ASTR 380
Terraforming Other Planets

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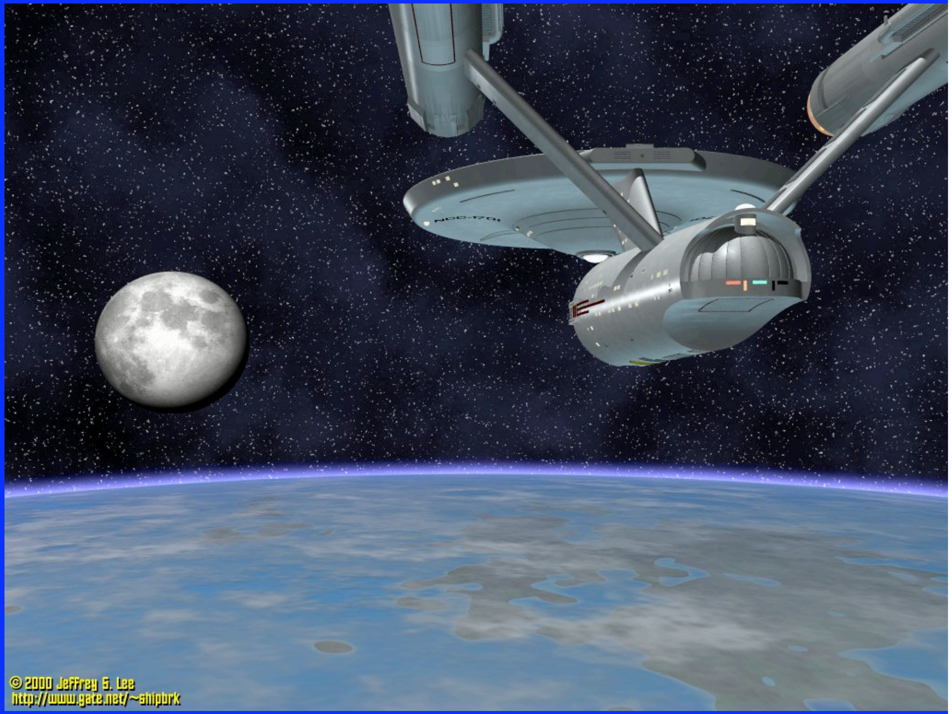
Outline

- Definitions and context
- Terraforming Mars
- The far future

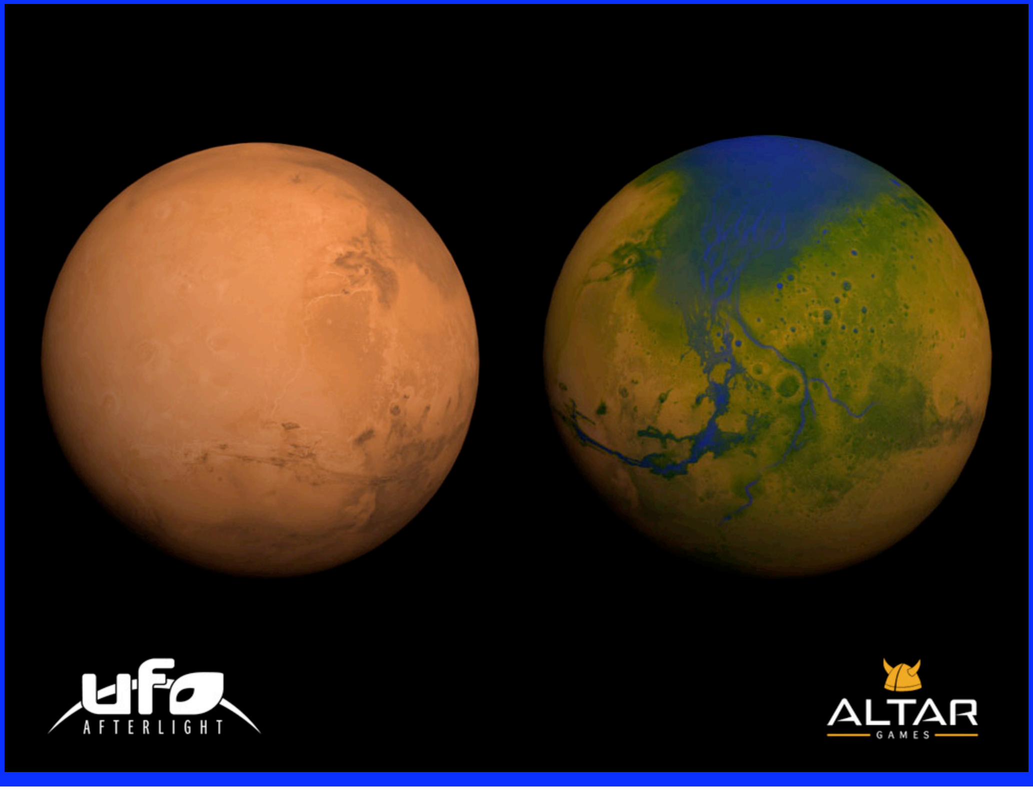
Habitable Planet

- “Class M” planets of Star Trek
- Basically, step on, take a satisfying breath, and start colonizing!
- Don’t know how common these are



Biocompatible Planet

- Planet with physical parameters to be habitable
- Doesn’t have to be life on it now
- Classic example: Mars, which we will now consider in detail




Terraforming
Mars
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Goals of Terraforming

