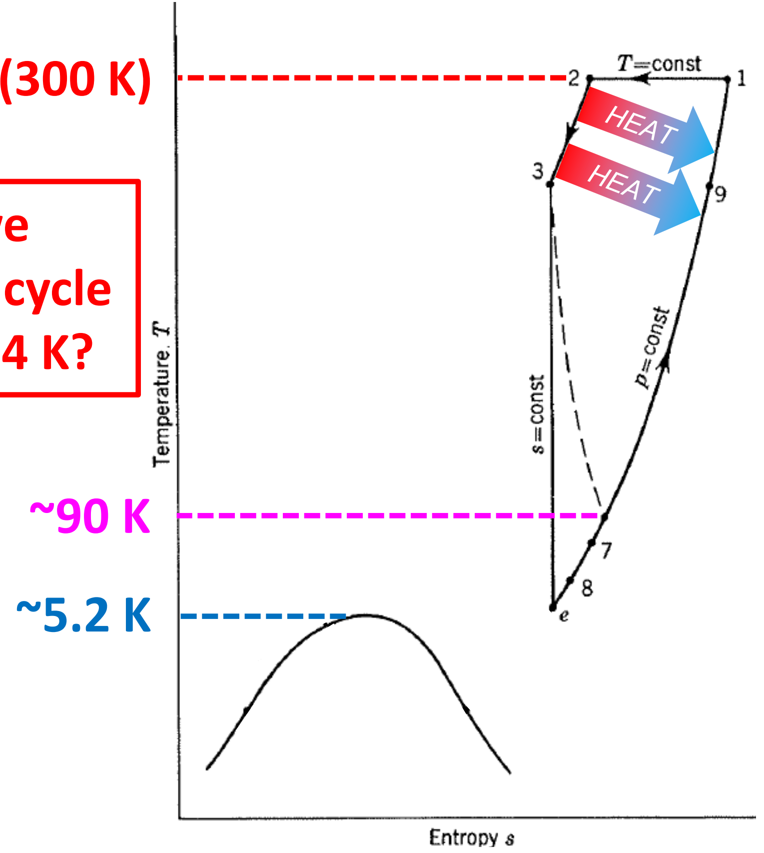
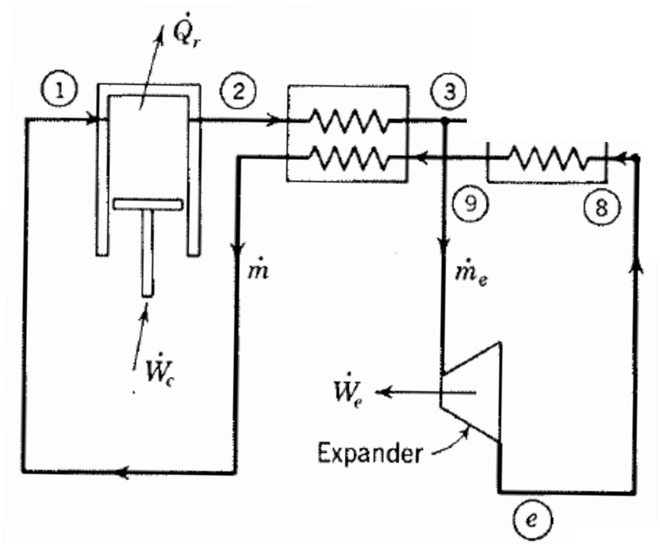


Image sources: "Cryogenic Systems" R. Barron and slides from John Weisend II

Cryogenic Cycle Basics, cont.



Repeat the same expansion and heat exchanging process as we did at 90 K

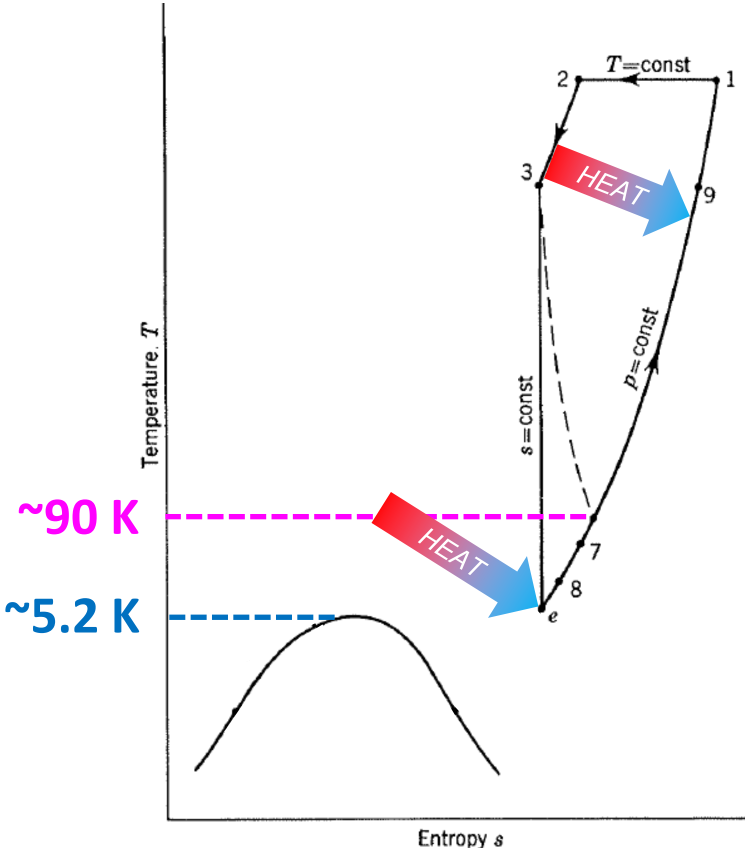


Image sources: "Cryogenic Systems" R. Barron and slides from John Weisend II

What Does a Real Cryogenics Plant Look Like?

This is just one part of it!

Image sources: pip2.fnal.gov, inside.fnal.gov

What Does a Real Cryogenics Plant Look Like (cont.)?

Cryoplant cold boxes at the European Spallation Source Accelerator and Target Moderator Cryoplants in Lund, Sweden

Cryo Module Test Facility coldbox at Fermilab

Image sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

What Does a Real Cryogenics Plant Look Like (cont.)?

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Compressor system at the European Spallation Source Accelerator Cryoplant in Lund, Sweden

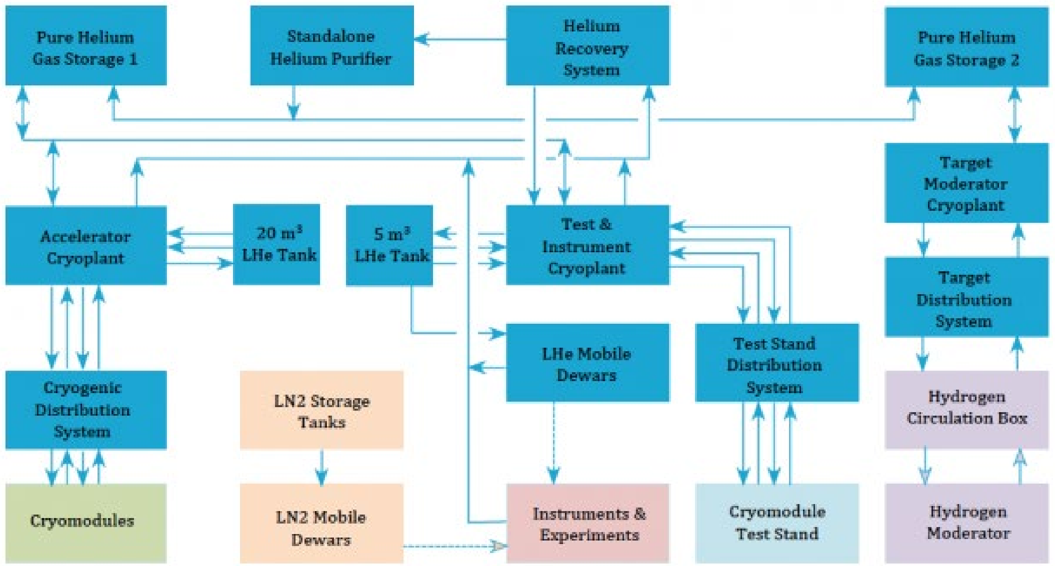
Compressor system and oil removal skids at the European Spallation Source Target Moderator Cryoplant in Lund, Sweden

Image sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

What Does a Real Cryogenics Plant Look Like (cont.)?

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

- Major components of a helium cryogenics plant:
  - Distribution Box:
    - Connects refrigeration plant with distribution lines.
  - Storage vessels:
    - Liquid Nitrogen
    - Liquid Helium
    - Gaseous Helium
  - Purifier: Removes impurities from the helium.
    - Contamination control is very important to reliable operation!
  - Control System



Fermilab

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025, ess.eu

What Does a Real Cryogenics Plant Look Like (cont.)?

- More about storage vessels:
  - When warmed, cryogenic liquids expand to approximately 700 times their liquid volume.
    - Even small quantities of liquid helium require large storage tanks so that the system remains a “closed system.”

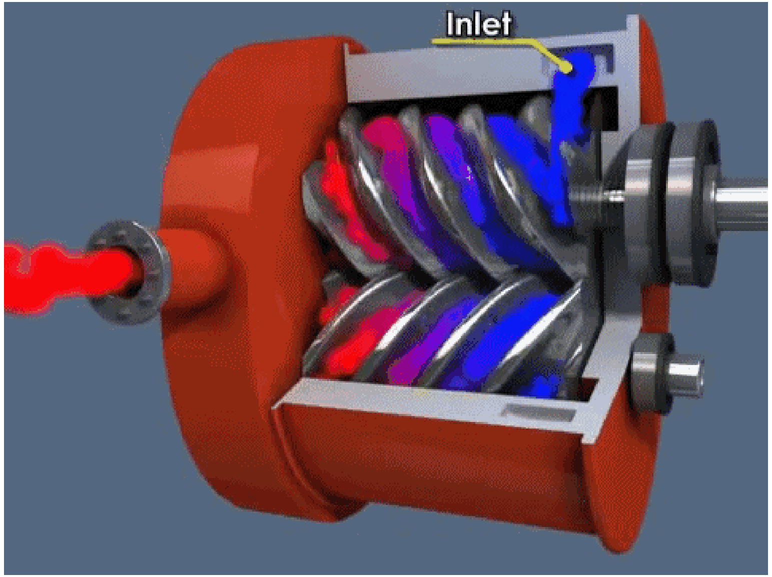
Warm storage vessels at Taiwan’s National Synchrotron Radiation Research Center

Image sources: nsrrc.org.tw/english

What Does a Real Cryogenics Plant Look Like (cont.)?

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

- Helium Screw Compressors
  - Operate at room temperature.
  - Are oil flooded.
    - They simultaneously compress a mixture of He gas and oil.
  - Require water cooling to remove heat due to compression.
  - The vast majority of the electrical power used in cryogenics plants is used by these compressors.
    - These motors can be over 300 horsepower per motor!



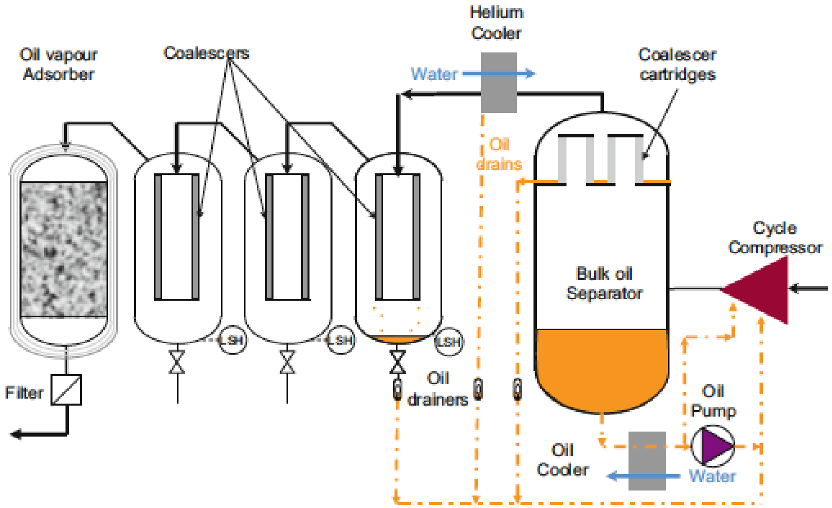
Fermilab

Image sources: compressedair-intel.blogspot.com

What Does a Real Cryogenics Plant Look Like (cont.)?

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

- Oil Removal Systems:
  - Remove oil down to the parts per billion level!
    - Critical for proper operation of the cryogenics plant.
  - Important to build in redundancy.
  - Ideally, filtration media an be "regenerated."

