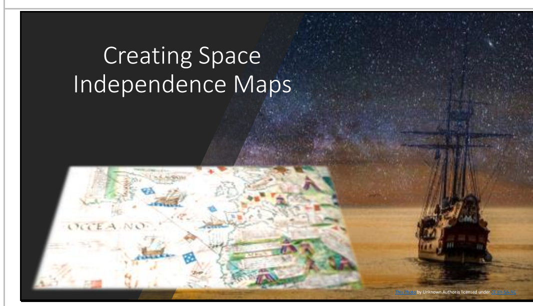
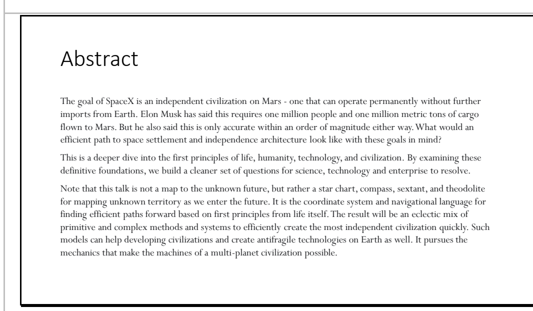
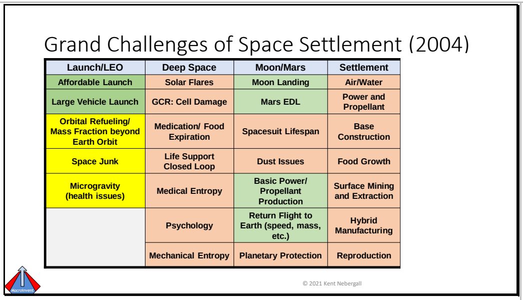


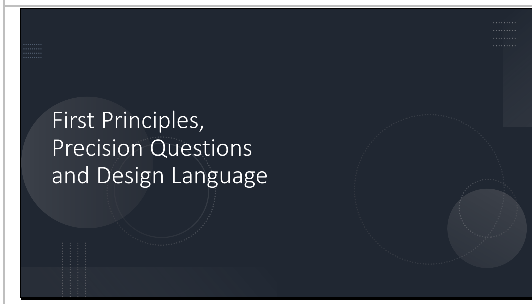
Early cartographers used celestial navigation to build out their maps of the land beneath their feet. That said, they needed a proper star chart before building charts of the lands directly in front of them. In the same way, we can build our key performance indicators for space independence here and now.



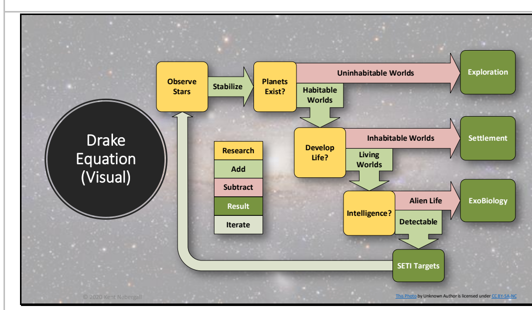

Grand Challenges of Space Settlement (2004)

Launch/LEO	Deep Space	Moon/Mars	Settlement
Affordable Launch	Solar Flares	Moon Landing	Air/Water
Large Vehicle Launch	GCR: Cell Damage	Mars EDL	Power and Propellant
Orbital Refueling/ Mass Fraction beyond Earth Orbit	Medication/ Food Expiration	Spacesuit Lifespan	Base Construction
Space Junk	Life Support Closed Loop	Dust Issues	Food Growth
Microgravity (health issues)	Medical Entropy	Basic Power/ Propellant Production	Surface Mining and Extraction
	Psychology	Return Flight to Earth (speed, mass, etc.)	Hybrid Manufacturing
	Mechanical Entropy	Planetary Protection	Reproduction

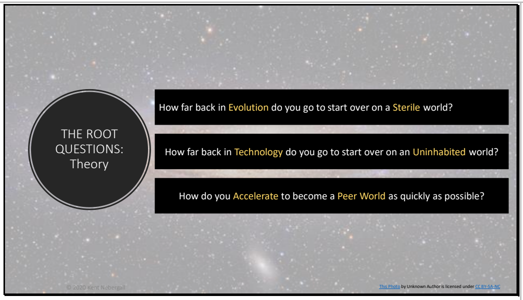
This has been my reference table in nearly every Mars Society talk for eighteen years now. Note that it stops at Settlement.
(CLICK)
It’s time to work out the next column, the Independence column.