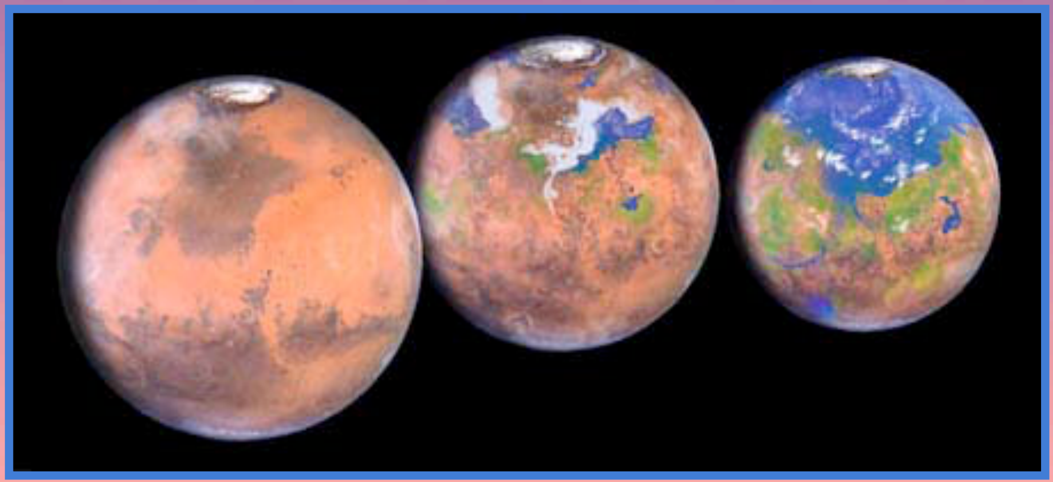
- A planet that supports life from Earth:
  - Temperatures approx. 0±40°C
  - Abundant liquid water
  - Breathable air
  - Fertile soil that supports plant growth
  - Sunlight
- Walk on the surface without a spacesuit.

Why Mars?

- Not too far from the Sun
- Approx. 24 hour diurnal cycle
- Not excessively cold (-140°C .. 20°C, avg -63°C)
- Has water, CHNOPS, metals
- Has seasons like Earth
- Can hold an atmosphere
- Because we think we can

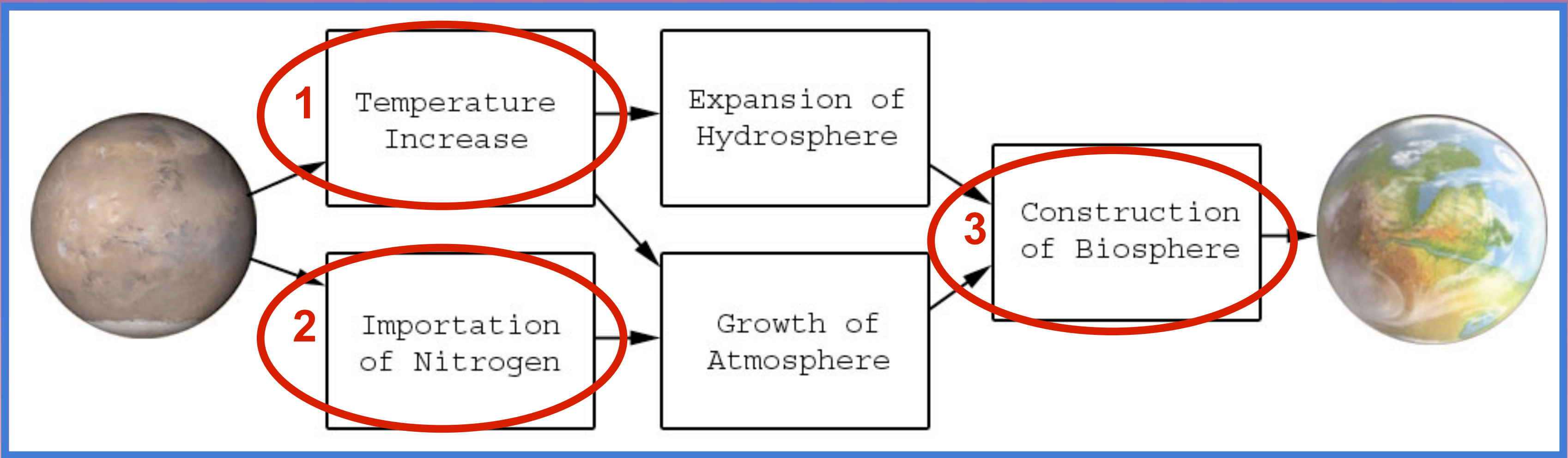
Usual Approach

- Warm Mars by several degrees.
- CO_2 and water vapour sublime from polar caps and regolith.
- Greenhouse effect warms planet further, releasing more CO_2 and water vapour, generating more heat and so on: "**runaway greenhouse**".
- Liquid water becomes more prevalent on the surface.
- Introduce life. Photosynthetic organisms convert CO_2 into O_2.
- Eventually atmosphere and temperature suitable for animals, including humans.