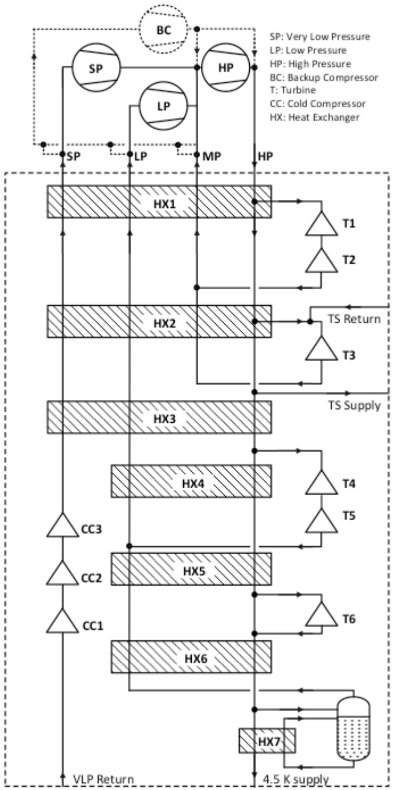


Fermilab

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025, ess.eu

What Does a Real Cryogenics Plant Look Like (cont.)?

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



European Spallation Source Accelerator Cryoplant

Real-life cryogenics plant diagrams!

Note: Some plants connect to a vacuum pump to lower temperature below 2 K!

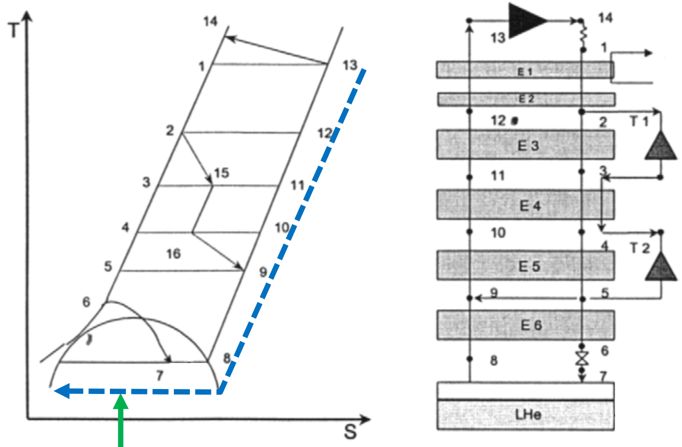


Figure 2 HELIAL T-S diagram and cycle design

Source: *"Evolution of the standard helium liquefier and refrigerator range designed by Air Liquide DTA, France,"* A. Caillaud et. al. Proceedings of EPAC08, Genoa, Italy.

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025, ess.eu

What Does a Real Cryogenics Plant Look Like (cont.)?

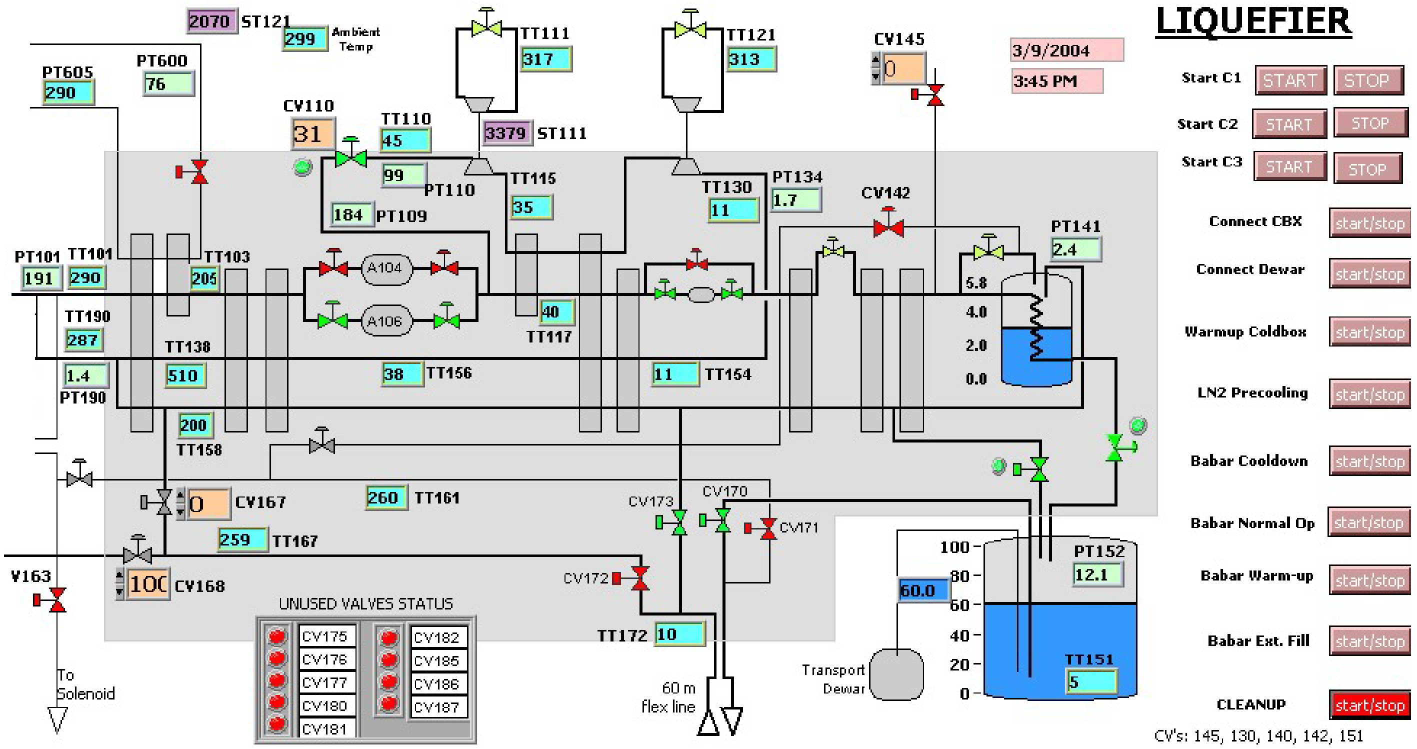


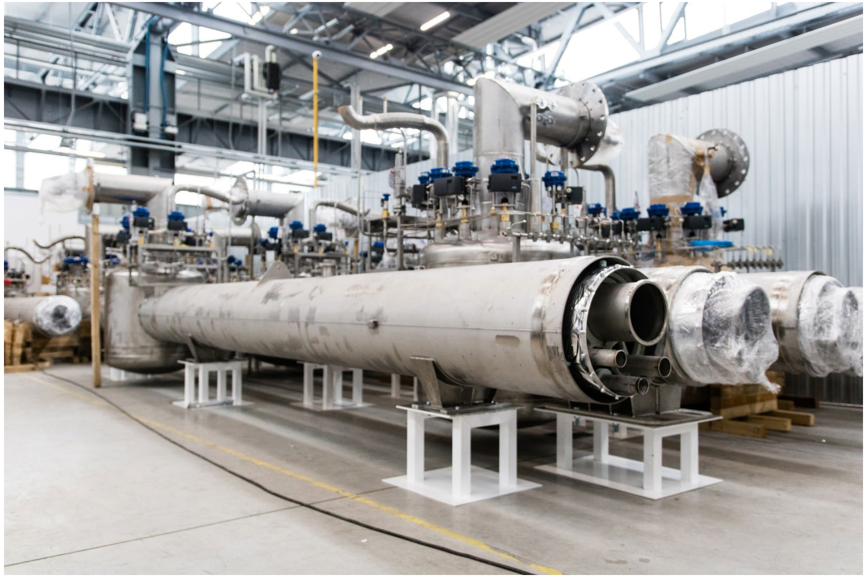
Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025, ess.eu

How Much Does a Cryogenics Plant Cost?

- The Illinois Quantum and Microelectronics Park is expected to pay **$77 million dollars for two cryogenic plants**, “*cryoplant resources, equipment and facilities necessary to support the quantum computing facilities*” to be built at IQMP per its November 14, 2024 board meeting notes.
- Other cryogenic plants, such as at ITER cost **83 million Euros for three cryogenic plants**.

Image and slide sources: chicagotribune.com, iter.org/node/20687/eur-83-million-contract-signed-liquid-helium-plant

Cryogenic Distribution Systems



These systems can add significant costs to the installation of a cryogenics plant!

Image sources: kriosystem.com.pl/en, mtm-inc.com

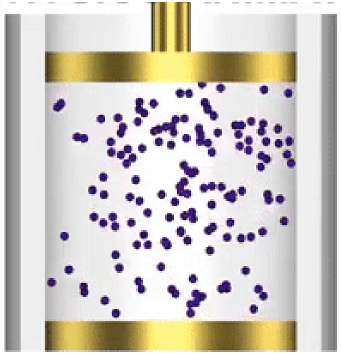
5-minute break

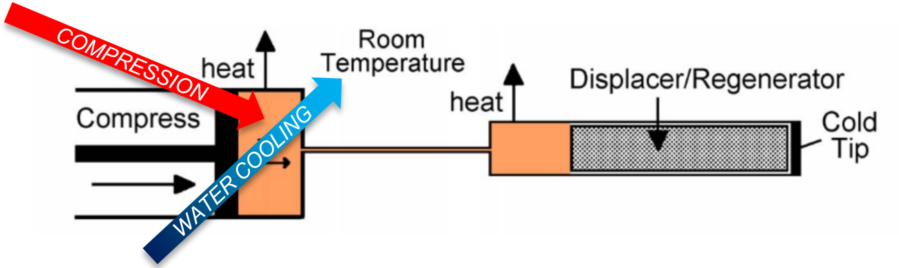
Cryocoolers

- Small closed cycle stand-alone refrigerators with cooling capacities ranging between 1 and 100 W at cryogenic temperatures.
  - Definition obtained from S. W. Van Sciver, "Helium Cryogenics," 2nd edition.
- These are generally simple to use, typically only require electricity and cooling water inputs.
  - After that, you basically just "turn on" the switch (after a good vacuum is reached first)!
- The simplest cryocooler to explain is the Stirling-cycle cooler, so we will start with that!
  - Note: This won't be easy!

Image sources: gasworld.com

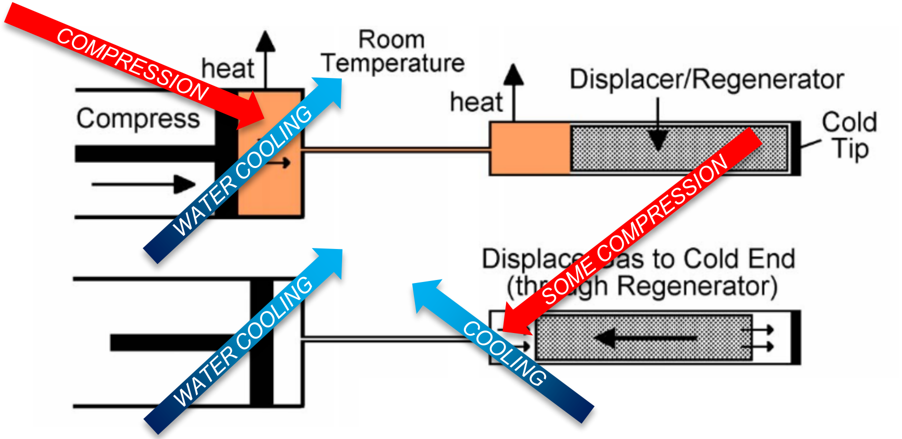
Cryocoolers, cont.