We need to start with the first principles and correct questions.
Elon Musk has said “Once we could frame the question correctly… the answer flowed once the question could be framed with precision. “
He often gives the example of the Deep Thought computer from the Hitchhiker’s Guide to the Galaxy a case of stating the question so poorly that the answer is meaningless.
I’m going to show you a set of what business modelers call design canvases. The beauty of these canvases is that they can be used for not only business, but biology, architecture, logistics, and engineering, simply by changing the items being measured and compared. So whatever field you are working in, you use the same canvas but with different layers and units of measure.

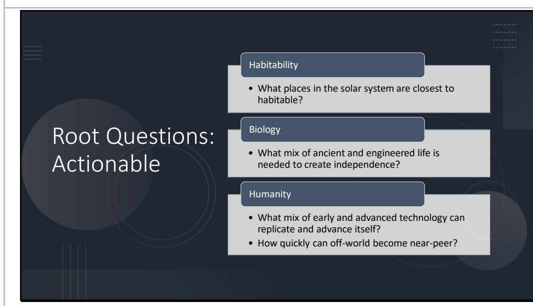


This is my graphic of the Drake Equation. The point of this is that the field of science changes depending on if we find habitability, or life, or civilization.
We are going to flip the design language of this diagram from science to engineering.
We will use this to BUILD an extraterrestrial civilization rather than look for one.

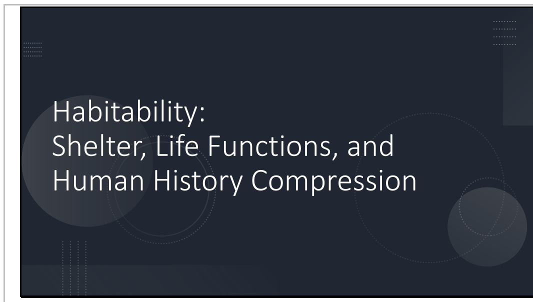


At the root is – how far back in evolution and technology do you go to start over on a sterile world? And how do you accelerate to become a peer of the home world?

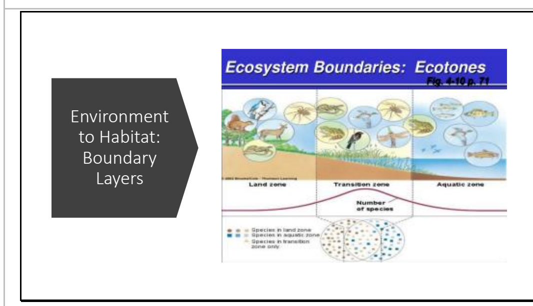
We must have solution for efficient biological and technological world building.



The first element is habitability – we want to settle in a place with complete resources and minimal stress on biology.
This seems obvious. But think how much is invested in going after economic resources in remote regions. Note that even on earth, those places rarely become independent.
Second, we need a biological mix that has the best chance of independence. This may be a mix of tenacious species along with some that are bred specifically for the new ecology.
Third, we are shortcutting eons of evolution and centuries of technology growth.
We want to eventually have essentially a ”Turing Complete” technology base. In computing, Turing Complete means a programming language that can perform all classical computing functions. It becomes unlimited despite having a very finite number of components and functions.



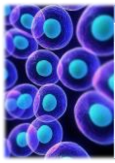
So the first challenge his habitability- bringing life to mars and mars to life, as Robert Zubrin summarizes it.



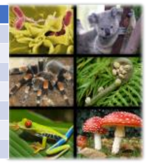
Within terrestrial ecosystems, we have boundaries between environments with transitions. One aspect of boundaries in nature is that the two zones have different properties like thermal mass that respond differently to day-night cycles or sunlight. These transition zones are energy pumps into ecosystems. For example, sea breezes or tides pump energy into ecosystems while the two systems try to return to equilibrium.