Flowchart

- Goal is a self-regulating equilibrium, probably best achieved by a well-designed, stable, global biosphere.
- Note addition of N_2 importation – to be discussed.
- 3 primary planetary engineering tasks:



Task 1:

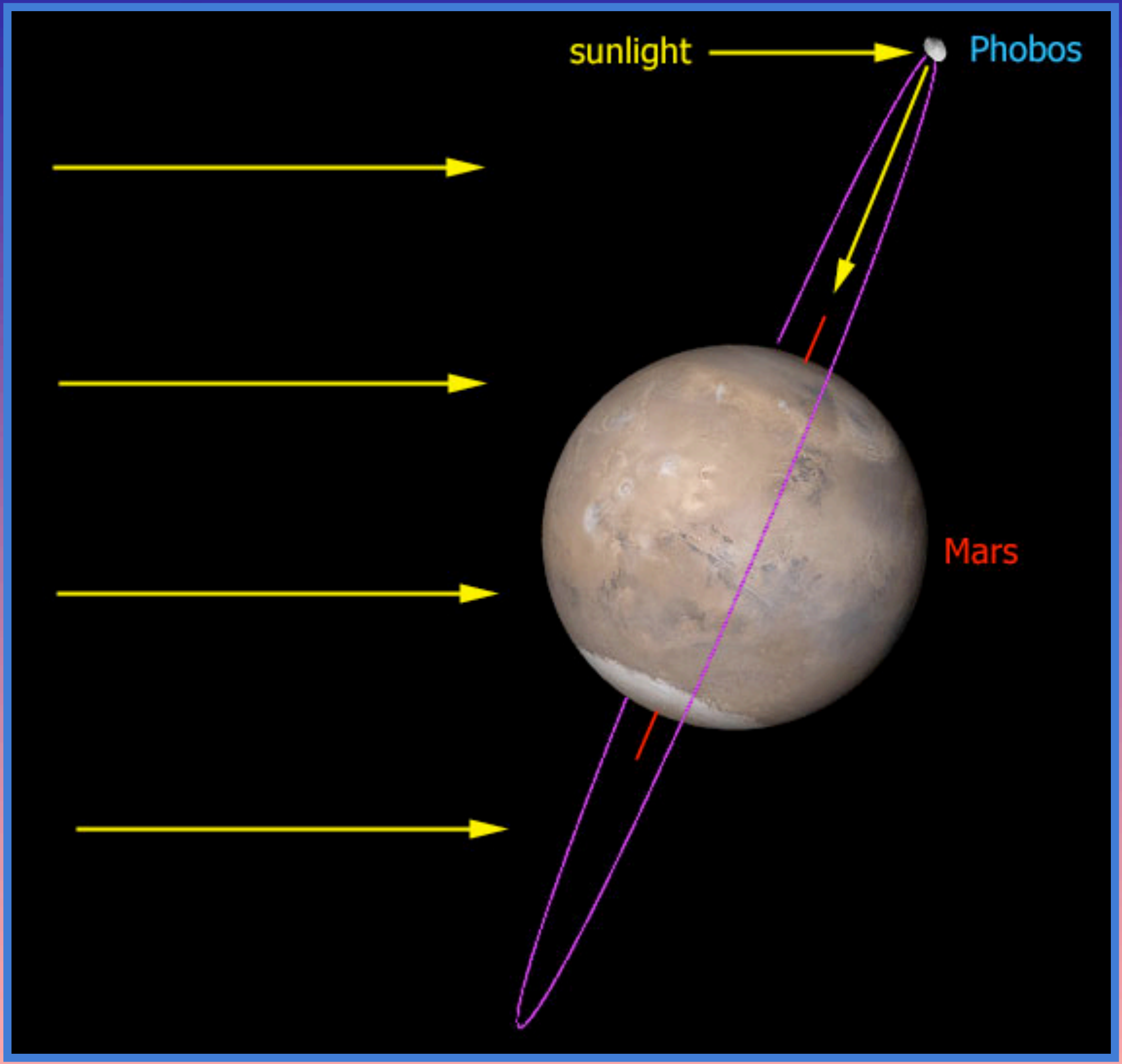
Increasing Temperature

- Bulk of T increase comes from greenhouse effect.
- Some initial warming required to kick-start.
- Popular ideas:
  - Space-based mirrors
  - Greenhouse gases
  - Albedo reduction

The New Phobos: Mars's 2nd Sun

- Phobos's orbit in decay.
- Move Phobos into a higher, stable orbit. Repositioning minor planets already examined in context of NEOs.
- *Better yet*, move Phobos into a stable *polar* orbit, and cover its near side with array of mirrors.
- Sunlight reflected down onto both poles ~3 times per day, all year round. Triggers sublimation of CO_2 and water vapour.
- Each mirror on a 2-axis mount, computer-controlled to track the Sun. Solar-powered system.
- Phobos only 22km diameter, but could extend mirror array wider by building a framework into space.
- **Primary advantage:** Phobos provides a source of material for mirror fabrication, e.g. Fe, Al
- Phobos appears like a second sun with half diameter of Sol, travelling from N to S.

Phobos Mirror



Greenhouse Gases

- CFCs excellent GHG, but short-lived in high-UV, also ozone-depleting.
- PFCs much longer-lived, 6500-9200 times more effective than CO_2 and non O_3-depleting. Could build PFC factories.
- O_3 good greenhouse gas which increases with O_2 levels, and also needed to provide radiation protection.
- NH_3 obtainable from asteroids.
- **Methane:** CH_4 is 23 times more effective GHG than CO_2
  - Cheap: can be produced industrially from H_2 and CO_2 (ISPP).
  - Can also be manufactured biologically.
  - Non-toxic and increases ozone production.

