SYSTEMS THINKING IN CHEMISTRY EDUCATION, STICE

CHEMISTRY TEACHERS' DAYS 2019

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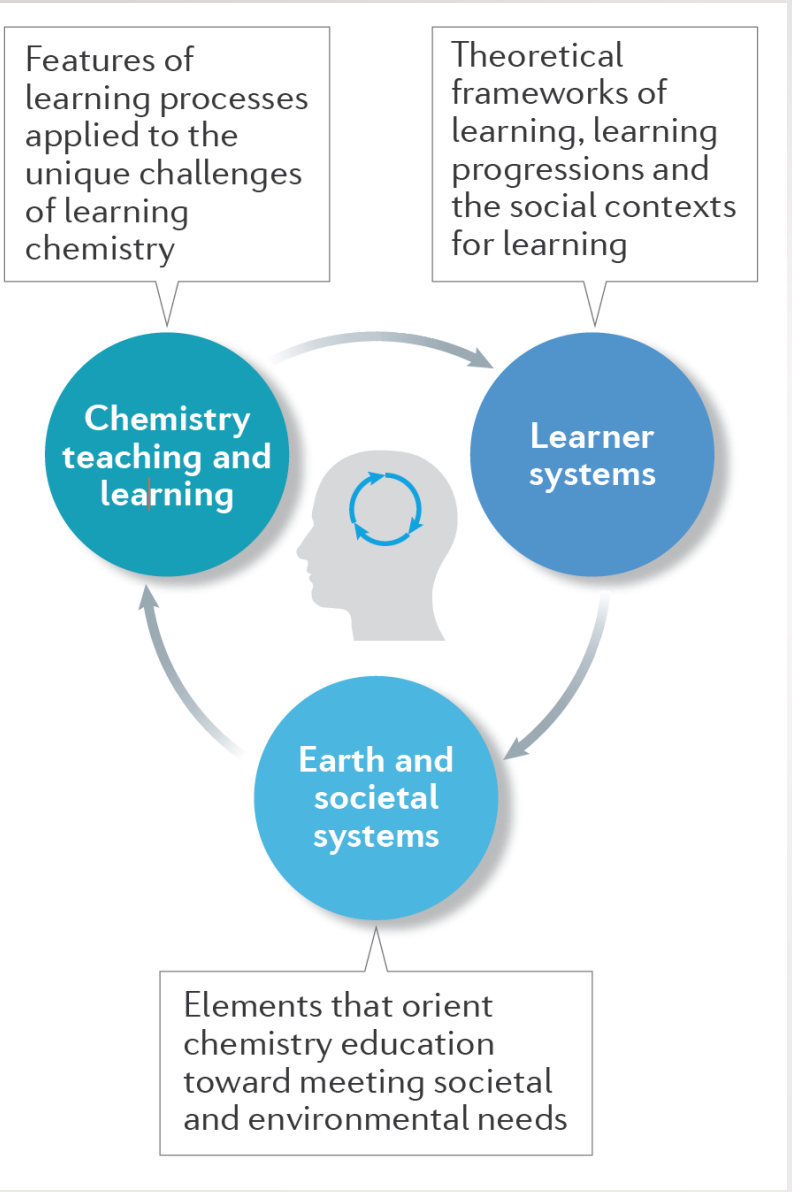
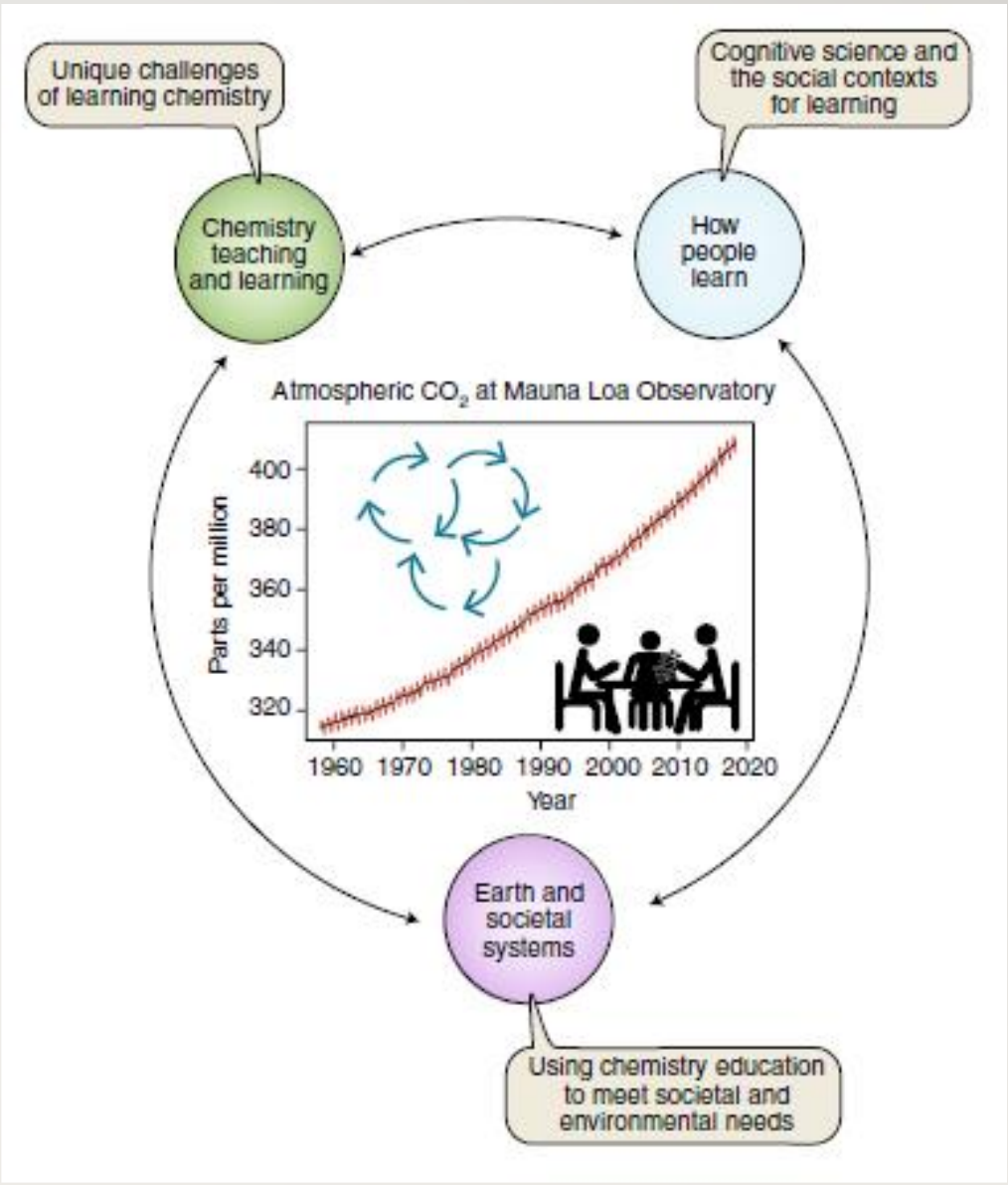
Systems Thinking in Chemistry Education

- An international project of IUPAC
- STICE is a framework with the goal of articulating learning objectives and strategies to infuse systems thinking into secondary and post-secondary chemistry education
- Places chemistry learners at the centre of a system of learning connected through 3 nodes or sub-systems
- 3 nodes interact and provide feedback to each other
- System of learning experienced by the students has emergent properties arising from these interactions