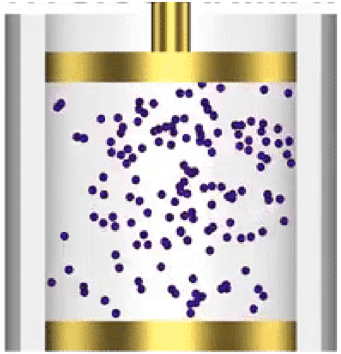
Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

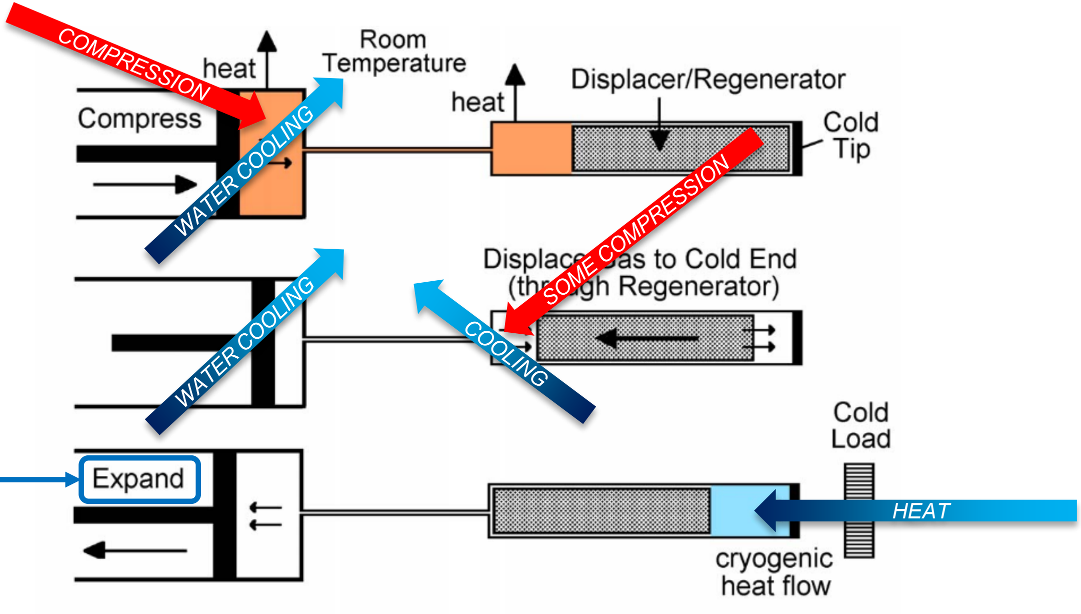
Cryocoolers, cont.



Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

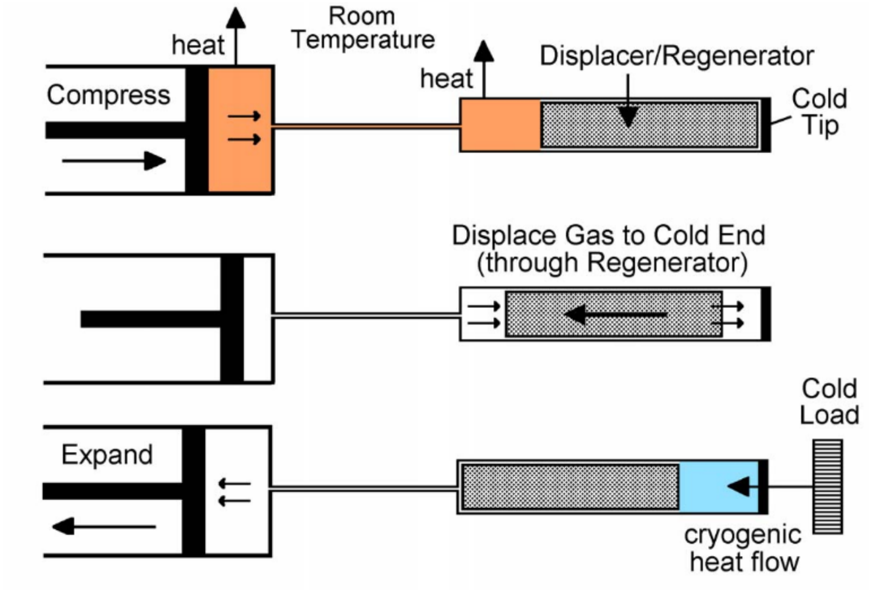
Cryocoolers, cont.





Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

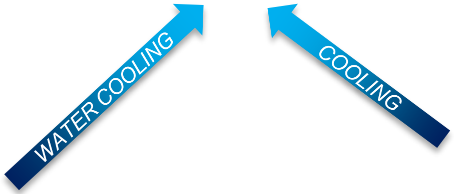
Cryocoolers, cont.



Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

Let’s Take a Ride with the Displacer

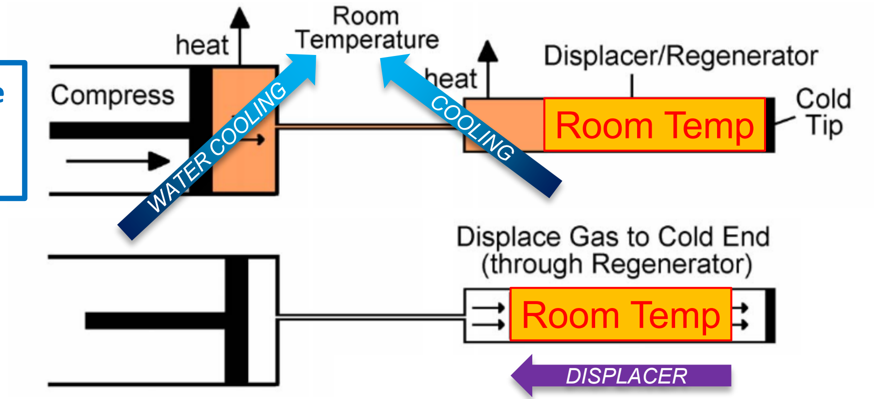
Important point: We are starting the cycle from the beginning here (just like we did in the last slide)



Source: *“Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,”* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

Let's Take a Ride with the Displacer, cont.

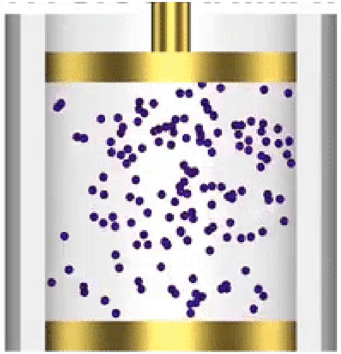
Important point: We are starting the cycle from the beginning here (just like we did in the last slide)

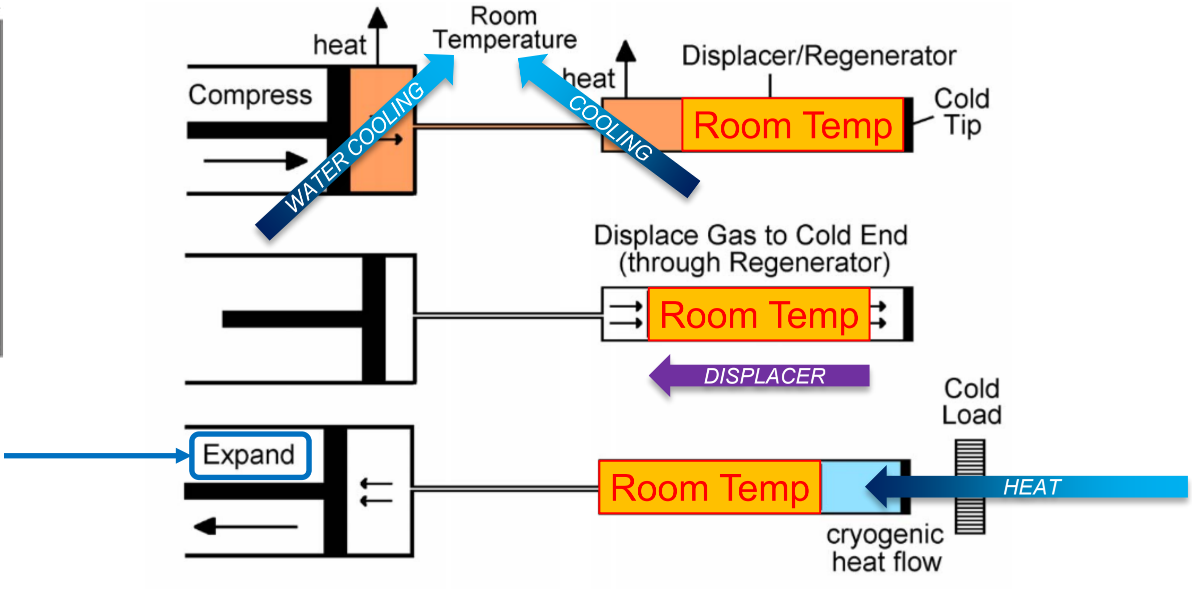


Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

Let's Take a Ride with the Displacer, cont.

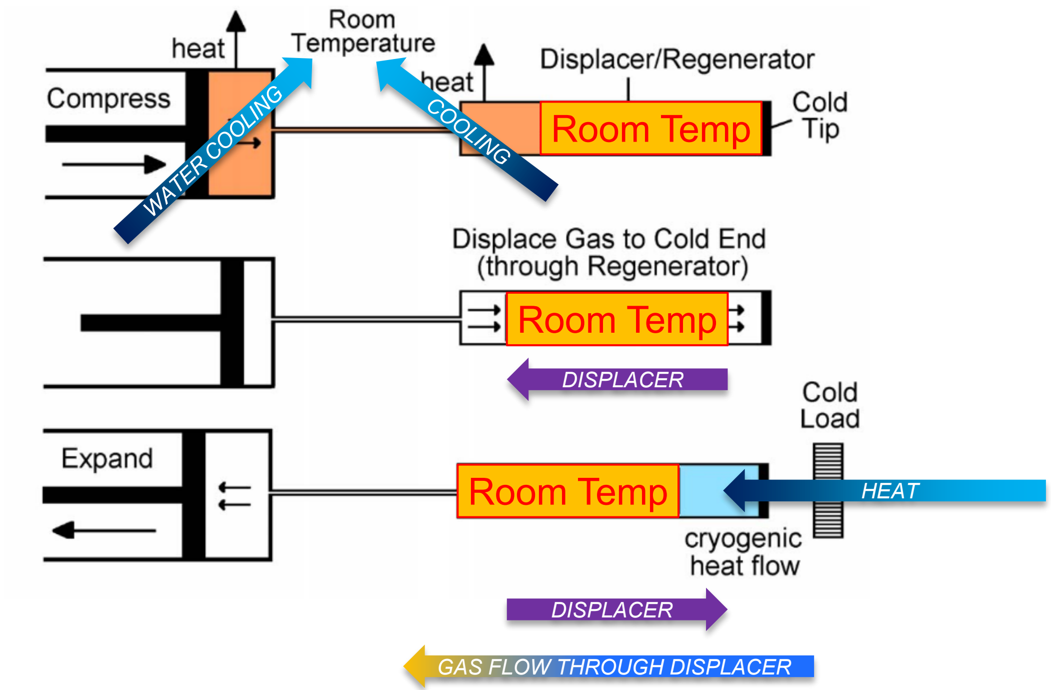
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER





Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

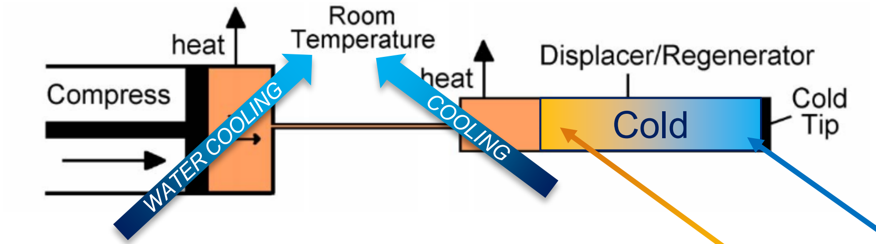
Let's Take a Ride with the Displacer, cont.



Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

Let's Take a Ride with the Displacer, cont.

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

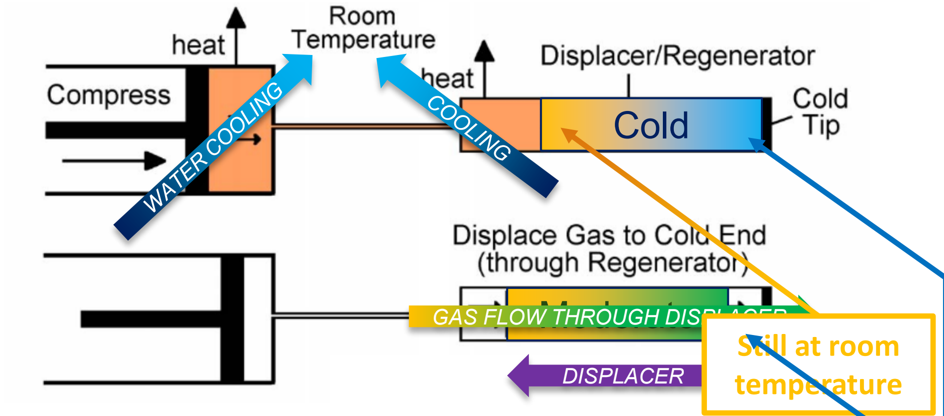


Still at room temperature

Important point: Displacer tip is now colder than in previous cycle!

Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

Let's Take a Ride with the Displacer, cont.