Introduce Methanogens

- Extremophilic methanogens could be engineered to live on Mars and produce methane. Stage 1 of biosphere.
- Subsurface first (chemotrophic), surface later (phototrophic).
- Might already be there. CH_4 in Martian atmosphere is a clue.
- If so, extant organisms could be made more prolific *and/or*, might spread as planet warms and more H_2O.
- Methanogens are anaerobic and will die out as O_2 levels rise, unless new strains are engineered.

Albedo Reduction

- Prev suggestions:
  - Dark-coloured algae/lichen.
  - Spreading black dust on poles – unfeasible in Martian winds.
- Longer-term solution:
  - Engineer plants with dark-green leaves.
  - Can offset T drop as CO_2 levels decrease.

Summary: Warming

- 1. Phobos mirrors. Triggers global warming.
- 2. Early biosphere: methanogens.
- 3. Long-term warmth: plants with dark-green leaves; also *aerobic methanogens*.

Task 2: Atmosphere Engineering

- Mars's atmosphere almost wholly CO_2, small amounts of N_2 and Ar, trace elements of other gases.
- However, very thin: only ~0.8kPa.
- Ideally, terraformed atmo will be like Earth's: 79kPa N_2, 21kPa O_2. What's the minimum?
- Require at least 16kPa O_2 = minimum safe breathable partial pressure of oxygen.
- Equivalent to altitude of about 3km on Earth. (About 20% of newcomers would experience altitude sickness.)
- O_2 manufactured from CO_2 by photosynthetic organisms.

Nitrogen

- Mars has only 2.7% atmospheric N_2 and unknown quantities of other N compounds.
- Importance of N_2 frequently overlooked by terraformers.
- Nitrogen fundamental to all DNA-based life, component of amino acids & nucleic acid bases. Probably insufficient nitrogen for planet-wide biosphere.
- On Earth, N_2 also serves as a buffer gas, reducing oxygen toxicity, fires and corrosion. O_2 levels higher than 35% cause spontaneous combustion of biosphere.
- We need more N_2 .

How Much Nitrogen?

- Need approx. *at least* twice as much buffer gas as O_2 to prevent fires, i.e. 32kPa.
- Noble gas (e.g. He, Ne, Ar)? N_2 is much easier to source, plus required by biosphere.
- Total minimum surface pressure for 2:1 N_2/O_2 atmo is ~48kPa (less than half Earth's). A 3:1 mix (64kPa) would be better, 4:1 best.
- (For H&S, keep thickening atmosphere beyond terraforming goals until same as Earth.)
- Bare minimum atmosphere:
  - O_2: 6.85×10^{17} kg
  - N_2: **1.2×10^{18} kg**

Where to get all this N_2?

- 3 options:
  - Earth
  - Venus
  - Titan
- Earth – unlikely, probably cause global climate change.
- Venus – close, but requires separation of 3.5% N_2 from 96.5% CO_2. (This option better if simultaneously terraforming Venus.)
- Titan – atmo 98.4% N_2, remainder CH_4 (which we like). Far away, but robotic atmosphere-mining tankers would have simple design. Just fly through atmo and fill the tanks.