RUSSIA
CANADA
CHINA
INDIA
IRAN
LIBYA
EGYPT
SUDAN
KENYA
TANZANIA
SOMALIA
ANGOLA
NAMIBIA
INDIAN OCEAN
IUPAC
IOCD

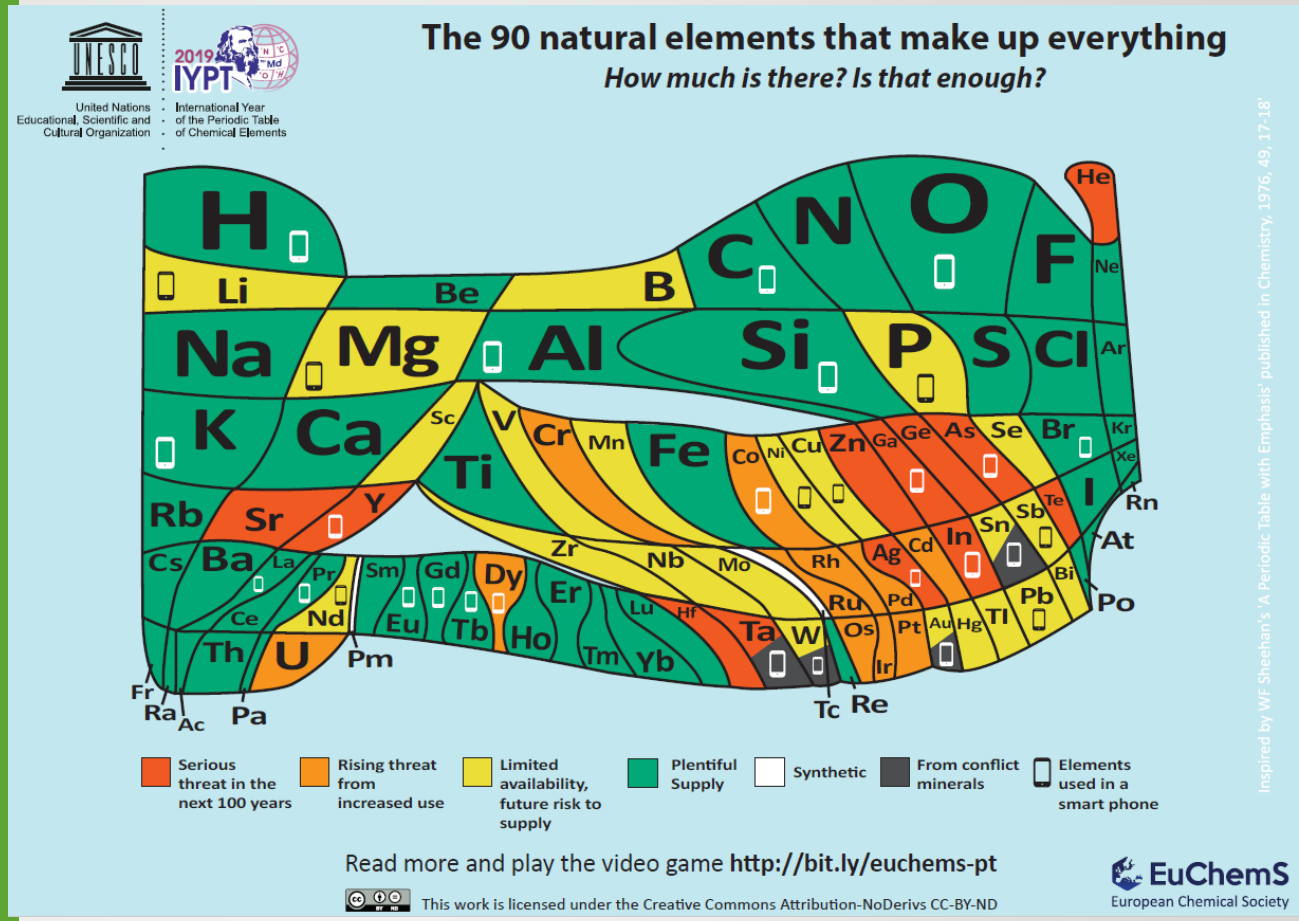

Features of learning processes applied to the unique challenges of learning chemistry
Theoretical frameworks of learning, learning progressions and the social contexts for learning
Chemistry teaching and learning
Learner systems
Earth and societal systems
Elements that orient chemistry education toward meeting societal and environmental needs


Unique challenges of learning chemistry
Cognitive science and the social contexts for learning
Chemistry teaching and learning
How people learn
Atmospheric CO_2 at Mauna Loa Observatory
Parts per million
400
380
360
340
320
1960 1970 1980 1990 2000 2010 2020
Year
Earth and societal systems
Using chemistry education to meet societal and environmental needs

Why Systems Thinking?

- Shift from reductionist to a more holistic approach
- Reductionist approach means that we understand complex systems by the analysis of their simpler components
- Successful in increasing scientific knowledge
- In education a reductionist approach (learning of discrete, unconnected facts out of context) is not consistent with how people learn.
- Understanding facts does not lead to an understanding of a discipline overall
- Students learn most meaningfully when they can connect what they learn to the context in which it applies.
- Reductionist approaches claim an objective view of science but ignore the human influence on how science is done and how data is interpreted

Endangered Elements – benefits and issues

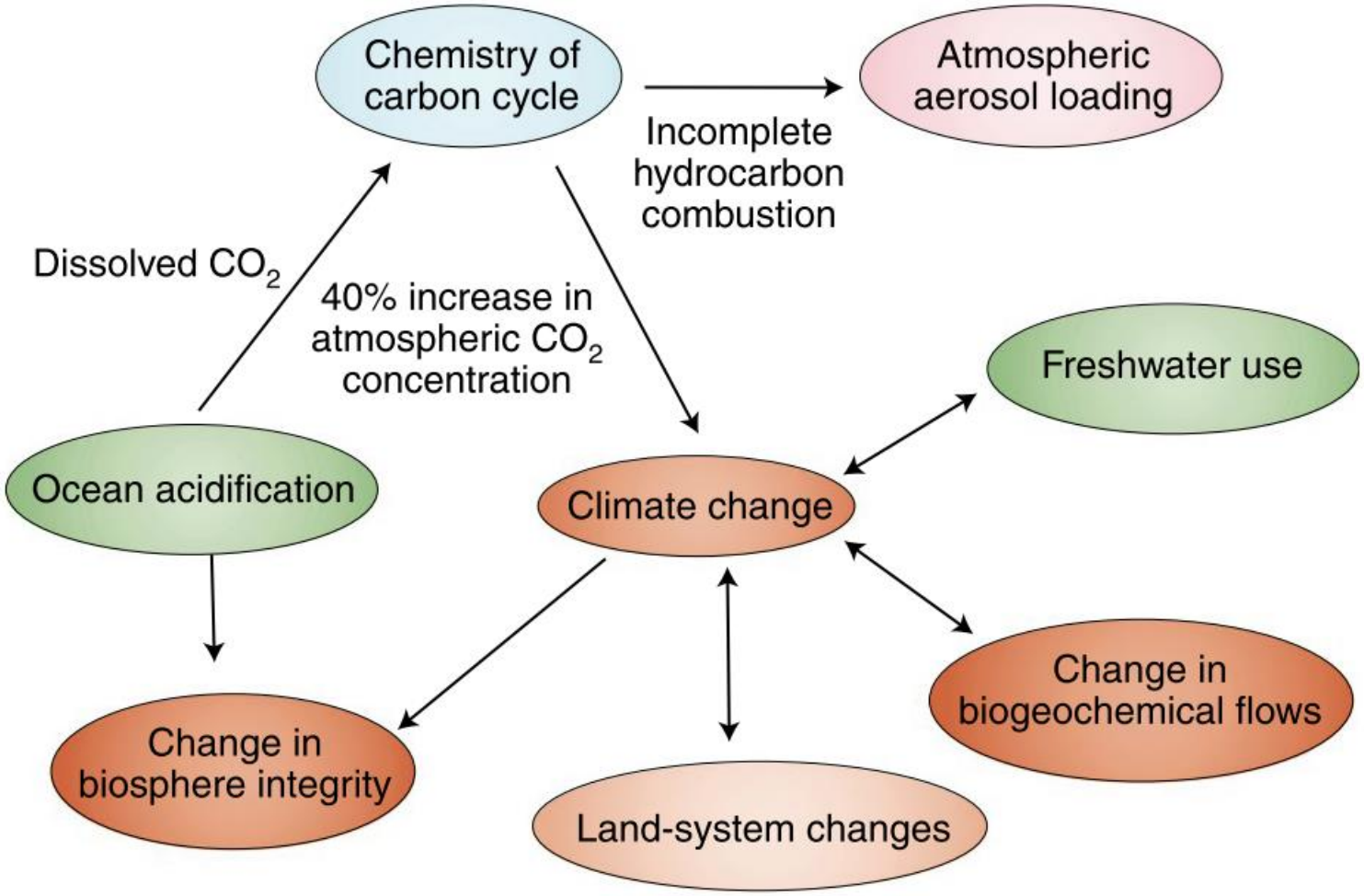


Periodic Table of Endangered Elements
(European Chemical Society, 2019)

Systems Thinking

- Complements reductionist approach
- Challenges facing mankind such as sustainability and climate change are global and holistic
- Chemists play central role in creation of new technologies but current practices of consumption are not sustainable
- Future chemists need to think holistically and systematically to maximise resource efficiency and minimise hazards and pollution
- Science research and learning informed by system thinking will focus on
  - The system as a whole not just a collection of parts
  - How a system changes over time
  - Variables that *cause* behaviours
  - Organisation and interrelationships between the parts of a system
  - How systems-level phenomena emerge from interactions between the system's parts
  - The interactions between a system and its environment

(Orgill et al., 2019)