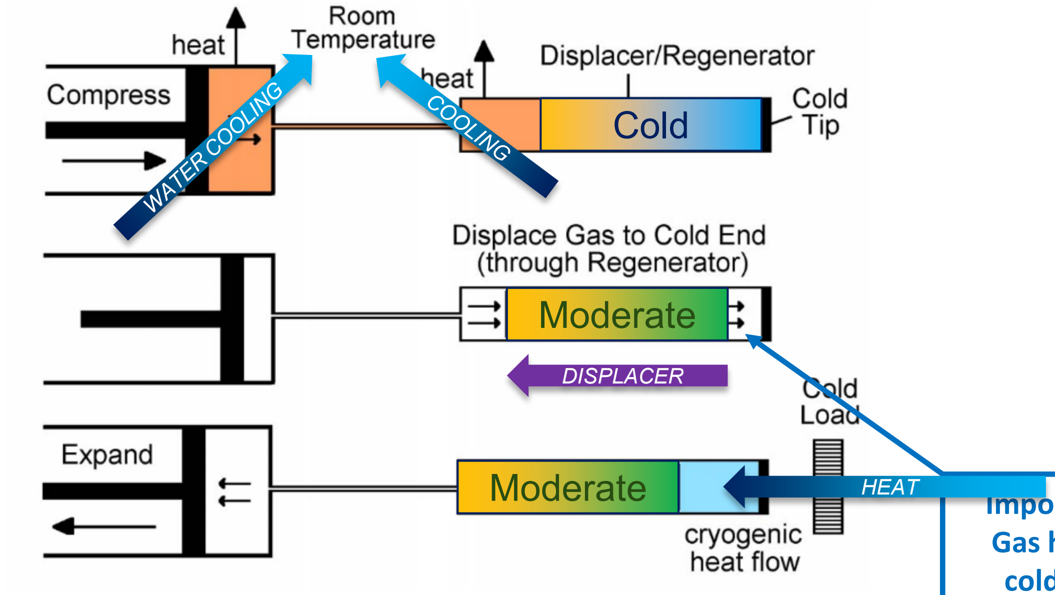


Important point: Displacer is now colder than in previous cycle!

Important point: Gas here is now colder than in previous cycle (gets cooled by regenerator)!

Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

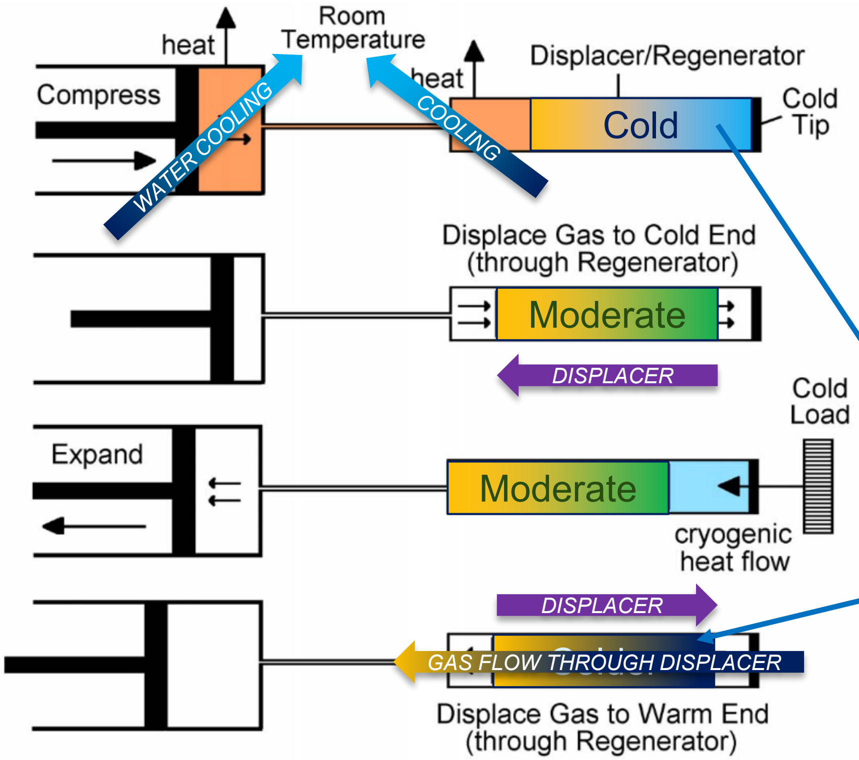
Let’s Take a Ride with the Displacer, cont.



Important point: Gas here is now colder than in previous cycle (gets cooled by regenerator)!

Source: *“Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,”* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

Let's Take a Ride with the Displacer, cont.



Important point: Displacer gets colder with time!

Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

Stirling Cryocooler in Reality

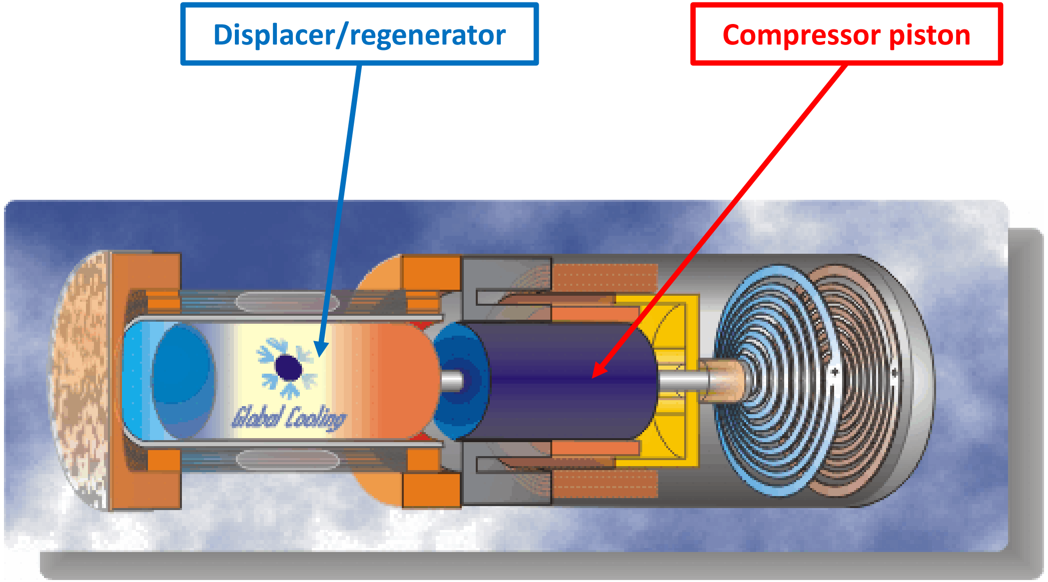


Image sources: rigidchill.com

Other Cryocooler Cycles

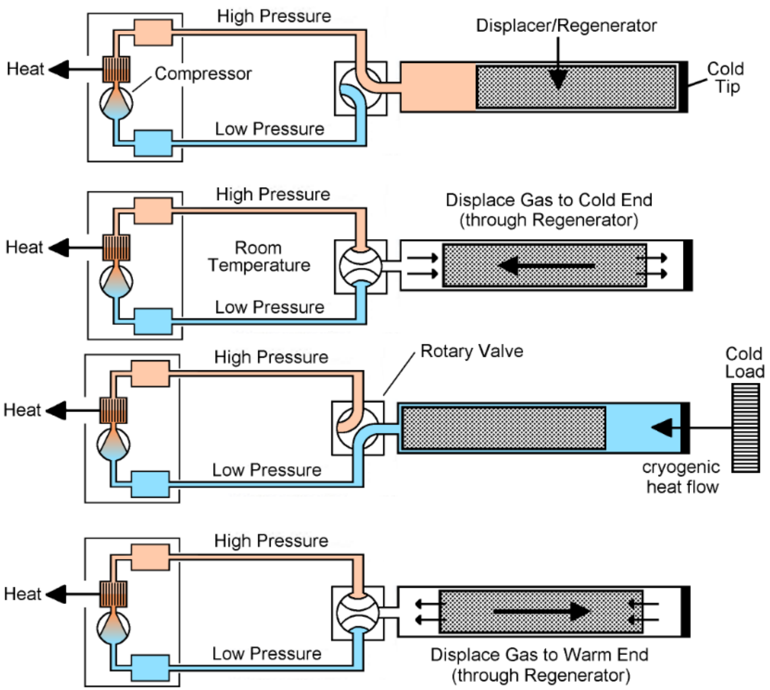


Figure 17. Schematic of Gifford McMahon refrigeration cycle.

- Gifford McMahon:
  - Similar cold end to Stirling cryocooler with moving displacer/regenerator.
  - Main differences from Stirling cryocooler:
    - Compressor changed from piston-type to continuous type.
    - Oscillating flow comes from constantly revolving valve between compressor and cold end.

Source: *"Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,"* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

Other Cryocooler Cycles, cont.

- Pulse tube:
  - Can have Gifford McMahon compressor style.
  - Cold block is in between regenerator and pulse tube.
  - Displacer is a “virtual gas piston”
    - Virtual gas piston is “timed” by a careful selection of inertance tube diameter and reservoir volume dimensions.

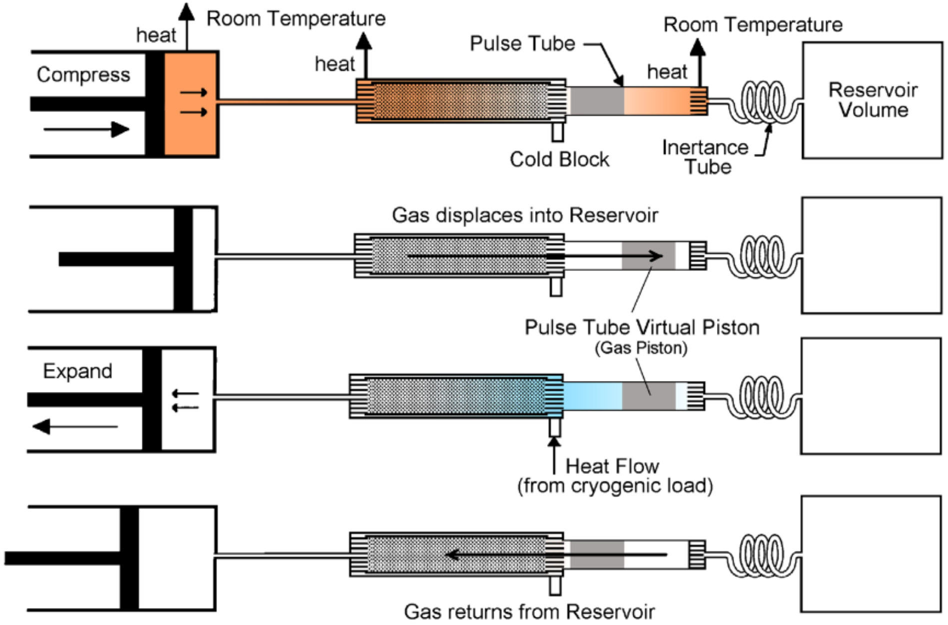


Figure 10. Schematic of pulse tube cooler refrigeration cycle.

Source: *“Chapter 6 Refrigeration Systems for Achieving Cryogenic Temperatures,”* R. Ross. In book: Low Temperature Materials and Mechanisms (pp.109-182)

Cooling Methods Below 1 Kelvin

- Sub-atmospheric ^4He
- Sub-atmospheric ^3He
- Dilution Refrigerators
- Adiabatic Demagnetization Refrigerators (ADR)
- Nuclear Demagnetization Refrigerators
- Laser cooling

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

Helium Vapor Pressure Chart

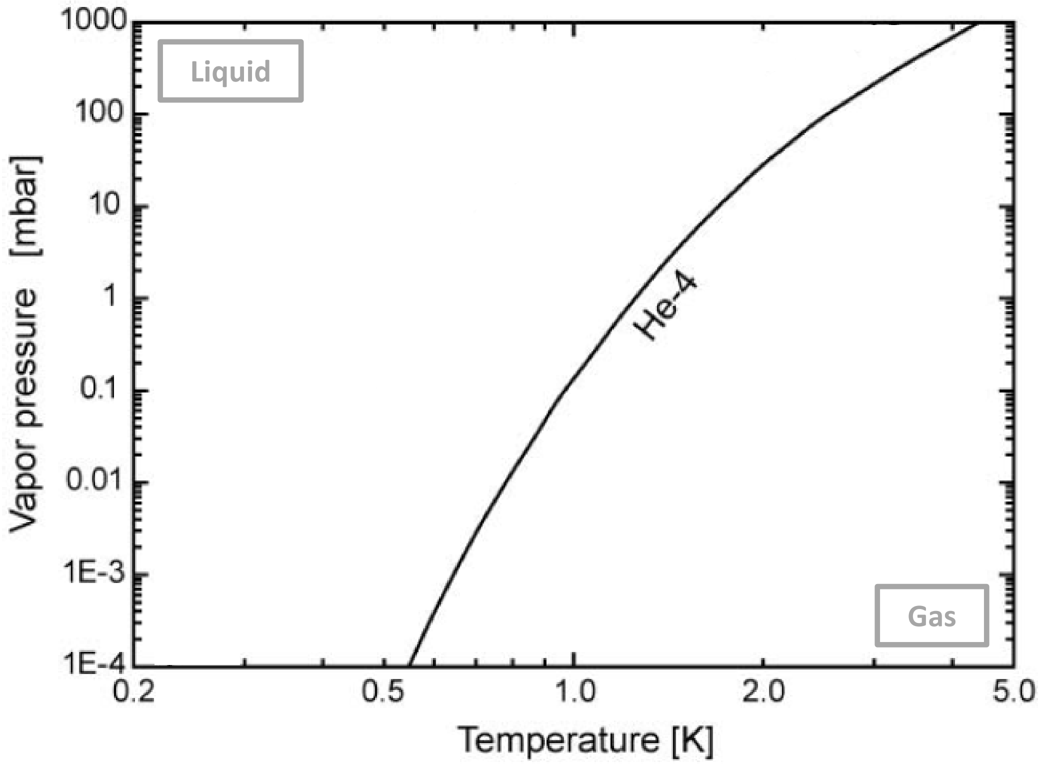


Image and slide sources: K. Hock, “Cooling Techniques,” Lecture notes of PHYS393, University of Liverpool (2011)

Helium Vapor Pressure Chart, cont.