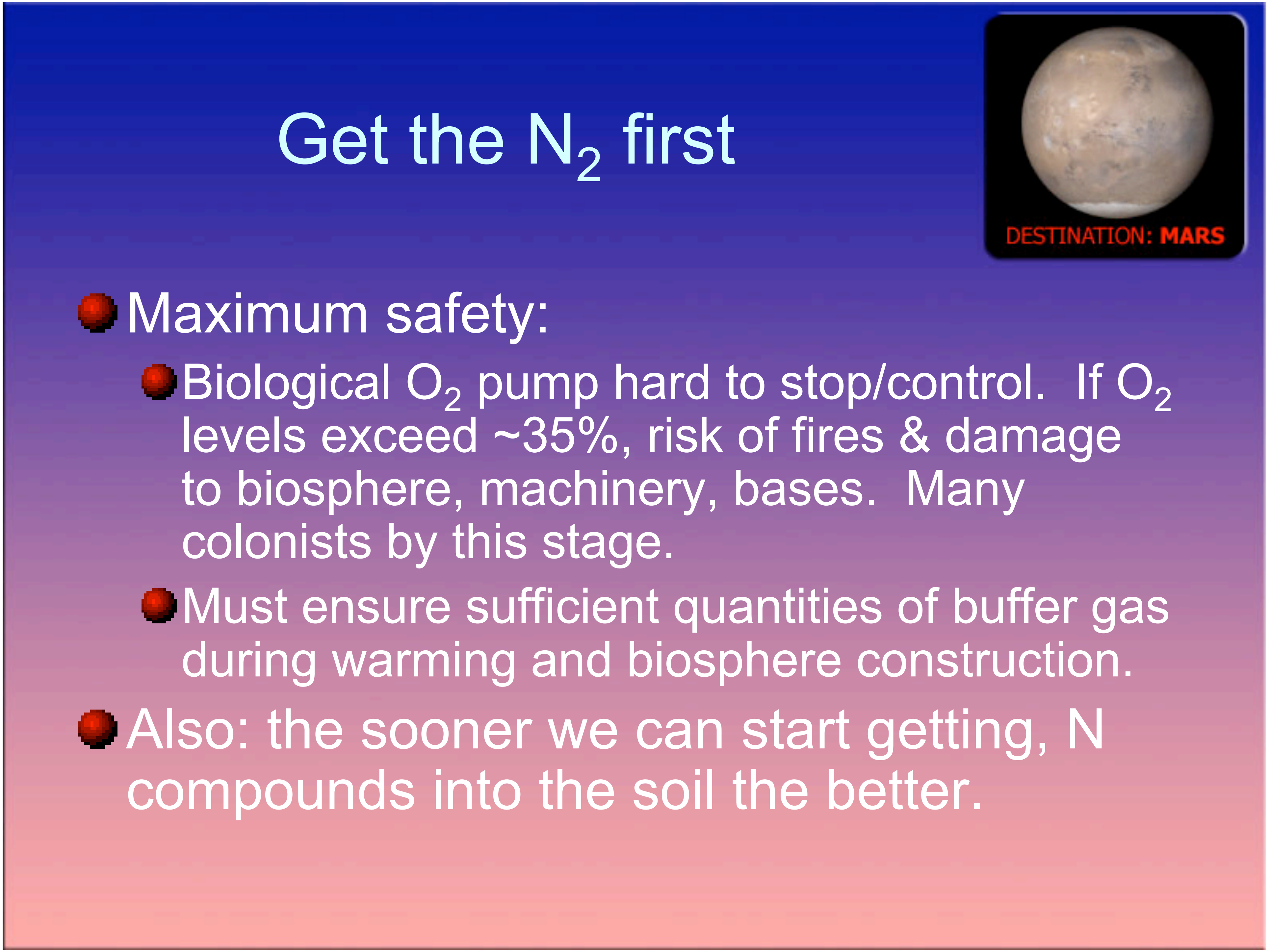
Mining Titan's Atmosphere

- Titan's atmo contains approx. $9x10^{18}$ kg N_2 and we want $1.2x10^{18}$ kg N_2, so we are talking about transporting about ~13% of it to Mars.
- How long will it take?
- Let's say, 1st year we build 5 spherical tankers with r=100m. Est. round-trip to Titan = 10y.

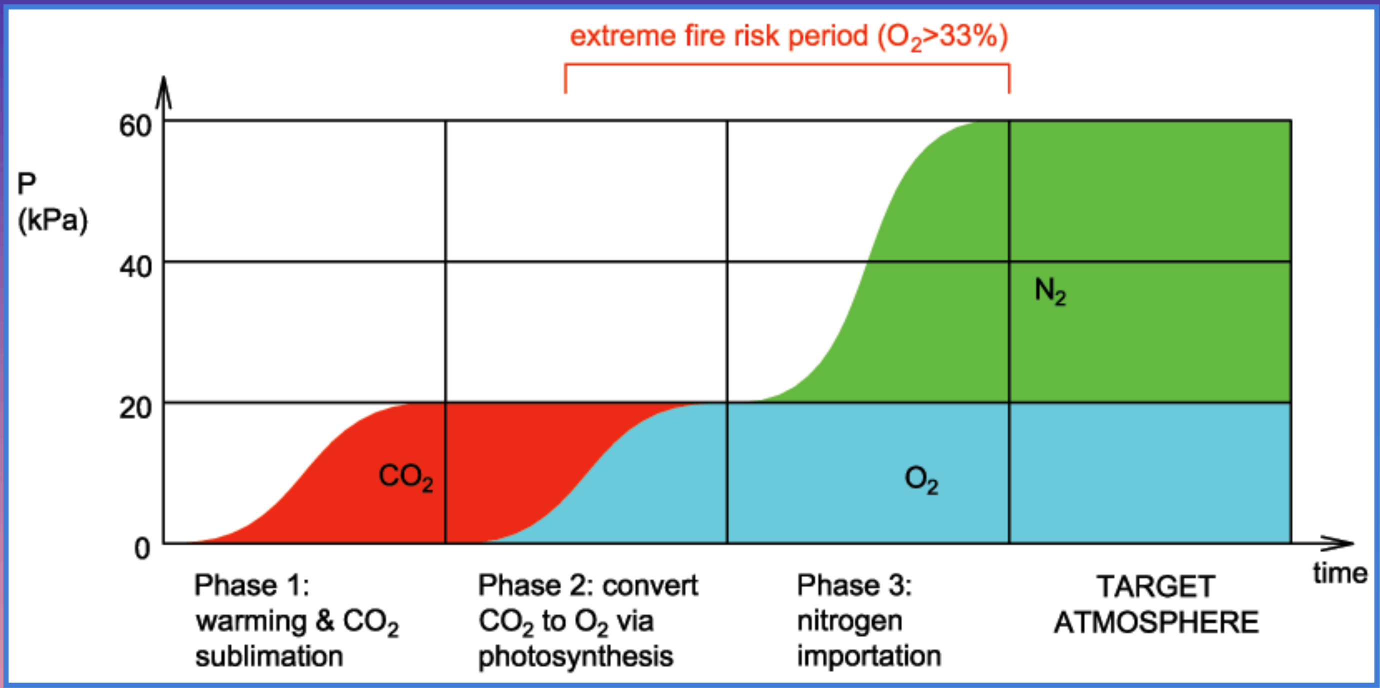
- Tech improves yearly. On average, every year we build 10% more ships than the previous year, with 10% larger radius, & decrease round-trip time by 10%....
- Have obtained required N_2 in just 4 decades.
- Even if it takes 2-3 times this long, this is not excessive compared to other tasks.