Chemistry of carbon cycle
Atmospheric aerosol loading
Incomplete hydrocarbon combustion
Dissolved CO_2
40% increase in atmospheric CO_2 concentration
Freshwater use
Ocean acidification
Climate change
Change in biogeochemical flows
Change in biosphere integrity
Land-system changes

Definitions

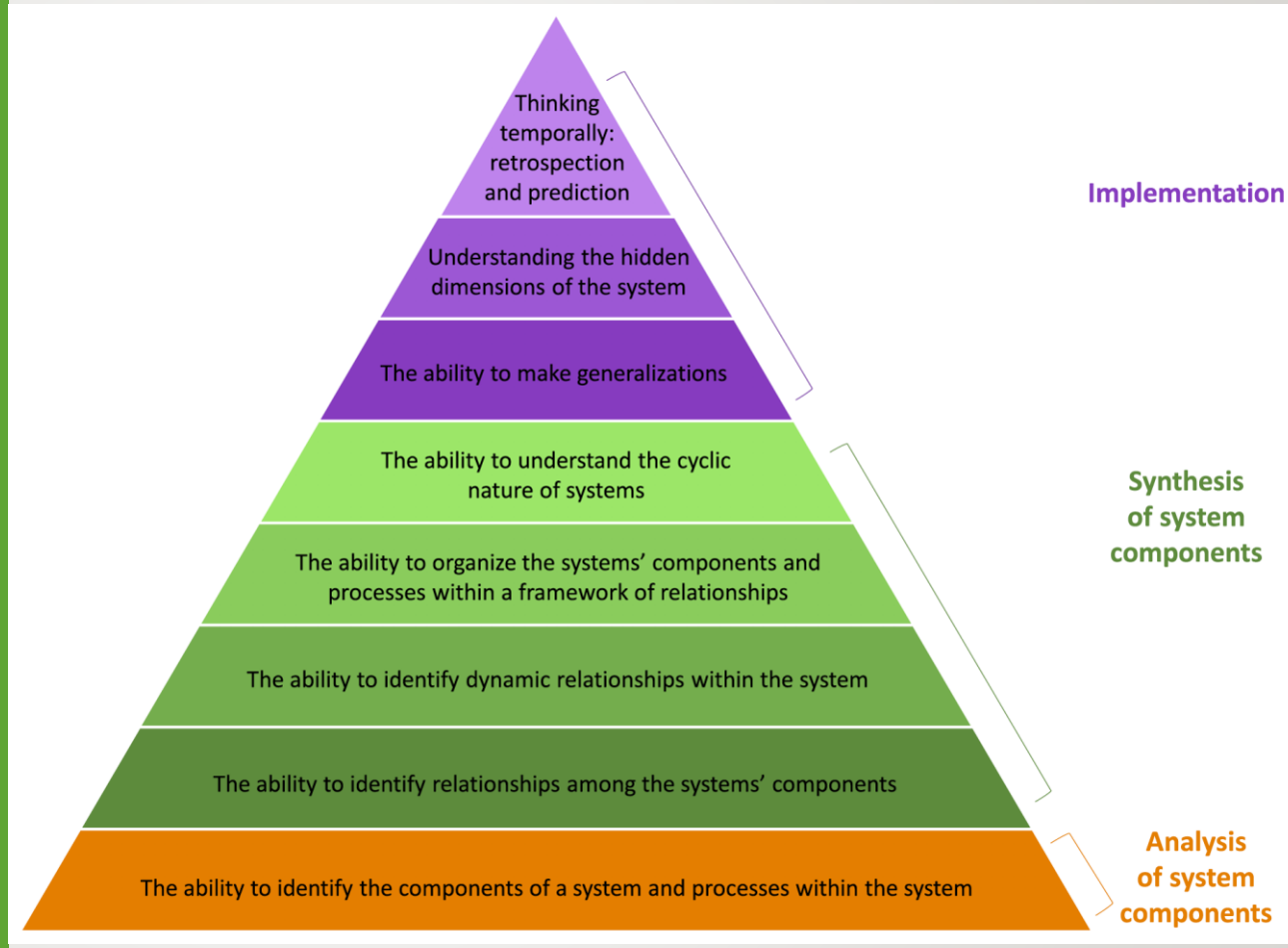
Systems

- exist at multiple scales (macro, micro etc)
- have purpose
- all parts must be present for a system to carry out its purpose
- order of arrangement affects performance of a system
- systems maintain stability through feedback

Systems thinking

- visualizes the interconnections and relationships between the parts of the system
- examines behaviour that changes over time
- examines how systems-level phenomena emerge from interactions between the system's parts

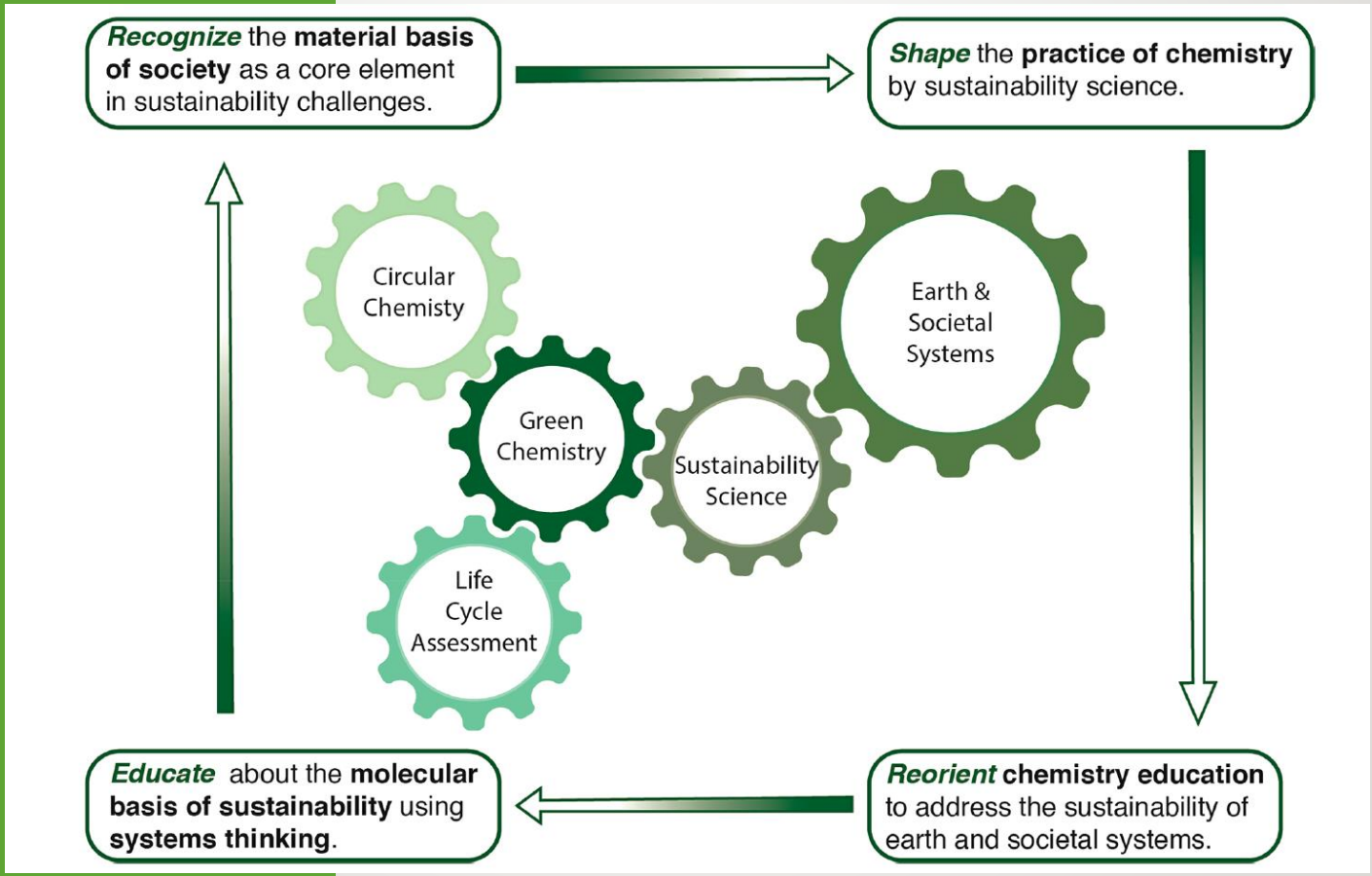
A systems thinking hierarchy



Orgill, M., York, S., & MacKellar, J. (2019). Introduction to Systems Thinking for the Chemistry Education Community. *Journal of Chemical Education*. doi: 10.1021/acs.jchemed.9b00169