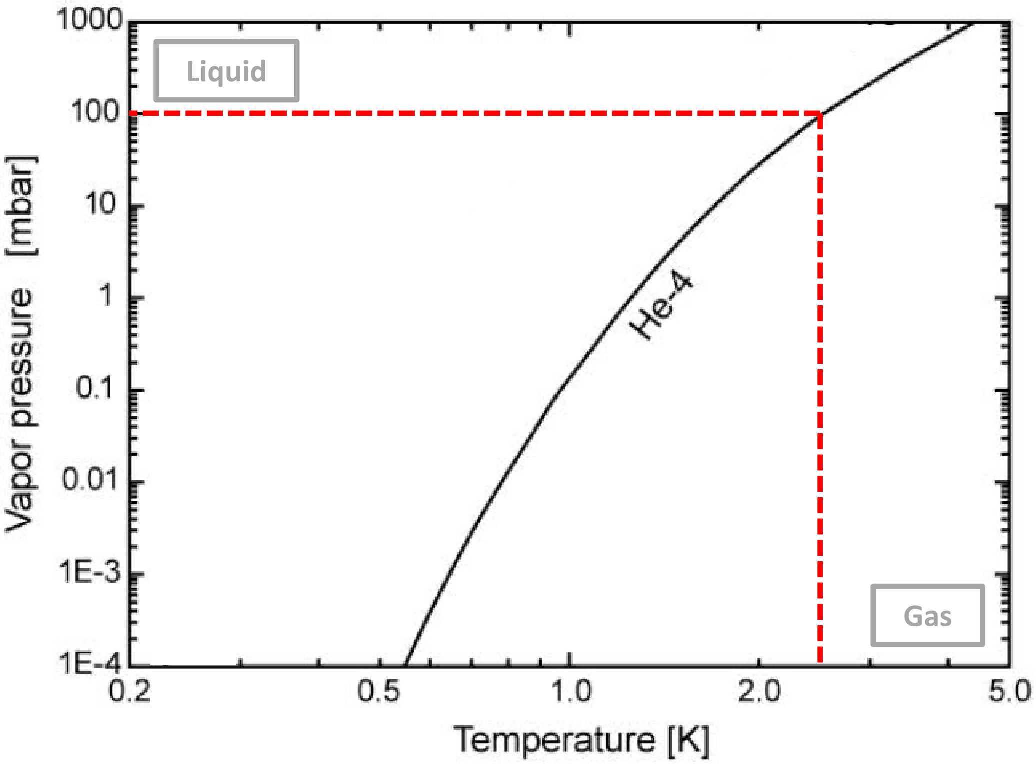


Image and slide sources: K. Hock, "Cooling Techniques," Lecture notes of PHYS393, University of Liverpool (2011)

Helium Vapor Pressure Chart, cont.

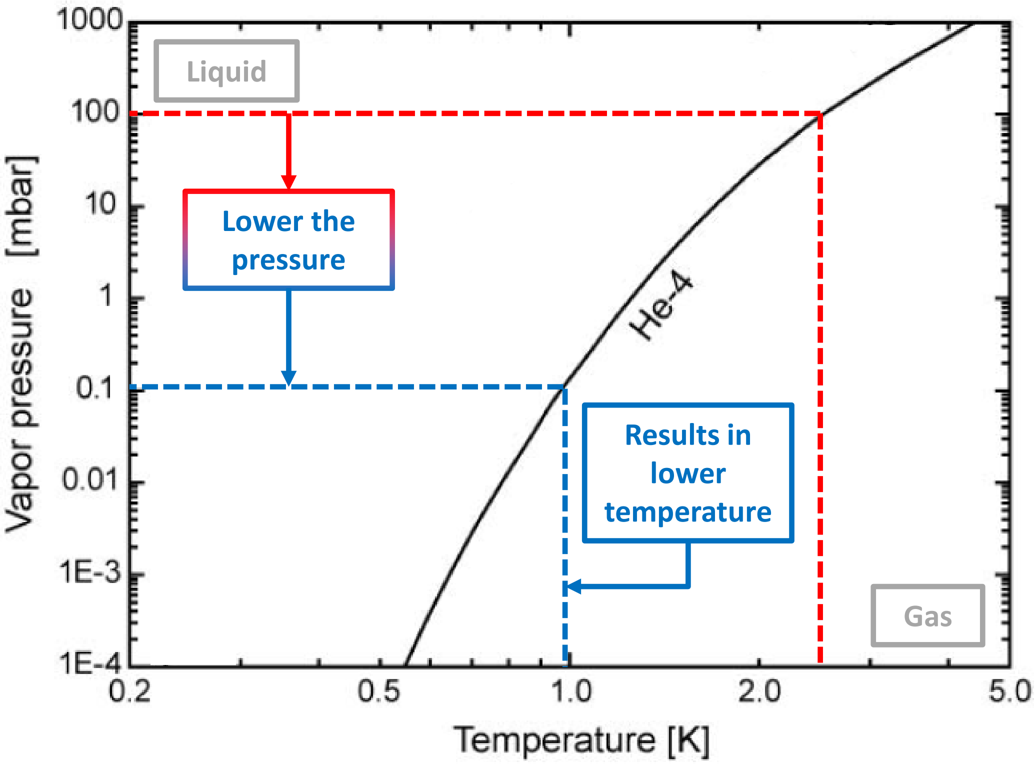
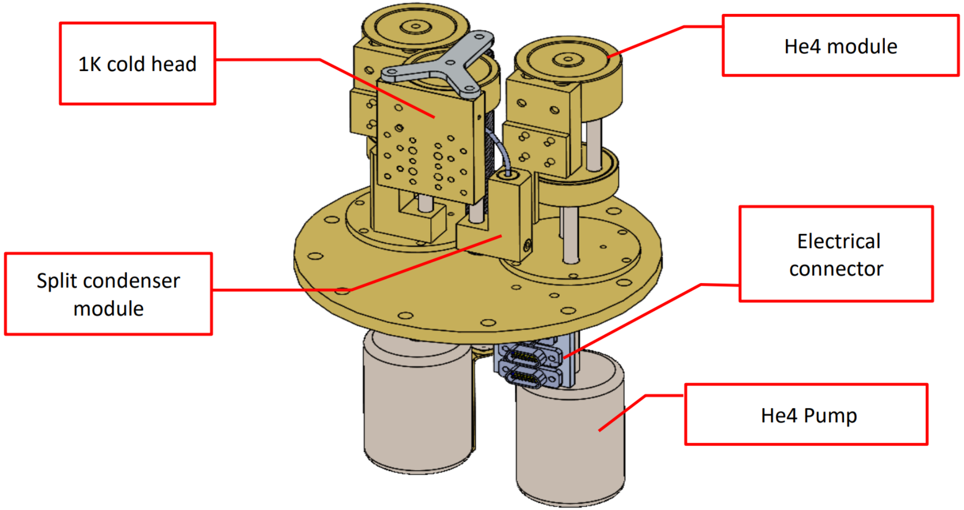


Image and slide sources: K. Hock, "Cooling Techniques," Lecture notes of PHYS393, University of Liverpool (2011)

Limits to Pumping on ^{4}He

- We can reduce the temperature of liquid helium by reducing its pressure.
  - But there is a limit!
- The vapor pressure of ^{4}He becomes very small below 1.2 K, so cooling below this temperature using this technique is not practical.
- To the right is an example of a continuous ^{4}He sorption cooler from Chase Research.
  - 100 µW cooling power around 850 mK.



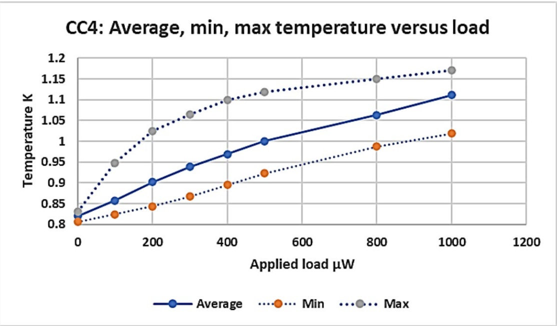


Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

Helium Vapor Pressure Chart, cont.

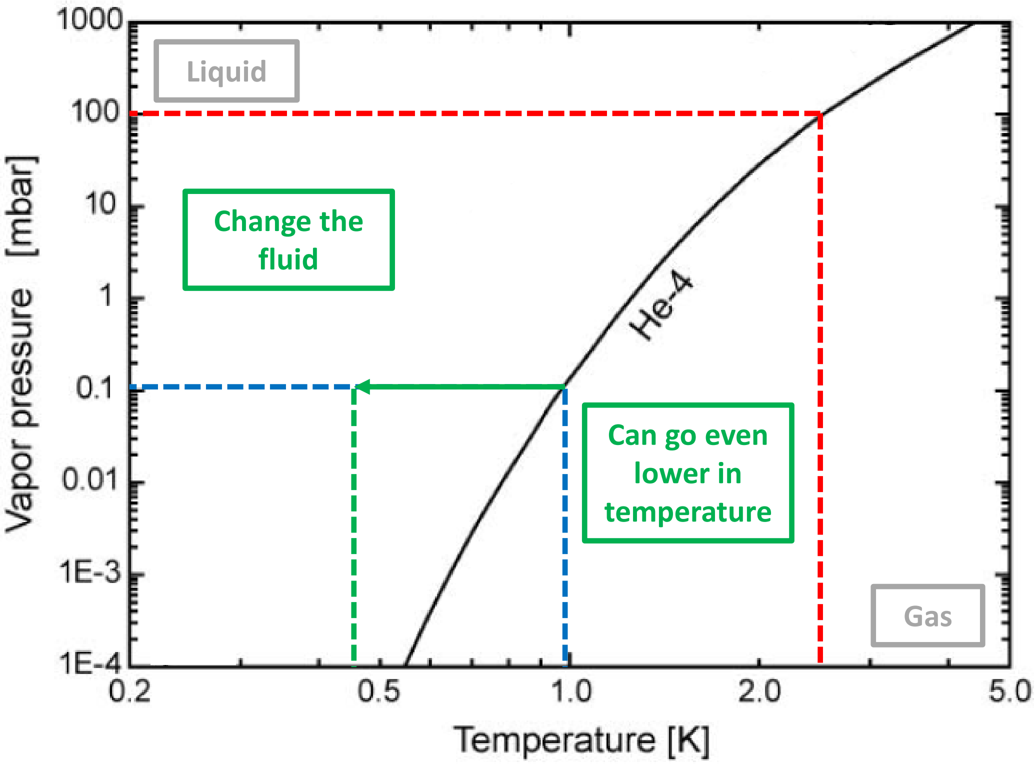


Image and slide sources: K. Hock, “Cooling Techniques,” Lecture notes of PHYS393, University of Liverpool (2011)

^{3}He Details

- Helium has two stable isotopes, ^{3}He and ^{4}He.
- ^{3}He is extremely rare – only 0.000137% of all naturally occurring helium is ^{3}He.
  - Note: ^{3}He can be produced in certain nuclear reactors.
  - Because of this, ^{3}He is very expensive (> $1,000 per STP Liter).