Managing CO_2 & O_2 Levels

- Will we have enough CO_2?
  - CO_2 may not come out of regolith easily.
  - CO_2 dissolves in water, the colder the better. As hydrosphere expands, CO_2 levels will drop & not replaced by O_2.
  - In water, CO_2 can react with minerals to form carbonates – hard to return these to atmosphere. (High acidity may inhibit carbonate formation)
- Will we have too much CO_2?
  - Estimated 40kPa CO_2 can be sublimated if loosely bound in regolith. But we only need 16 - 21kPa O_2.
- Maximizing phytoplankton mass can offset carbonate production by converting dissolved CO_2 to O_2.
- Some bacteria can liberate CO_2 from carbonate rock.
- O_2 can be produced by electrolysis or metal refining.
- Can always get more CO_2 from Venus.

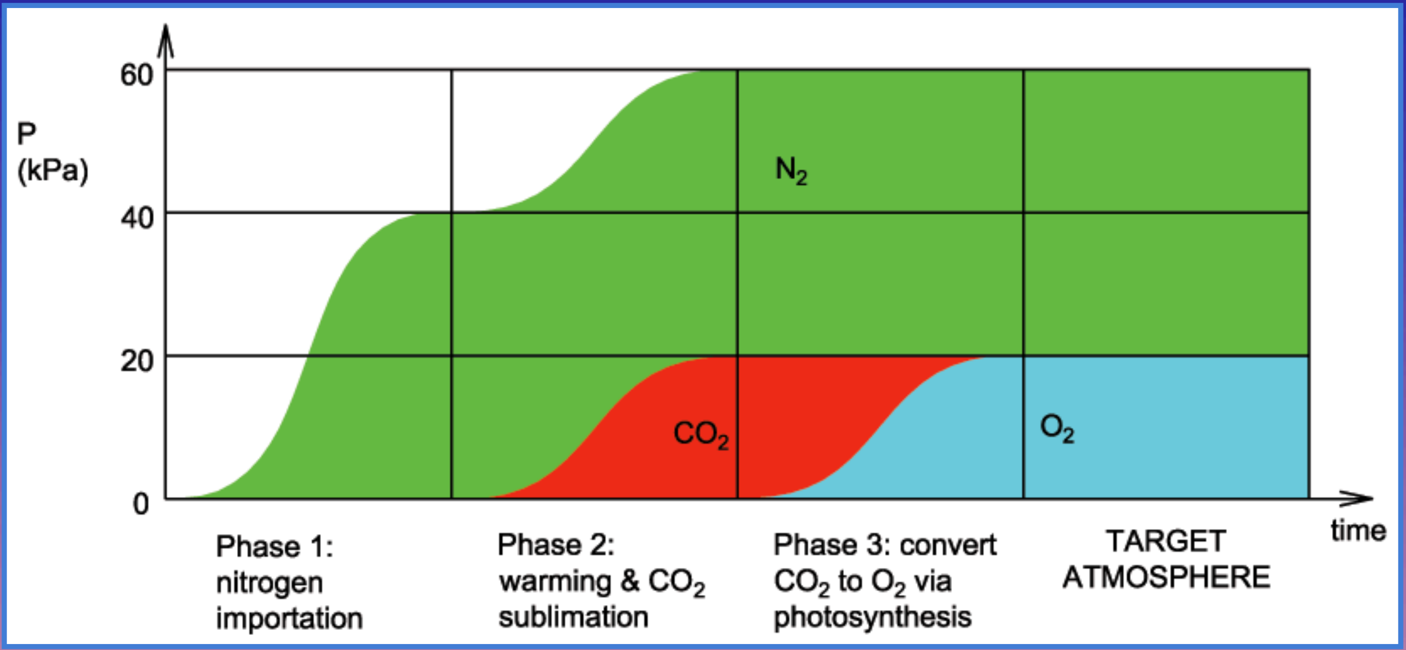

Get the N_2 first
DESTINATION: MARS
Maximum safety:
Biological O_2 pump hard to stop/control. If O_2 levels exceed ~35%, risk of fires & damage to biosphere, machinery, bases. Many colonists by this stage.
Must ensure sufficient quantities of buffer gas during warming and biosphere construction.
Also: the sooner we can start getting, N compounds into the soil the better.