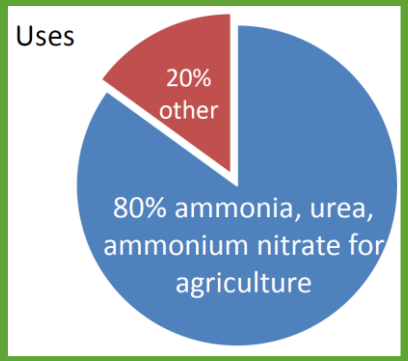
STICE - the molecular basis of sustainability

- Foregrounds Earth and Societal systems node
- "the ways in which the material basis of society and economy underlie considerations of how present and future generations can live within the limits of the natural word"



P.G. Mahaffy, S. A. Matlin, T. A. Holme, J. M. Whalen. *Integrating the molecular basis of sustainability into general chemistry through systems thinking*. **J. Chem Educ.** 2019

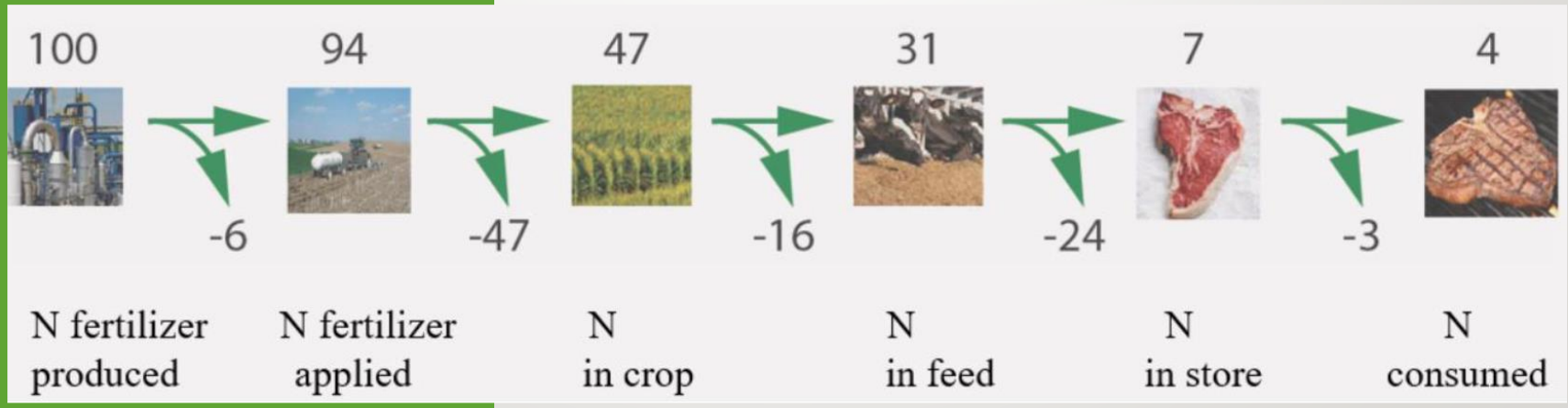
The most important technological invention of the 20th century?



$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$$

A failure of systems thinking in chemistry education??

- NH_3 synthesis in equilibrium chapter of textbooks (sanitised sidebar about Fritz Haber)
- Classroom treatment and assessment focuses on system responses to changing concentrations, temperature and pressures (including calculations)
- No connection usually made between chemical reaction and either the survival of 40% of our planet's human beings or the threat to our planetary boundaries of our massive fixed nitrogen footprint.