With space settlement, the boundary between habitat and near-vacuum is much more intense, but the principles are the same. We can use such systems for thermal management and in other cases use the pressure differences to drive flows. We can also use radiation by running wastewater outside the shielding, for example.

Traditional Life Functions: Defined



Cellular	Organism
Metabolism	Movement
Response	Sensitivity
Homeostasis	Respiration
Growth	Growth
Reproduction	Reproduction
Excretion	Excretion
Nutrition	Nutrition



In biology, there are two lists of life functions. Cellular life functions are for microbes. Organism life functions are for larger plants and animals.
Note that larger organisms also need homeostasis. As humans, we expand homeostasis with not only skin, but clothing and shelter.
Also note that these terms are designed to distinguish the living from non-living in real time. They are silent on the subject of long-term survival.

Harmonized
Life Functions

Abstraction
Movement
Sensitivity
Response
Homeostasis
Nutrition
Respiration
Excretion
Metabolism
Growth
Reproduction
Adaptation
Efficiency

Here is our first navigational benchmark – Life itself. The abstraction column combines the two lists of traditional life functions. In green, I've added two longer term survival functions.
Adaptation is the ability of a system to optimize itself to changes over time and in cycles.
Efficiency is defined as converting time and raw materials to productive work. It has been a key factor in evolution since the earliest cells started to use glucose, mitochondria, oxygen, and sunlight. It is also a major factor in the survival of civilizations.
Note that robotic systems also face equivalent challenges. They need to navigate and use energy efficiently.

First Principle
Life Functions

	Information	Energy	Matter
Abstraction	**External Interaction**	**Energy Management**	**Repair & Replace**
Movement	Active	Active	
Sensitivity	Active		
Response	Active		
Homeostasis	Active		
Nutrition	Active	Active	Active
Respiration	Active	Active	Active
Excretion		Active	Active
Metabolism	Active	Active	Active
Growth		Active	Active
Reproduction		Active	Active
Adaptation	Active	Active	Active
Efficiency	Active	Active	Active

Life functions are then viewed within the spectrum of interaction, energy management, and the ability to repair, replace, and reproduce the body itself. At an even more abstract layer, these terms are measured in information, energy, and matter. We can measure these with precision with physics and information theory. We also build a common framework for biology and architecture from first principles.
Now let's go to the human level.

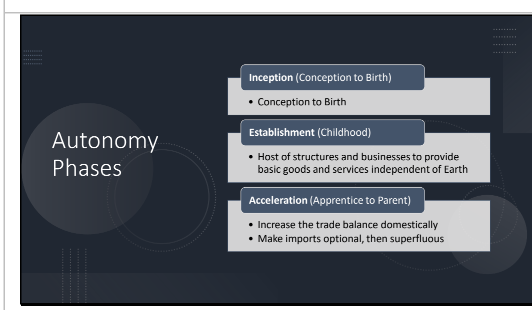
Energy Density/Efficiency, Invention, Information

Energy System	Utilization Inventions	Information
Human Power	Hunting, Gathering, Migration, Villages, Basic Farming, Textiles	Language
Fire	Metallurgy, Sterilization/Cooking, Light, Heat	Engineering
Animal Power	Farming, Roads, Cities, Travel, Mass Warfare, Writing, Trade	Math
Wind Power	Ocean going vessels, Navigation	Celestial Navigation
Steam (Wood)	Fast transport on rail/oceans. Paddle-wheels/wood boats.	Telegraph
Steam (Coal)	Ironclad ships with screw propellers. Steel and other alloys.	Fast News
Petroleum (Kerosene)	Indoor lighting, advanced industrial chemistry of petroleum.	[Radio]
Electricity	Indoor lighting, Distributed mechanical/heat power.	Telephone
Petroleum (Gasoline)	Internal combustion, Cars, Aircraft, early rockets.	[Television]
Chemical Rockets	Moon landings, Solar system exploration, etc.	Satellites
Nuclear Power	Nuclear power plant, Submarines/Aircraft carriers, NERVA.	[Computers]

Here is my map of human history in terms of **energy, invention, and information.** Invention is a set of technologies instantiated in matter, the same way a creature is based on DNA instantiated in an individual body.