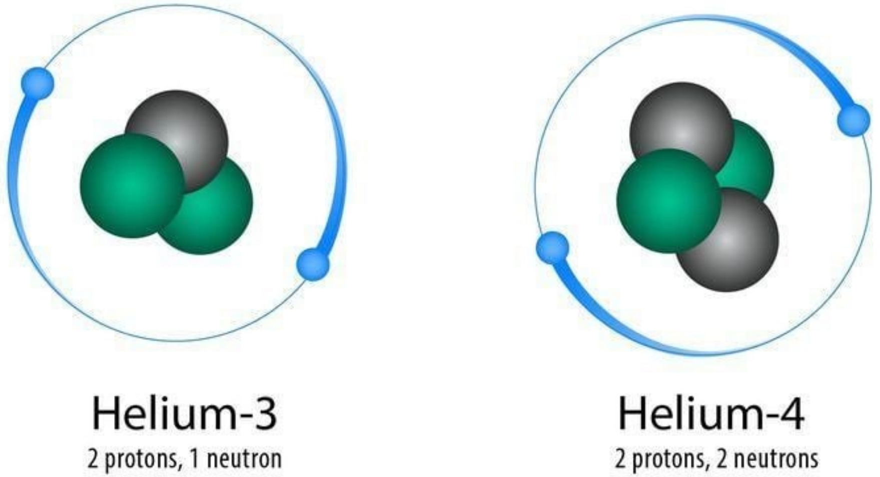


Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025, alchetron.com

Limits to Pumping on ^{3}He

- Pumped ^{3}He systems can provide cooling down to 200 to 300 mK.
- To the right is an example of a continuous ^{3}He cryostat from ICEOxford.
  - 100 µW cooling power around 360 mK.
    - Same cooling power as ^{4}He sorption cooler from Chase Research but at a lower temperature!

DRY ICE 300mK Continuous

The DRY ICE 300mK Continuous Cryostat is designed to run continuously at He^3 temperatures (below 500mK). The system offers some of the highest cooling powers on the market, achieving up to 500µW at 400mK, making it highly suitable for large heat load experiments.

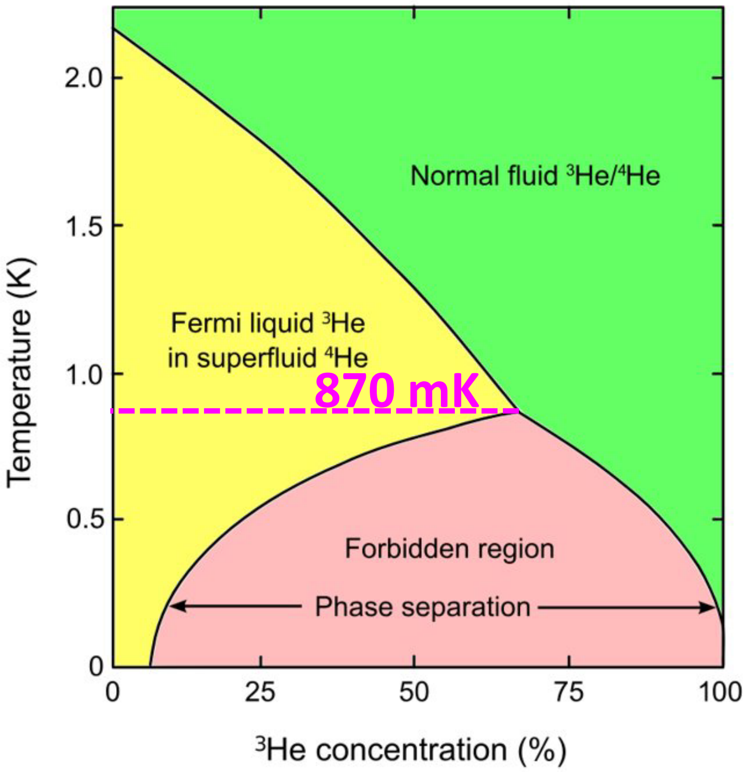
KEY FEATURES

- Base temperature: 330mK
- 100µW of cooling power @ 360mK
- 500µW of cooling power @ 350mK
- Continuous operation
- Ø 300mm sample space

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

Dilution Refrigerators

- These use a mixture of ^3He and ^4He and take advantage of three physical effects:
  1. Below 870 mK a $^3He/^4He$ mixture will separate into a ^3He rich zone sitting atop a denser ^4He rich zone.



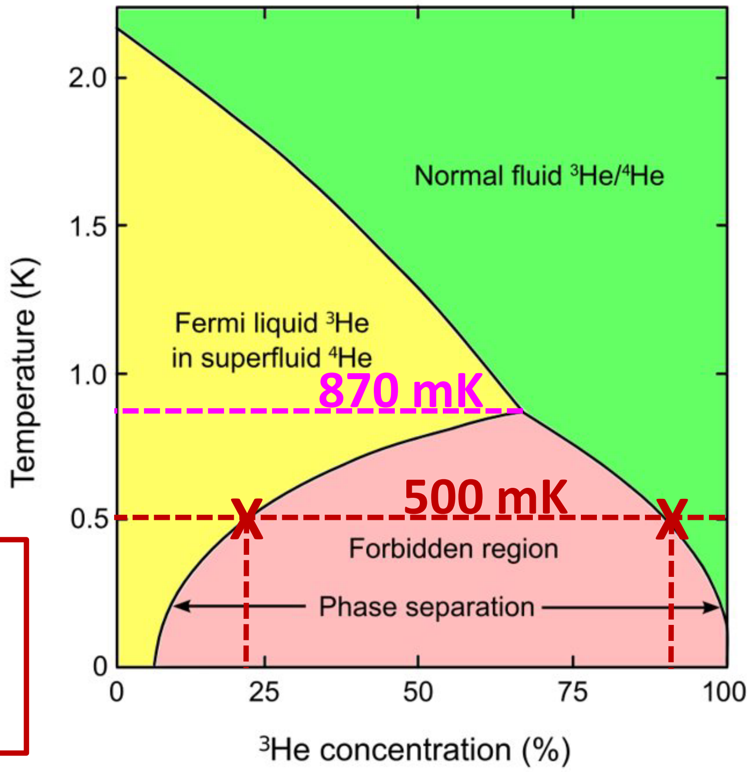
Source: File:Helium phase diagram.svg - Wikimedia Commons

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

Dilution Refrigerators

- These use a mixture of ^3He and ^4He and take advantage of three physical effects:
  1. Below 870 mK a $^3He/^4He$ mixture will separate into a ^3He rich zone sitting atop a denser ^4He rich zone.
  2. It requires energy to move a ^3He atom from the ^3He rich zone to the ^4He rich zone.

Two "phases" will exist at 500 mK, one with ~23% ^3He concentration and another one with ~90% ^3He concentration



Source: File:Helium phase diagram.svg - Wikimedia Commons

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

Dilution Refrigerators, cont.

- These use a mixture of ^{3}He and ^{4}He and take advantage of three physical effects:
  1. Below 870 mK a ^{3}He/^{4}He mixture will separate into a ^{3}He rich zone sitting atop a denser ^{4}He rich zone.
  2. It requires energy to move a ^{3}He atom from the ^{3}He rich zone to the ^{4}He rich zone.
     - This energy reduces the temperature of the ^{3}He/^{4}He mixture.
  3. Below 1 K, the vapor pressure of ^{3}He is higher than that of ^{4}He.
     - Thus, pumping on a ^{3}He/^{4}He mixture below 1 K has the result of ^{3}He atoms leaving the mixture first.

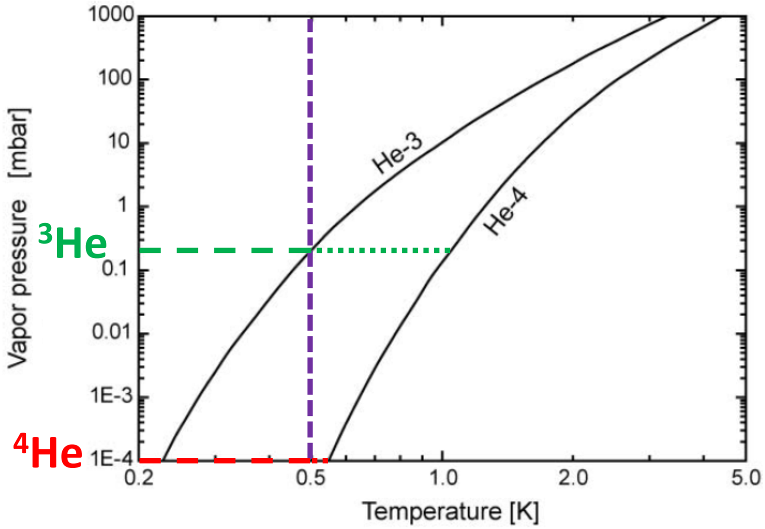
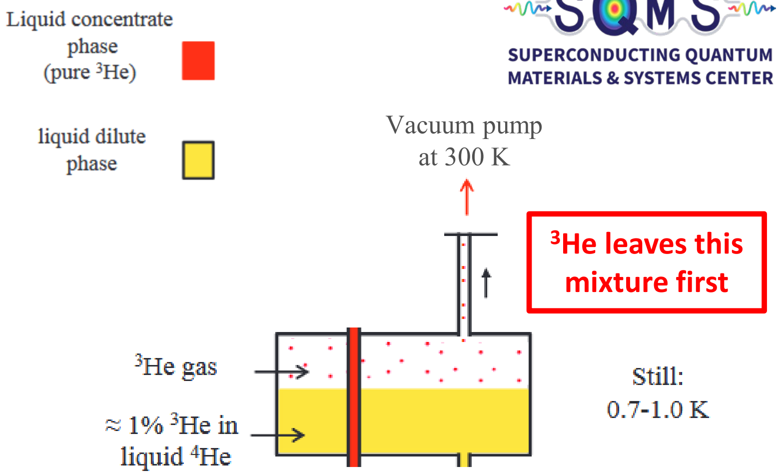


Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

Dilution Refrigerators, cont.

- These use a mixture of ^3He and ^4He and take advantage of three physical effects:
  1. Below 870 mK a $^3He/^4He$ mixture will separate into a ^3He rich zone sitting atop a denser ^4He rich zone.
  2. It requires energy to move a ^3He atom from the ^3He rich zone to the ^4He rich zone.
     - This energy reduces the temperature of the $^3He/^4He$ mixture.
  3. Below 1 K, the vapor pressure of ^3He is higher than that of ^4He.
     - Thus, pumping on a $^3He/^4He$ mixture below 1 K has the result of ^3He atoms leaving the mixture first.



Source: "*Development of a closed cycle dilution refrigerator for astrophysical experiments in space*," A. Volpe. Instrumentation and Detectors, Université Joseph-Fourier – Grenoble I, 2014. NNT: . Tel-00993970v1

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

Dilution Refrigerators, cont.

- These use a mixture of ^3He and ^4He and take advantage of three physical effects:
  1. Below 870 mK a $^3He/^4He$ mixture will separate into a ^3He rich zone sitting atop a denser ^4He rich zone.
  2. It requires energy to move a ^3He atom from the ^3He rich zone to the ^4He rich zone.
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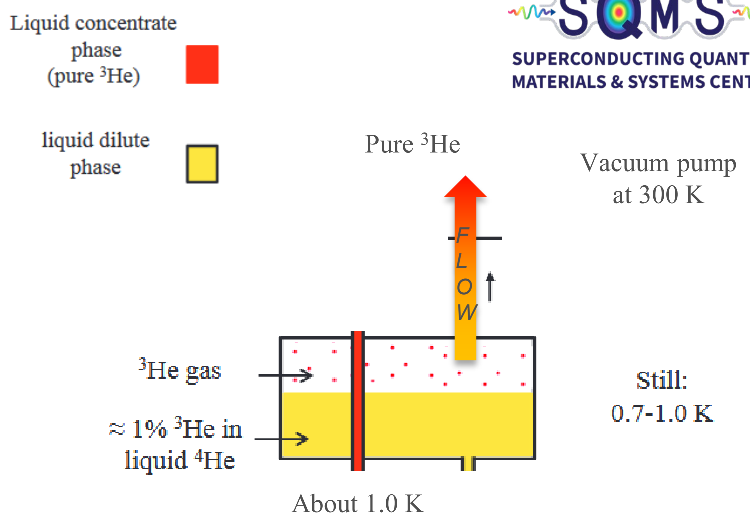

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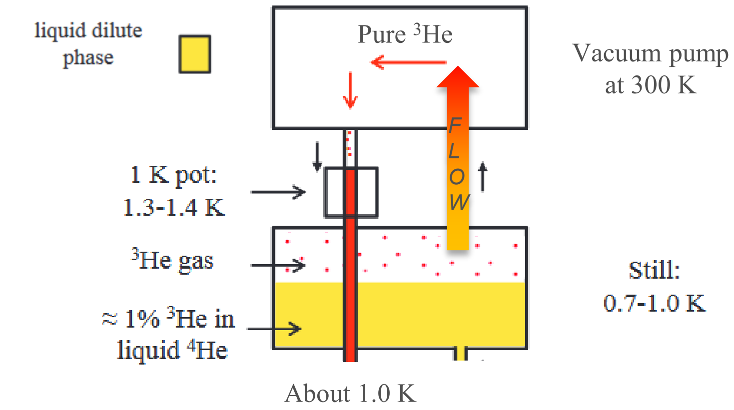
HOW?