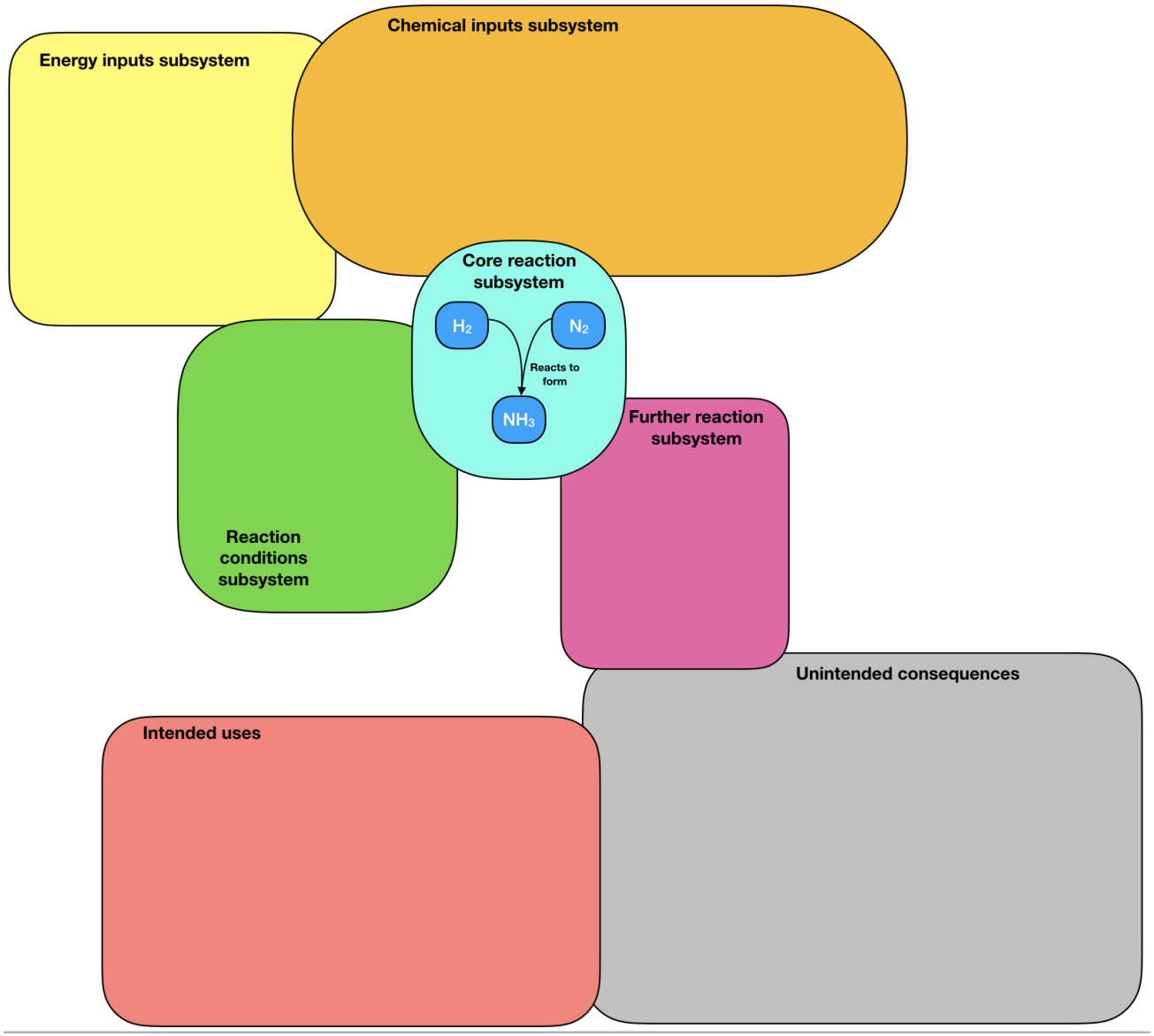


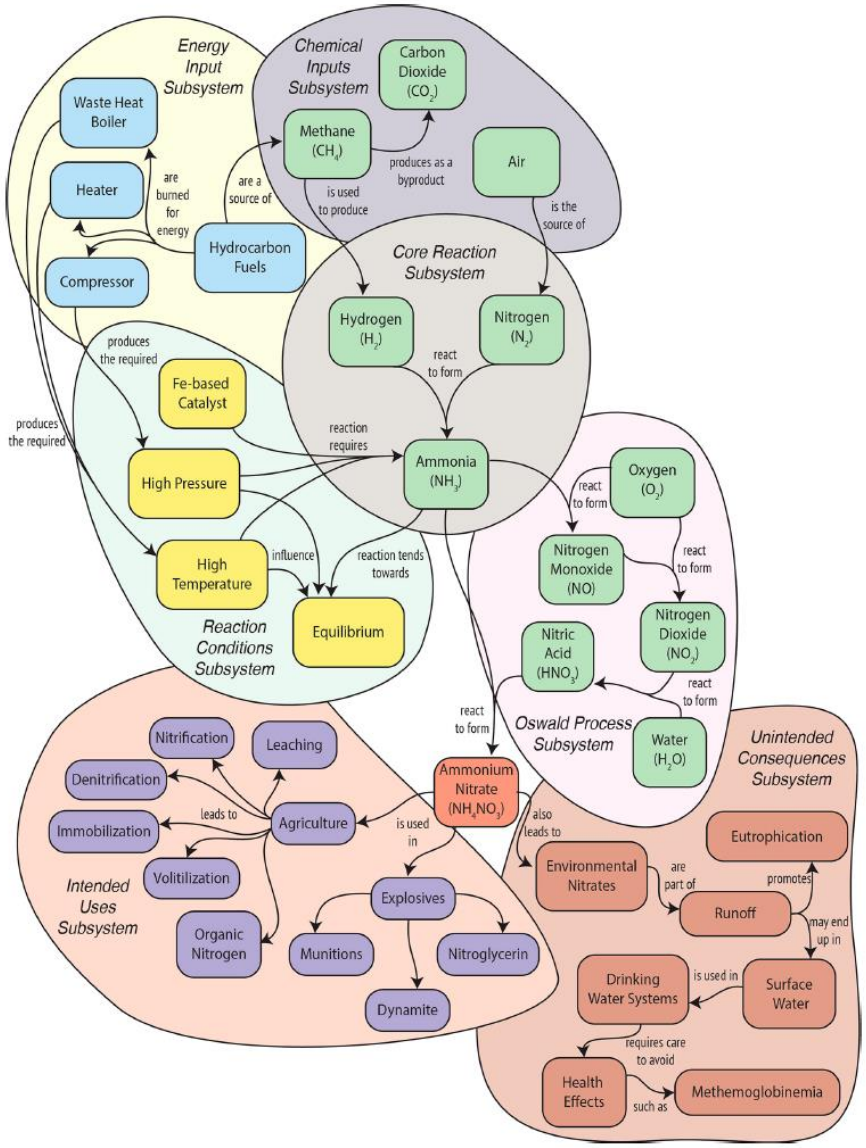
YOUR TASK

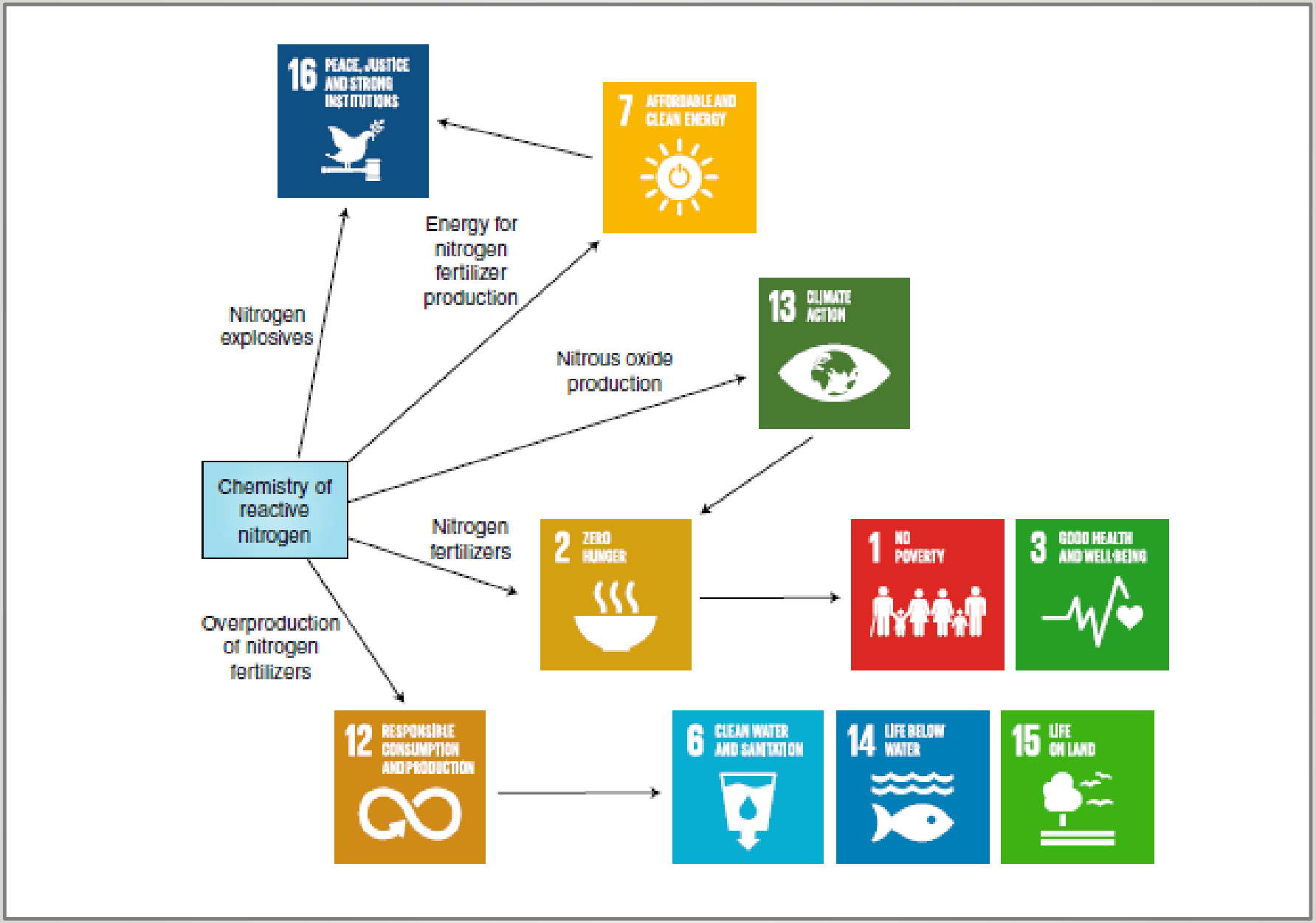
Generate a systems thinking map for the Haber process

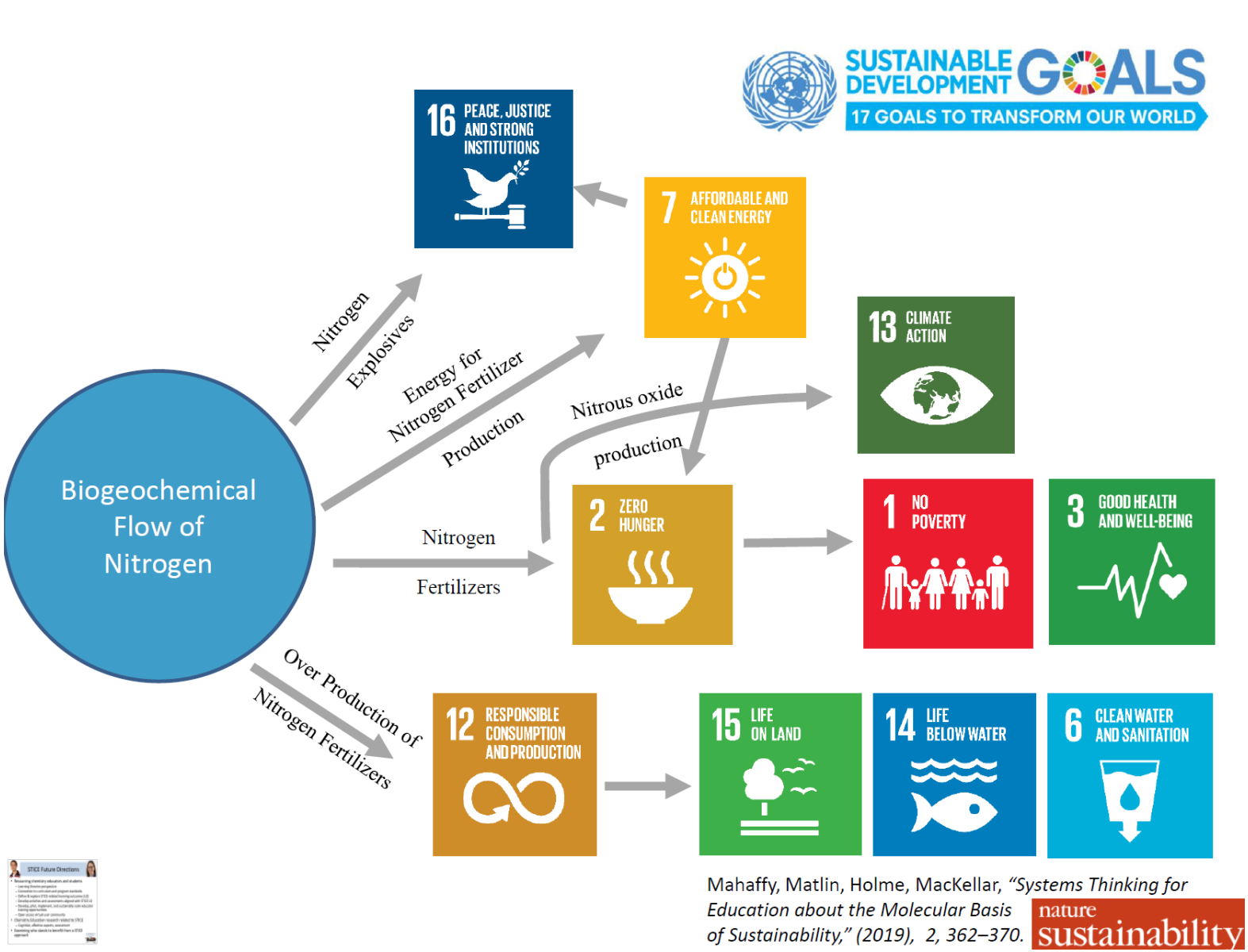
Some questions to ask:

- Where do the starting materials come from?
- What about the energy involved in production?
- What are the intended and unintended consequences of the use of the product?
- What happens to the product when it is no longer used?