Plan 1: Warming First



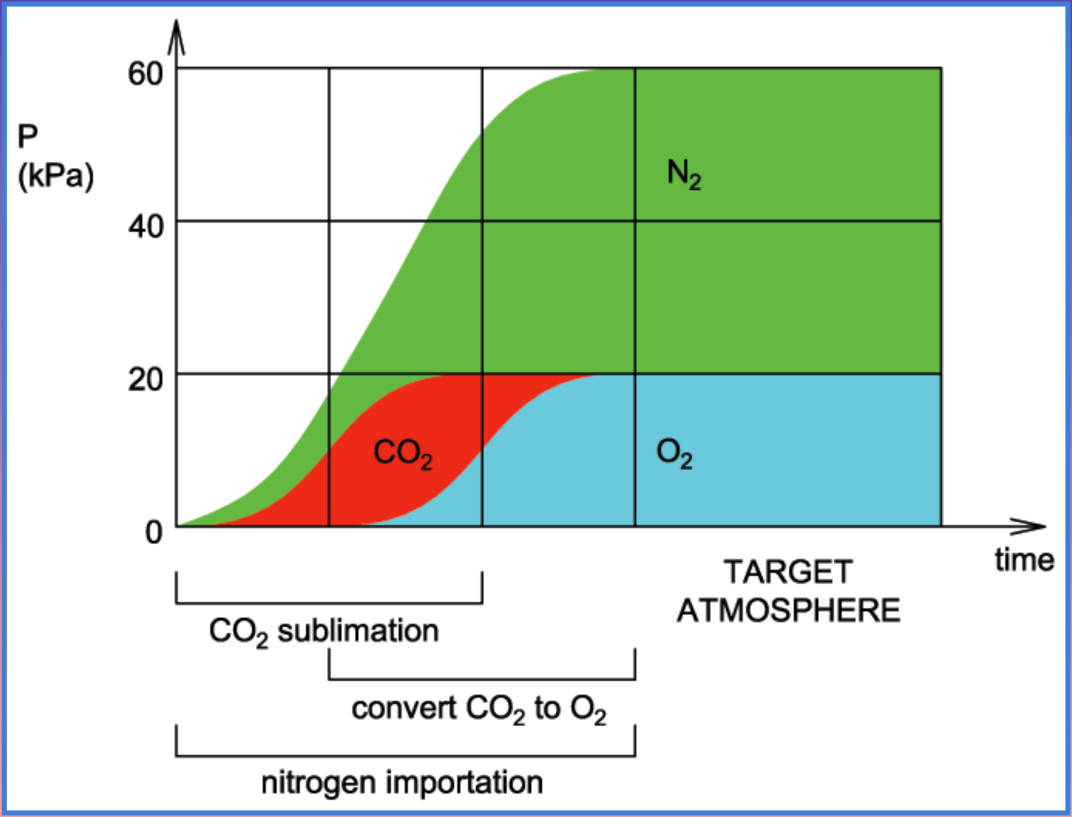
- Pros: Warm & wet early.
- Cons: High risk of fires leading up to and during Phase 3.

Plan 2: Get N_2 First



- Pros:
  - Atmosphere thick early (aids construction, improves safety).
  - Buffer gas in place.
  - Can start getting nitrates into soil sooner.
  - Allows for a long period of Mars research before more serious climate change.
- Cons: Cold and dry for a bit longer.

Plan 3: Concurrent Phases



- Pros:
  - Faster.
  - Warm & wet early.
  - Atmosphere thick early.
  - Nitrate production.
  - Buffer gas in place; O_2 always <35%
- Cons:
  - Fire risk if N_2 importation system breaks.

Task 3: Biosphere Construction

- Start at the bottom of the food chain and work up:
  - Basic chemical nutrients.
  - Microbes → Plants → Animals
  - Each generation improves environment for next.

Aquatic vs. Terrestrial Ecosystems

- Aquatic ecosystems will develop before terrestrial (land-based). Just like Earth:
  - 1. Life began in oceans: protection from UV, availability of nutrients.
  - 2. Aquatic plants converted CO_2 atmo to O_2.
  - 3. O_3 layer formed, providing UV protection.
  - 4. Life moved onto land.
- Mars cold & dry: aquatic bio-density will be greater than terrestrial. C.f. Earth:
  - Much more aquatic life at poles than at equator.
  - Why? CO_2 dissolves better in cold water, improves conditions for phytoplankton, and hence higher organisms.
  - Much less terrestrial life at poles than at equators.
  - Why? Too cold and dry.

Martian Microbes

- Primary engineers of planet.
- Role is to prepare environment for plants.
- Require ecosystem that performs a variety of roles:
  - Nitrogen-fixing
  - Nitrification
  - Methanogenesis
  - Alkalisation
- Genetic Engineering – combine DNA from:
  - Functional organisms
  - Extremophiles
  - Extant Martian life

Functional Microbes

- Nitrogen-fixing & nitrification: *Azotobacter, Rhizobium, Nitrosomonas, Nitrobacter*, etc.
- Chemoautotrophs/lithotrophs:
  - obtain E from inorganic molecules
  - synthesise organic molecules from CO_2.
- Methanogens – anaerobic, suited to low O_2, produce CH_4.

Extremophiles: Categories

- halophiles (salt)
- acidophiles (acid)
- cryophiles (cold)
- xerophiles (dryness)
- oligotrophs (lack of nutrients)
- radioresistant (radiation)

Extant Martian Life

- Will have useful genetic material, adapted for Mars.
- Probably lives below surface, and therefore chemotrophic.
- Cryophilic.
- Could be endolithic (living in rocks) or aquatic (sub-surface pools).
- Possibly methanogenic (low O_2 levels, plus would account for CH_4 in atmosphere).
- Combining Martian DNA with Terran species to create new organisms preserves genetic heritage – “managed evolution” may address moral question.

Martian Plants

- Aquatic species
  - Most important – these convert atmo. Hence the need to maximize wet areas by warming.
  - Phytoplankton (diatoms, dinoflagellates, cyanobacteria).
  - Macroscopic algae: kelp.
- Tundral species (cryophilic)
  - Arctic, Antarctic & Alpine ecosystems.
  - Mainly lichen, mosses, grasses, some flowers and woody plants, close to ground.
  - Lack of pollenating insects has caused evolution of vegetative methods of propagation, e.g. underground runners, bulbils, viviparous flowers.
- Desert species (xerophilic)
  - Cactii.