Let's introduce a new "tank"

Source: "*Development of a closed cycle dilution refrigerator for astrophysical experiments in space*," A. Volpe. Instrumentation and Detectors, Université Joseph-Fourier – Grenoble I, 2014. NNT: . Tel-00993970v1

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

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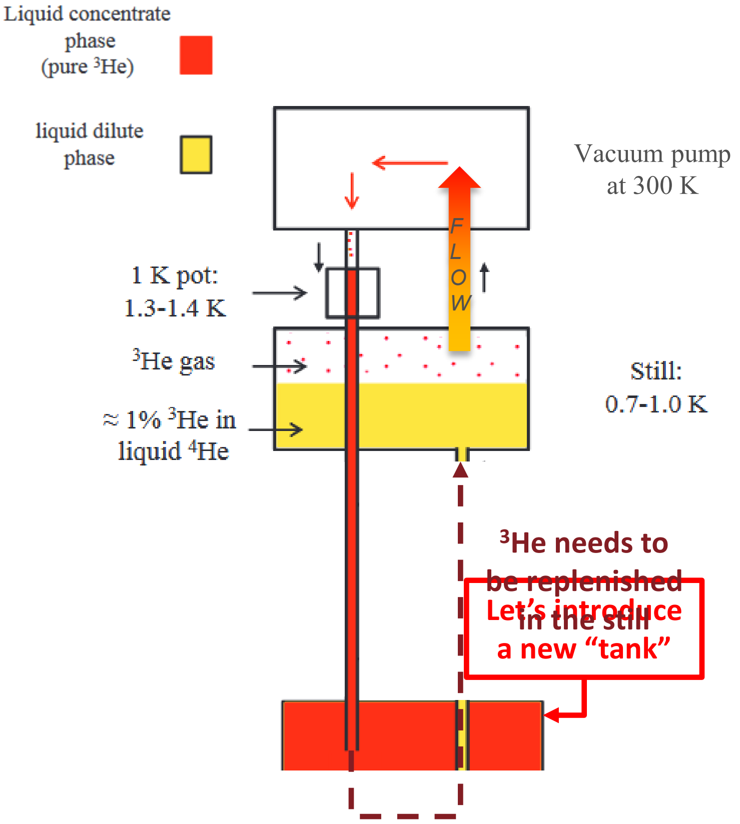

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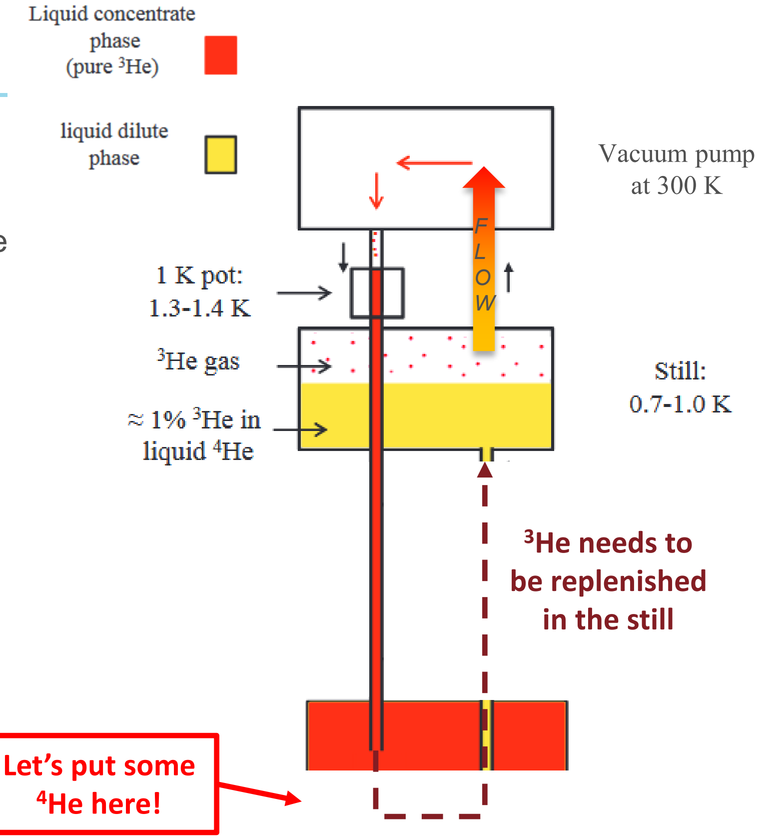

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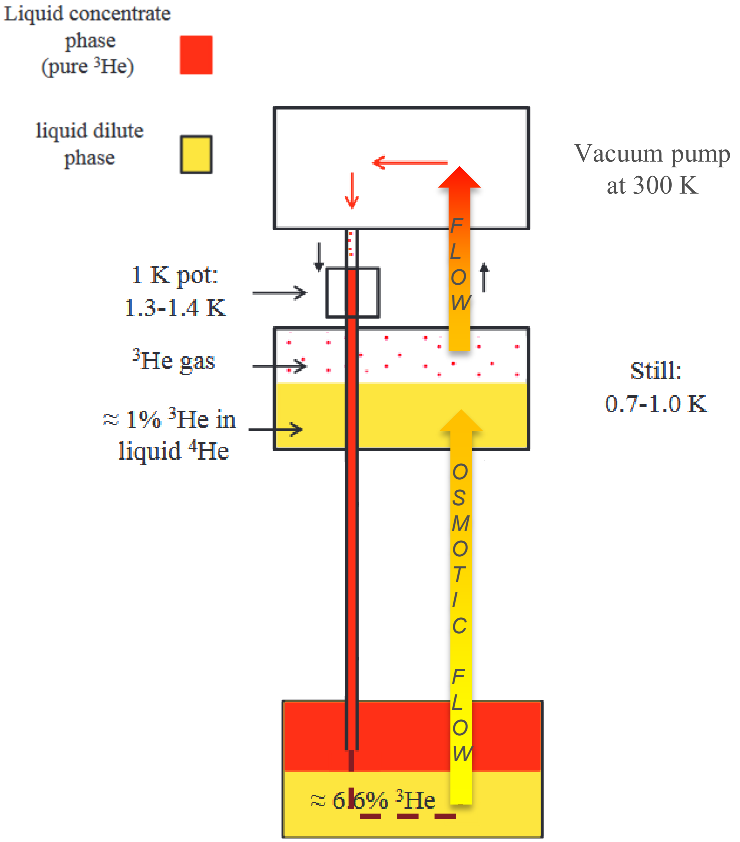
       - This results in net cooling effect at the mixing chamber.



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Fermilab

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

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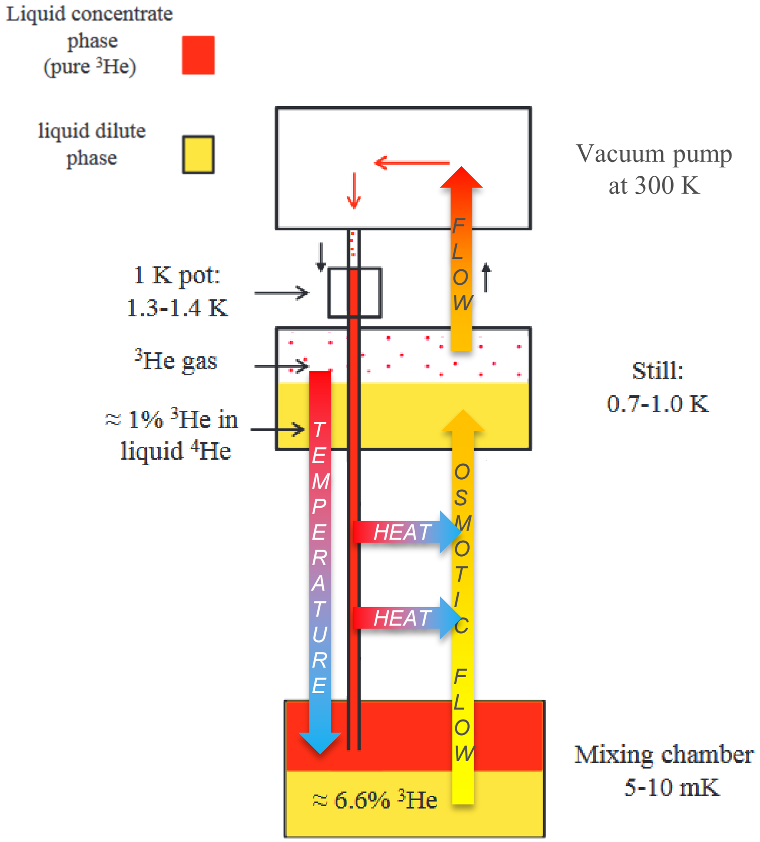
       - This results in net cooling effect at the mixing chamber.
     - To keep pressures in the still high enough allow a turbomolecular pump to pump out ^3He, the still is heated to approximately 700 mK.



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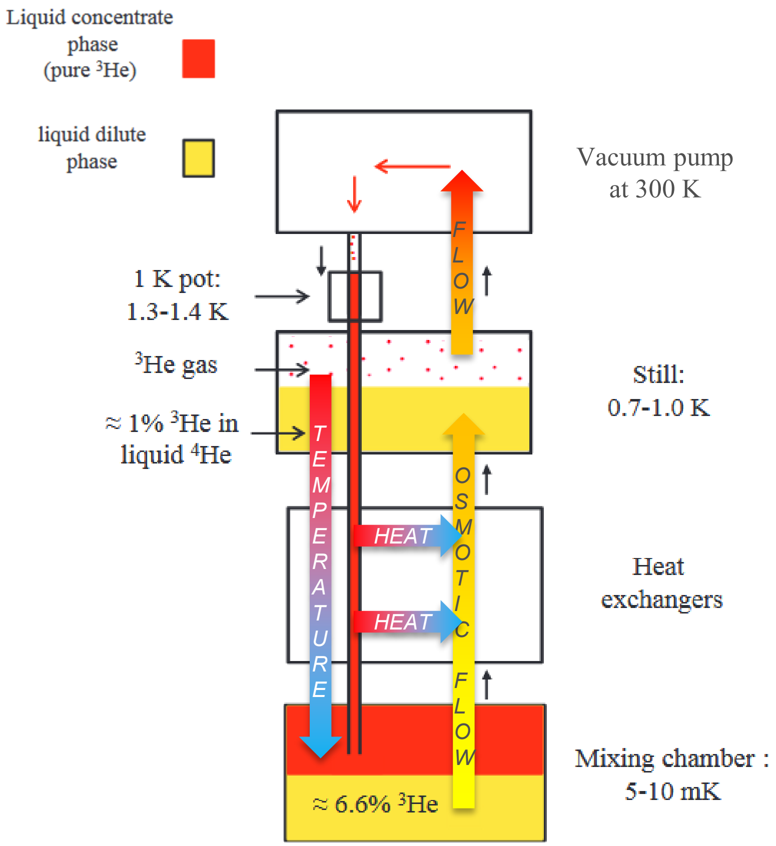
       - This results in net cooling effect at the mixing chamber.
     - To keep pressures in the still high enough allow a turbomolecular pump to pump out ^{3}He, the still is heated to approximately 700 mK.
- Practical limit to dilution refrigerator base temperature is 2 mK.
- As of today, the only commercially-available technology to provide continuous cooling below 200 mK.



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Dilution Refrigerators, cont.