Energy inputs subsystem
Chemical inputs subsystem
Core reaction subsystem
H_2
N_2
Reacts to form
NH_3
Reaction conditions subsystem
Further reaction subsystem
Unintended consequences
Intended uses


Energy Input Subsystem
Waste Heat Boiler
Heater
are burned for energy
Compressor
Hydrocarbon Fuels
are a source of
Chemical Inputs Subsystem
Carbon Dioxide (CO_2)
Methane (CH_4)
produces as a byproduct
Air
is used to produce
is the source of
Core Reaction Subsystem
Hydrogen (H_2)
Nitrogen (N_2)
react to form
Ammonia (NH_3)
reaction requires
produces the required
Fe-based Catalyst
High Pressure
High Temperature
influence
reaction tends towards
Equilibrium
Reaction Conditions Subsystem
Oswald Process Subsystem
Oxygen (O_2)
Nitrogen Monoxide (NO)
Nitrogen Dioxide (NO_2)
Nitric Acid (HNO_3)
Water (H_2O)
Ammonium Nitrate (NH_4NO_3)
Intended Uses Subsystem
Nitrification
Leaching
Denitrification
Immobilization
leads to
Agriculture
Volitilization
Organic Nitrogen
Explosives
Munitions
Nitroglycerin
Dynamite
Unintended Consequences Subsystem
also leads to
Environmental Nitrates
are part of
Runoff
Eutrophication
promotes
may end up in
Surface Water
Drinking Water Systems
is used in
requires care to avoid
Health Effects
such as
Methemoglobinemia

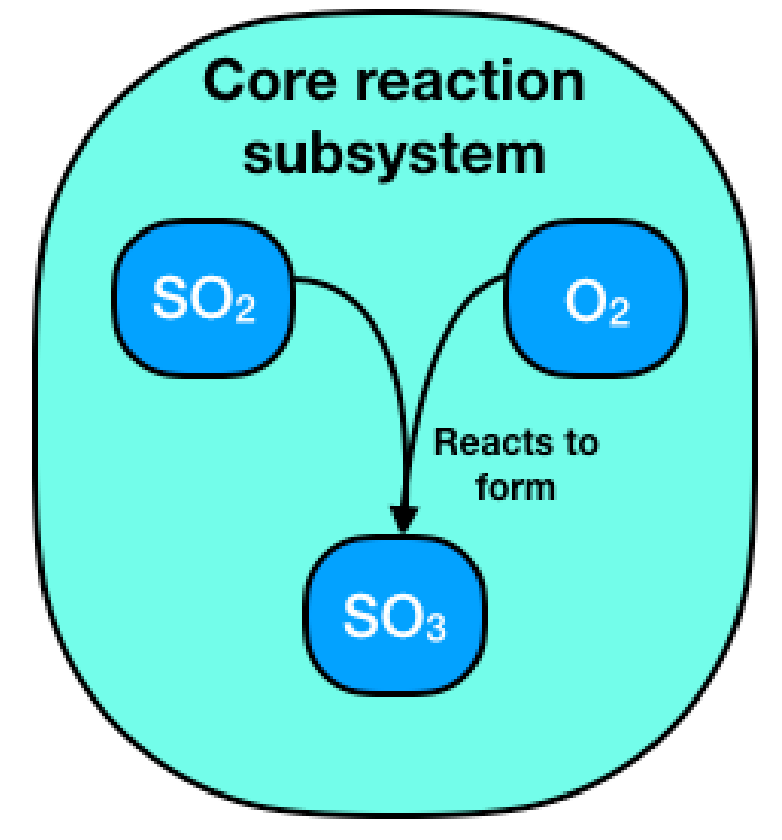

16 PEACE, JUSTICE AND STRONG INSTITUTIONS
7 AFFORDABLE AND CLEAN ENERGY
13 CLIMATE ACTION
2 ZERO HUNGER
1 NO POVERTY
3 GOOD HEALTH AND WELL-BEING
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
6 CLEAN WATER AND SANITATION
14 LIFE BELOW WATER
15 LIFE ON LAND
Chemistry of reactive nitrogen
Nitrogen explosives
Energy for nitrogen fertilizer production
Nitrous oxide production
Nitrogen fertilizers
Overproduction of nitrogen fertilizers



Mahaffy, Matlin, Holme, MacKellar, *"Systems Thinking for Education about the Molecular Basis of Sustainability," (2019), 2, 362–370.* nature sustainability

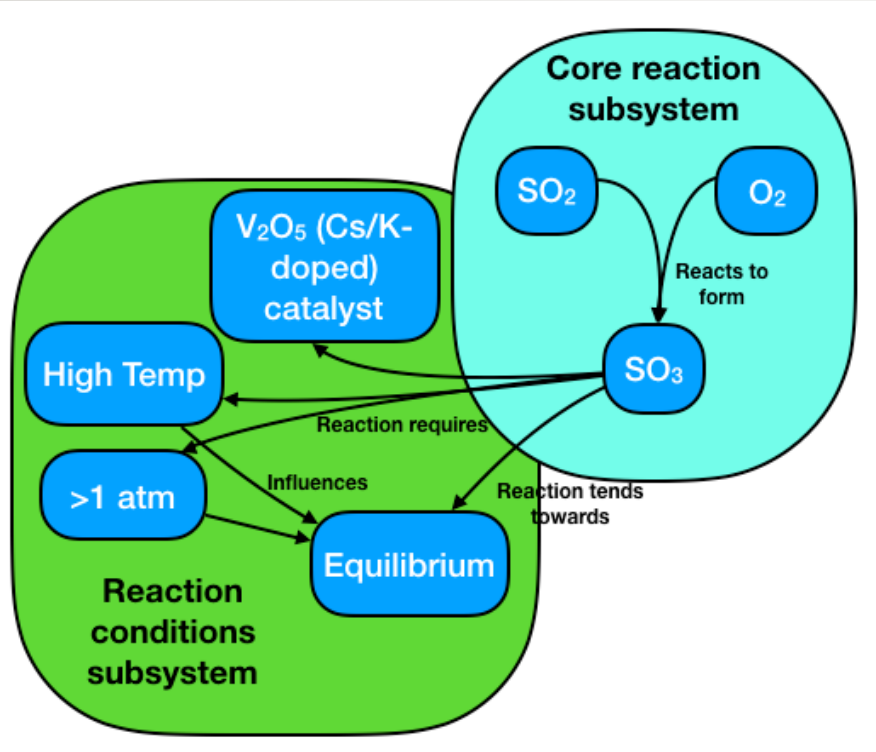
Systems Thinking Maps

- Using variant of systemigrams
  - Similar to concept maps, with a key distinction.
  - The goal is to explicitly incorporate the knowledge of boundaries on the stuff you are interested in (which is going to be a system)
  - Visualise the complexity and interactions across parts of a system, with minimal prose.
- Start with the 'the core'
  - Consider the systems inputs, and its outputs (consequences)
  - Then….what ask what happens as we change the boundaries on the system
  - Add in subsystems
    Where the starting materials come from
    Energy involved in production
    Intended and unintended consequences of the use of the product
    What happens to the product when it is no longer used