Fast Biosphere Propagation: Robotic Gardeners

- Robots very advanced at time of terraforming, esp. on Mars.
- Can greatly increase biosphere expansion rate.
- Colonies maintain farms of algae and other Mars-successful species.
- Satellites in Mars's orbit detect water, measure heat/O_2 output, growth rates.
- Data used to direct highly mobile robots (e.g. helicopters/balloons) to carry seeds/spores to best areas.
- Humans do research, but global gardening system can be fully automated.

Martian Animals

- Special purpose:
  - Stingless bees – pollenation
  - Earthworms – soil manufacture
  - Granivorous birds – seed propagation
- Aquatic:
  - Zooplankton, krill, squid, cold-water fish.
- Terrestrial:
  - Fish-eating birds, land mammals, etc. from polar environments.
- First mammals: cats and dogs descended from colonists' pets.

Radiation Protection

- Increasing O_2 levels build ozone layer.
- A magnetic field can be created by building a planet-circling conductor. Doubles as backbone for Martian power grid.

Mars Prospects

- Terraforming Mars requires a range of solutions.
- Three basic planetary engineering tasks.
- Phobos a useful platform for space mirrors.
- Need to ensure nitrogen levels high enough to dilute O_2, reduce fire risk.
- Use Solar System resources, not just Mars.
- Robotics and genetic engineering key technologies for biosphere construction.
- Every task affects the whole planet – all parts of process need to be managed concurrently.

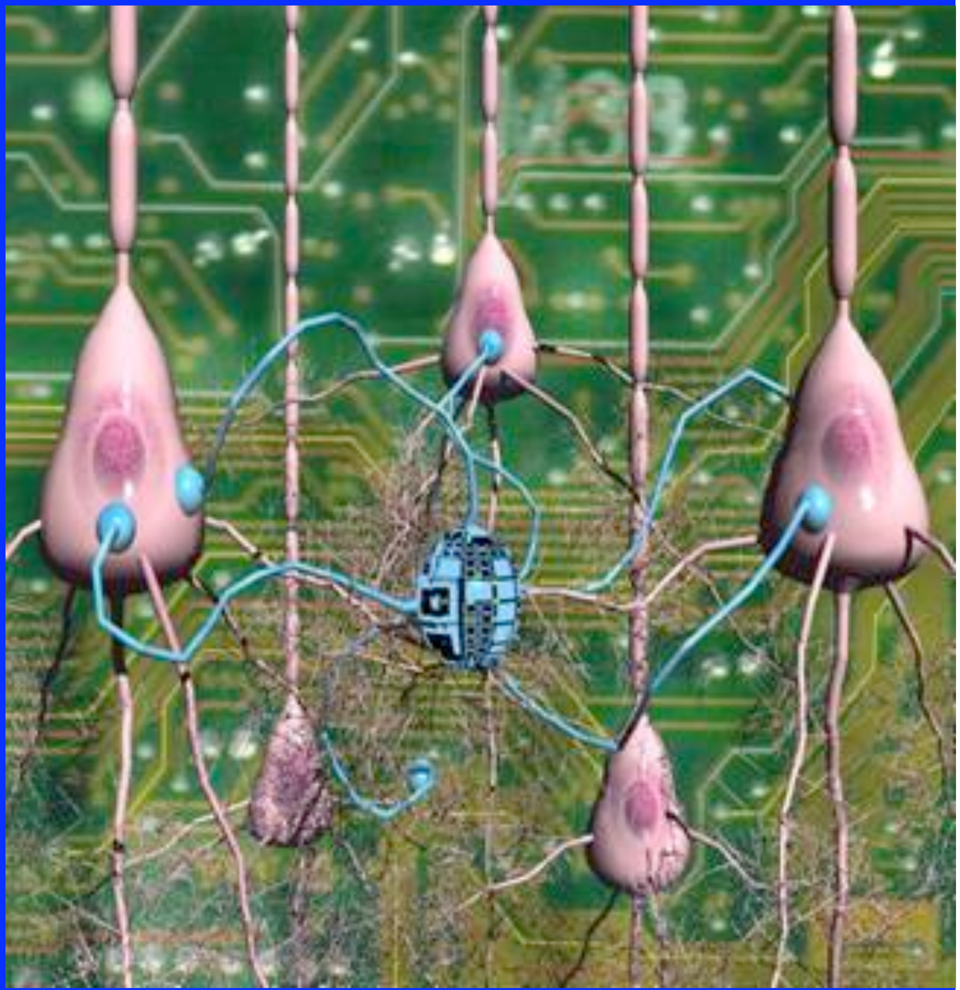
Colonies on Venus?

- Terraforming Venus is much tougher!
- But at 50 km, temp, pressure is like Earth
- Normal O_2:N_2 mixture floats
- Could have giant floating cities in atmosphere!

Methane_Harvester_final_by_gusti_boucher.jpg

Future Nanorobots?

- Far future!
- Might we make nanorobots that copy themselves and terraform planet?
- Exponential increase, so this could be fast
- Send out ahead of colony ships!



http://www.acceleratingfuture.com/michael/blog/images/bionanotechnology.jpg

Summary

- Terraforming Mars, though extended and hugely expensive, is within reach
- What are benefits and costs?
- Ethical questions: do we have right to modify planets like this?