Typical cooling power specifications for a "large" dilution refrigerator, such as Bluefors' XLD1000sl:

XLD1000sl	Guaranteed
Base temperature	10 mK
Cooling power at 20 mK	>30 μW
Cooling power at 100 mK	>1000 μW
Cooling power at 120 mK	>1400 μW
MXC Flange Diameter	500 mm

Fermilab

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

Adiabatic Demagnetization Refrigerators

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

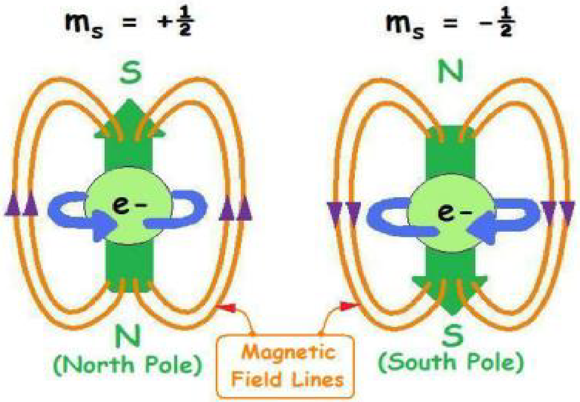
- A cooling technique involving:
  - Magnets
  - Entropy
  - Paramagnetic materials
- Generally mostly practical below 4 K.
- An Adiabatic Demagnetization Refrigerator (ADR) typically has:
  - A "salt pill"
  - A magnet
  - A heat sink
  - Thermal switches
  - Finally, the item to be cooled

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

Adiabatic Demagnetization Refrigerators

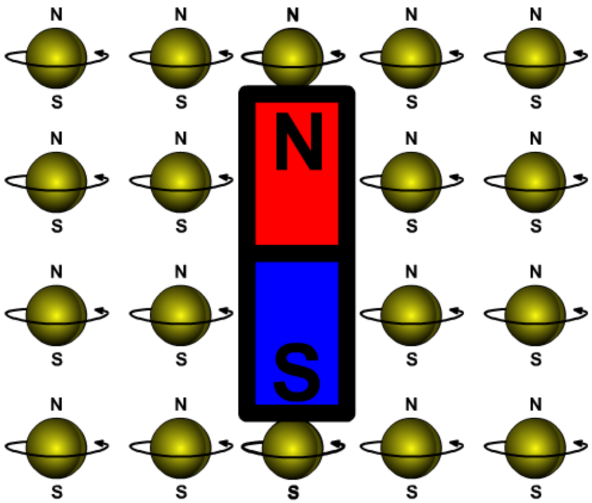
The Atom – Electron Spin

- **A spinning electron produces a magnetic field that makes the electron behave like a tiny magnet in an atom.**
- Opposite spins produce opposite magnetic fields that cancel. Therefore, most atoms have weak magnetic properties.
- But some atoms contain electrons that are not paired. These atoms tend to have strong magnetic properties.

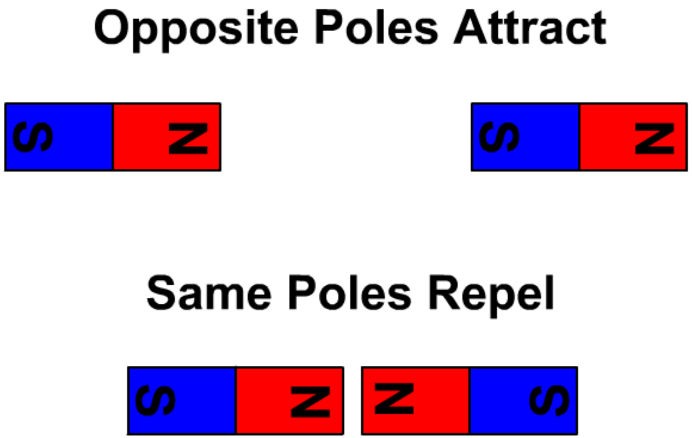


Source: https://www.slideserve.com/abedi/magnetism-2043617-powerpoint-ppt-presentation

Adiabatic Demagnetization Refrigerators, cont.



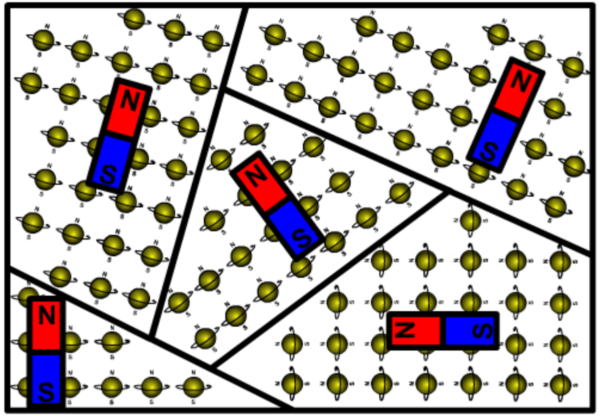
Ferromagnetic material: A type of material where almost every electron spins in the same direction, therefore the material as a whole exhibits strong magnetic properties

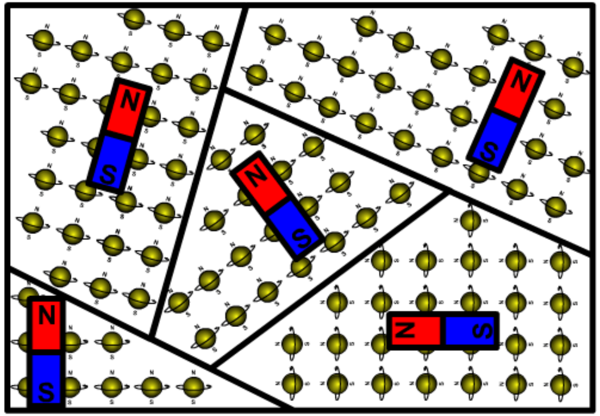


Magnet basics

Image sources: https://stickmanphysics.com/stickman-physics-home/magnets-and-magnetism/intro-to-magnetism/

Adiabatic Demagnetization Refrigerators, cont.



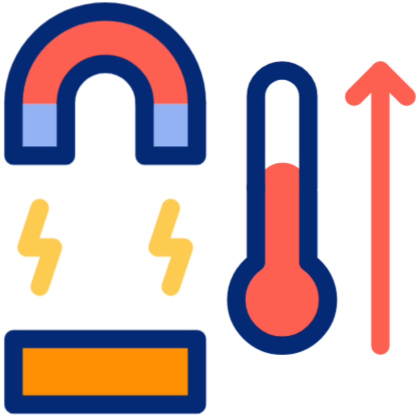


Materials which have mediocre magnetic properties really look like the above animation

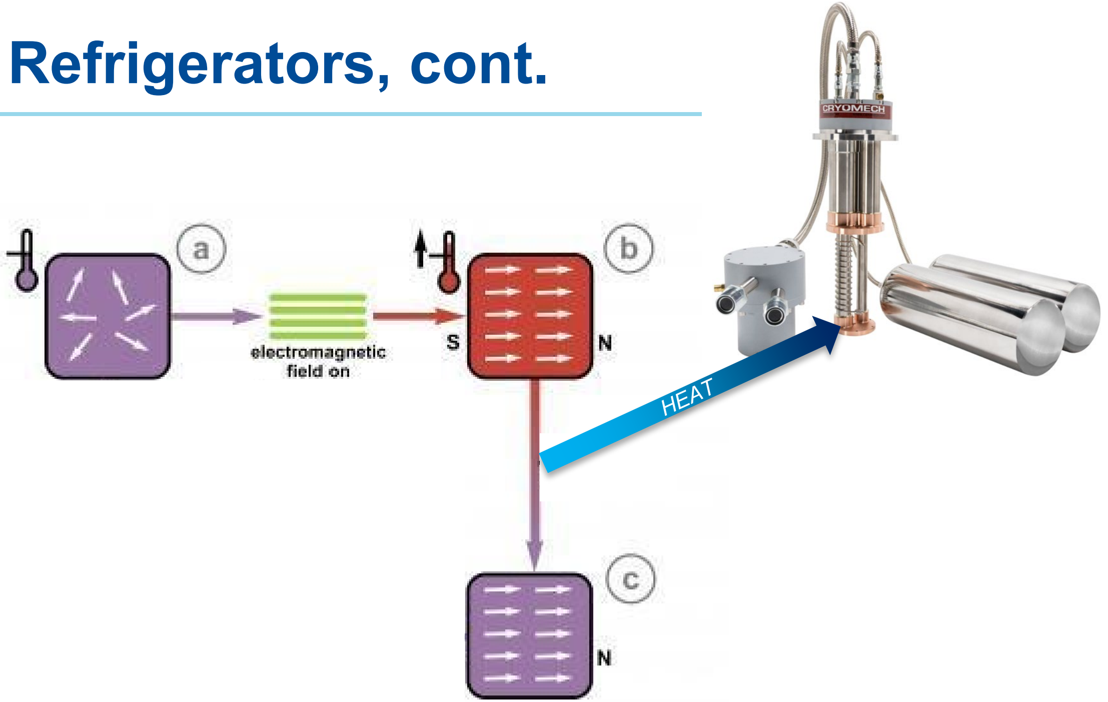
However, a special class of materials called paramagnetic materials can become “aligned” when an external magnetic field is applied. This “alignment” is temporary and disappears when the external magnetic field is removed.

Image sources: https://stickmanphysics.com/stickman-physics-home/magnets-and-magnetism/intro-to-magnetism/

Adiabatic Demagnetization Refrigerators, cont.



Magnetocaloric effect



Adiabatic Demagnetization Refrigerator cycle

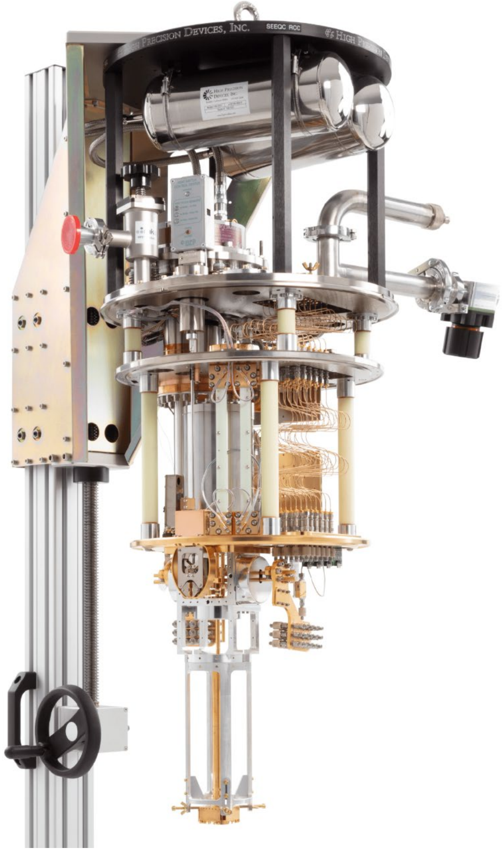
Image sources: flaticon.com, newenergyandfuel.com

Adiabatic Demagnetization Refrigerators, cont.

- The previous slide, expressed in words:
  - Step 1: The thermal switch is disconnected and the magnet is on.
    - As the magnetic field is increased, the magnetic regions in the solid align and the entropy of these regions decreases.
    - In order to keep the overall entropy constant, the entropy in the thermal vibrations increases (and thus the temperature increases).
  - Step 2: Next the thermal switch is connected and heat is transferred from the paramagnetic material to the heat sink while the magnetic field is held constant.
    - This reduces the temperature of the paramagnetic material back to its starting point.
  - Step 3: The thermal switch is now disconnected, isolating the paramagnetic material.
  - Step 4: The magnetic field is reduced.
    - The paramagnetic regions become disordered and absorb entropy from the thermal vibrations.
      - This results in the cooling of the paramagnetic material and of the object being cooled.

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025

Adiabatic Demagnetization Refrigerators, cont.



Danaher Cryo
Pursue the near impossible

System Specs

- 120 mJ at 100 mK cooling capacity
- ADR base temperature of 30 mK
- 250 hour no-load regulation at 100 mK
- FAA salt pill ~40 cc capacity

Image and slide sources: John Weisend II USPAS Cryogenic Engineering Course, 2025 and danahercryo.com

Fermilab Cryogenics Capabilities - mK Cryostats

- 8x Bluefors XLD1000 dilution refrigerators
  - One of these refrigerators has integral 9 T solenoid magnet
- Bluefors LD400 dilution refrigerator
- Oxford Instruments Triton XL dilution refrigerator with 14 T solenoid magnet
- HPD Model 103 Rainier ADR
- HPD Model 104 Olympus ADR
- Oxford Instruments Proteox MX dilution refrigerator
- 300 feet underground at the MINOS experimental hall:
  - CryoConcept HEXADRY UQT-B200 dilution refrigerator
  - Another Oxford Instruments Proteox MX dilution refrigerator (identical to above-ground example)
- 5,000 feet underground at SNOLAB (Canada)
  - Leiden Cryogenics LC-CF2500-Maglev-2PT dilution refrigerator
- Leiden Cryogenics CF-CS110-500 Maglev-1PT

Fermilab Cryogenics Capabilities - mK Cryostats, cont.

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The End!