Systems Thinking Maps

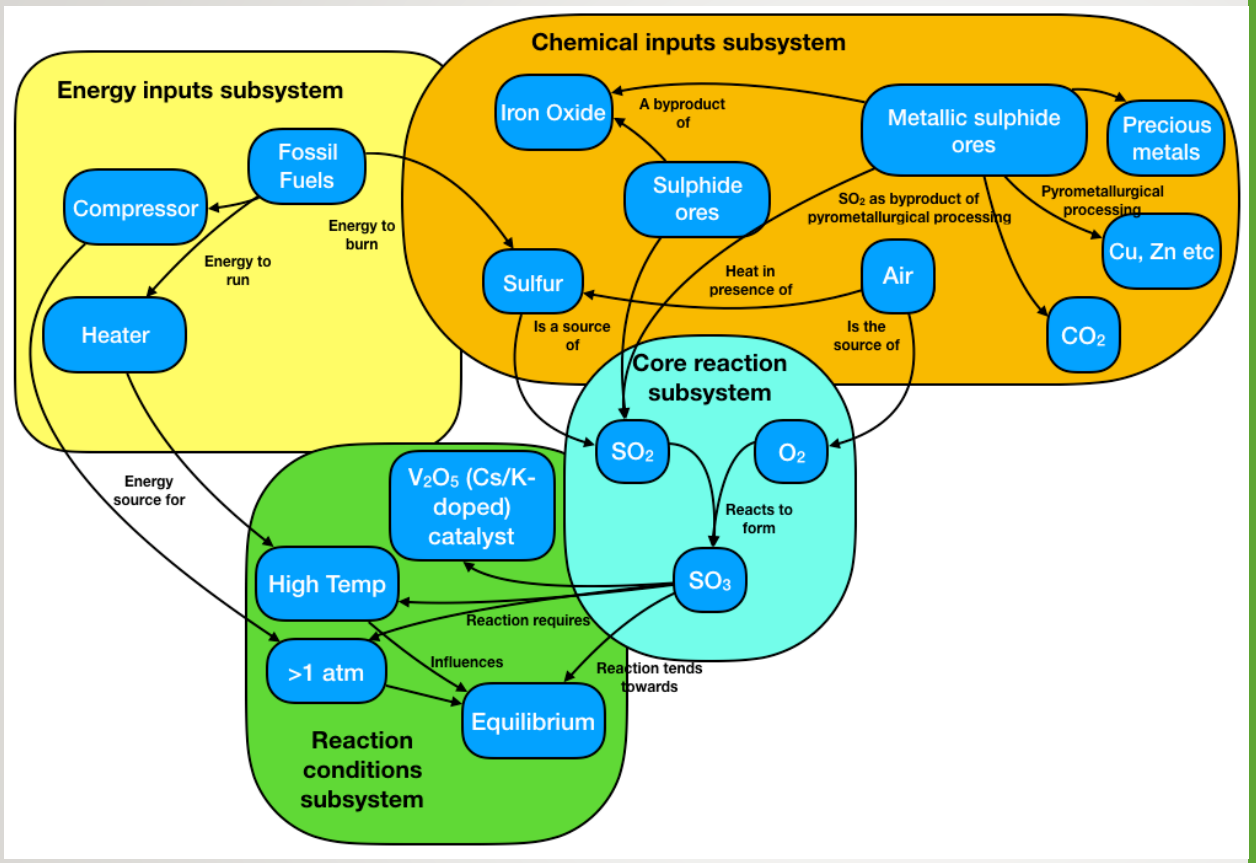
THE CORE:
Connecting with current content



Systems Thinking Maps

Add in subsystems:

Reaction conditions

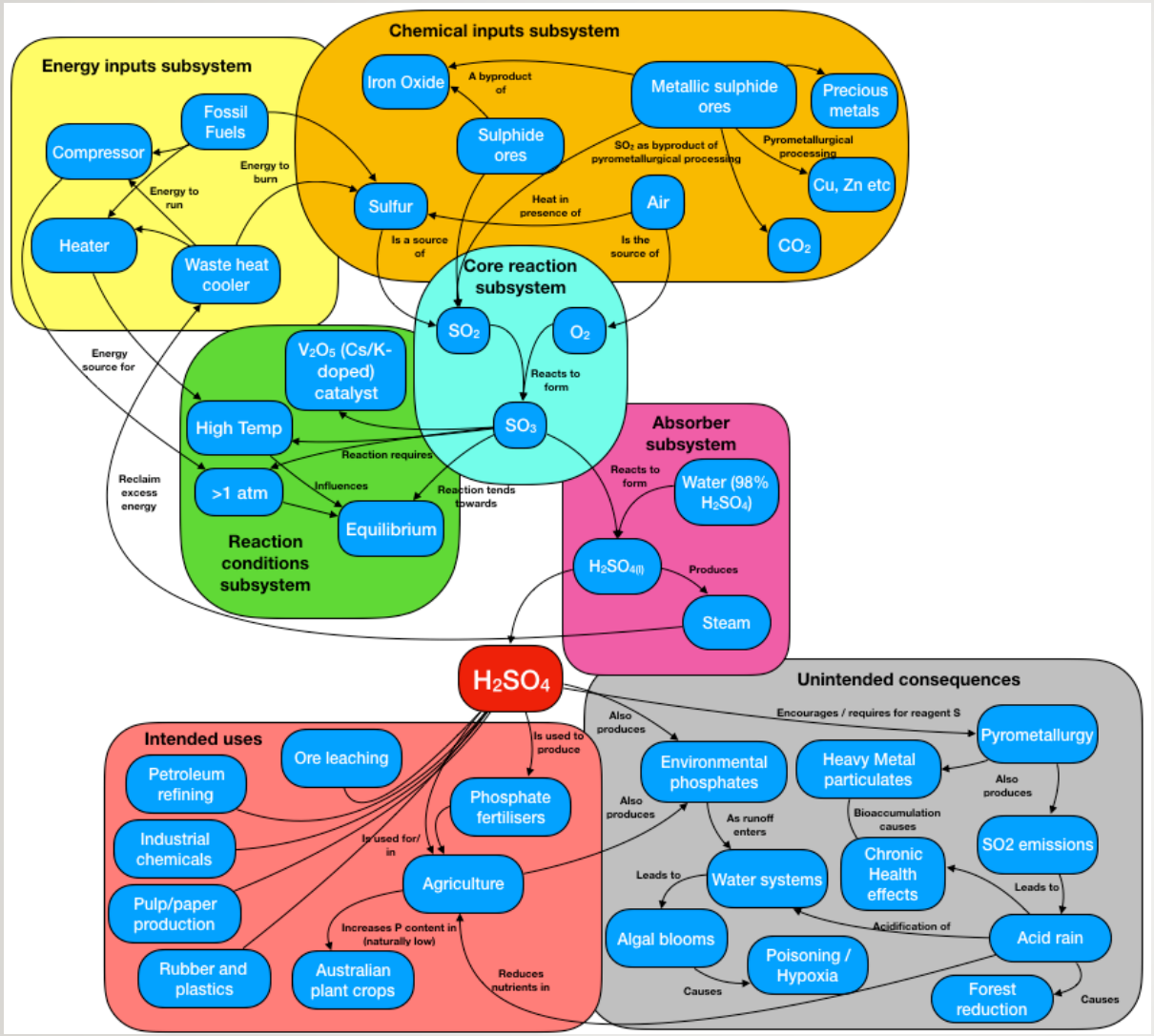


Systems Thinking Maps

Add in subsystems:

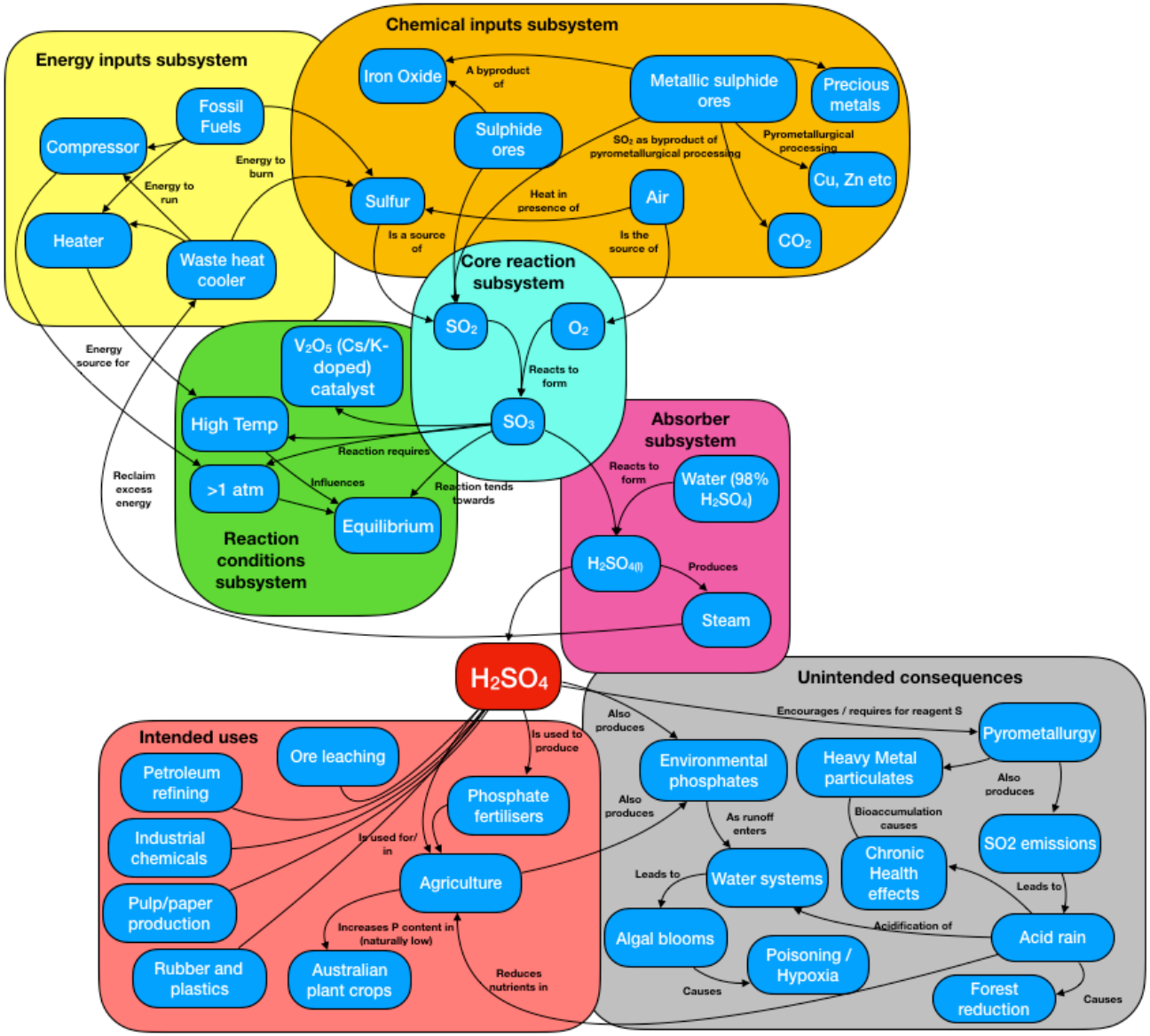
Where the starting materials come from

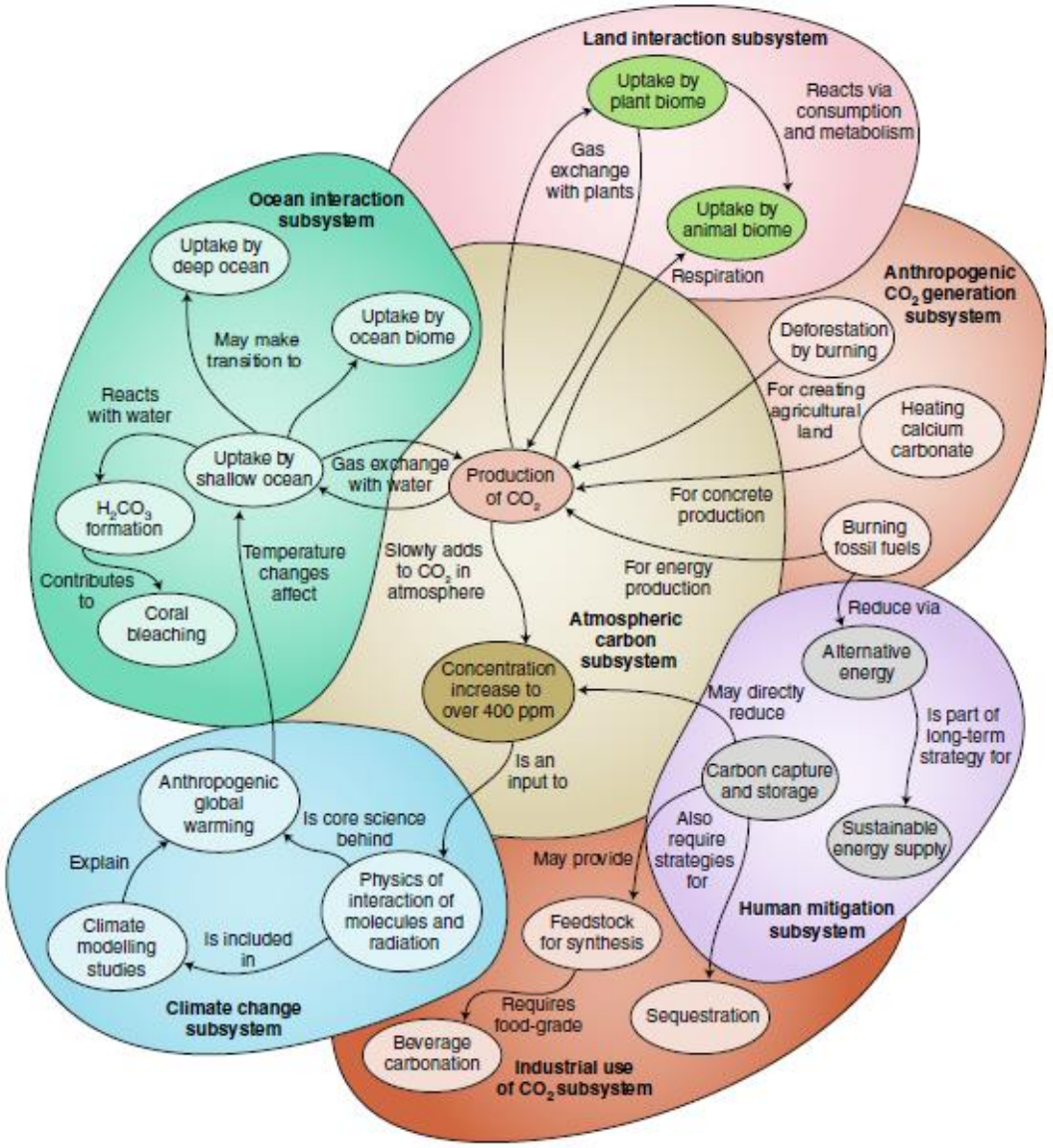
Energy involved in production



Systems Thinking Maps

Add in intended and unintended consequences


Energy inputs subsystem
Fossil Fuels
Compressor
Energy to run
Energy to burn
Heater
Waste heat cooler
Chemical inputs subsystem
Iron Oxide
A byproduct of
Metallic sulphide ores
Precious metals
Sulphide ores
SO_2 as byproduct of pyrometallurgical processing
Pyrometallurgical processing
Cu, Zn etc
Sulfur
Heat in presence of
Air
CO_2
Is a source of
Is the source of
Core reaction subsystem
SO_2
O_2
Reacts to form
SO_3
Energy source for
V_2O_5 (Cs/K-doped) catalyst
High Temp
Reaction requires
Reclaim excess energy
>1 atm
Influences
Reaction tends towards
Equilibrium
Reaction conditions subsystem
Absorber subsystem
Reacts to form
Water (98% H_2SO_4)
$H_2SO_{4(l)}$
Produces
Steam
H_2SO_4
Unintended consequences
Also produces
Encourages / requires for reagent S
Pyrometallurgy
Environmental phosphates
Heavy Metal particulates
Also produces
Also produces
As runoff enters
Bioaccumulation causes
SO2 emissions
Chronic Health effects
Leads to
Water systems
Leads to
Acidification of
Acid rain
Algal blooms
Poisoning / Hypoxia
Causes
Forest reduction
Causes
Intended uses
Ore leaching
Is used to produce
Petroleum refining
Phosphate fertilisers
Industrial chemicals
Is used for/ in
Agriculture
Pulp/paper production
Increases P content in (naturally low)
Rubber and plastics
Australian plant crops
Reduces nutrients in


Land interaction subsystem
Uptake by plant biome
Reacts via consumption and metabolism
Gas exchange with plants
Uptake by animal biome
Respiration
Ocean interaction subsystem
Uptake by deep ocean
Uptake by ocean biome
May make transition to
Reacts with water
Uptake by shallow ocean
Gas exchange with water
Production of CO_2
H_2CO_3 formation
Contributes to
Coral bleaching
Temperature changes affect
Slowly adds to CO_2 in atmosphere
Atmospheric carbon subsystem
Concentration increase to over 400 ppm
Is an input to
Anthropogenic CO_2 generation subsystem
Deforestation by burning
For creating agricultural land
Heating calcium carbonate
For concrete production
Burning fossil fuels
For energy production
Reduce via
Alternative energy
May directly reduce
Is part of long-term strategy for
Carbon capture and storage
Also require strategies for
Sustainable energy supply
Human mitigation subsystem
Anthropogenic global warming
Is core science behind
Explain
Physics of interaction of molecules and radiation
Climate modelling studies
Is included in
Climate change subsystem
May provide
Feedstock for synthesis
Requires food-grade
Beverage carbonation
Sequestration
Industrial use of CO_2 subsystem

What is the place of STICE in the future of chemistry education in NZ?