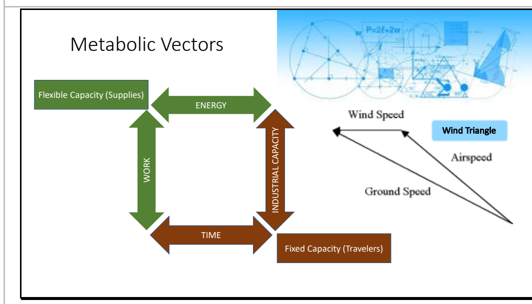
When a technology revolution matures, inventions are converged into an equilibrium of technology and resources. This becomes the foundation for the next technology revolution.

Energy, invention, and Information are the **material components of technology revolutions**. These revolutions are bursts of adaptation and efficiency that change the civilization from the inside out. But broader acceptance depends on **affordability and excitement**. Getting many people doing many experiments at once generates dramatic **growth and convergence**. It's a Cambrian explosion, much like the microcomputer revolution or the early days of aviation – thousands of garage tinkerers with Turing complete technologies expanding the art of the possible. These are the **velocities that drive further innovation**.



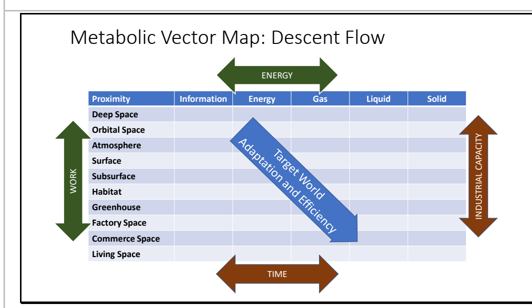
Independence at any level has three major phases – Inception, Establishment, and Acceleration. We are born, we learn, then we build more than we consume.
We start with inception, or the first landing. We move on to establishing an outpost, and finally focus on accelerating independence.

Let’s build a performance model for getting off the ground first.



An efficient system correctly matches work to industrial capacity, and time to energy. Systems that mismatch loose efficiency, which is a key life function at every level.

So what we want first is a form of vector equation framework that accounts for both energy and the ability to physically process it. Think of the green part as supplies and the red part as travelers being supplied. We can’t simply measure each pair of factors in isolation for the other or we won’t learn how efficient the system is.



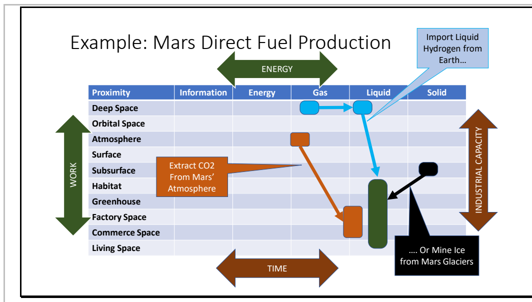
So we have direction and distance, now let’s add the map. This grid starts with living space at the bottom and deep space at the top, with various layers acting as natural boundaries within the system.

Horizontally, we break processes up materially from energy to gasses, liquids, and solids. These are our physical locations and states of matter within those locations.

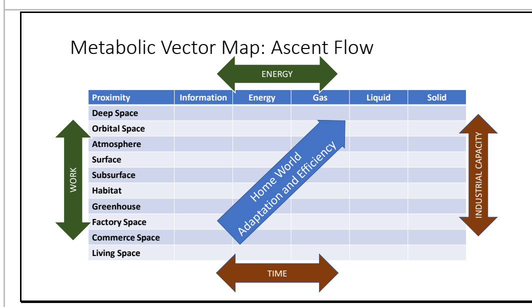
As planetary explorers, our first job is to move materials and energy from further up the chart to our human living spaces at the bottom of the chart.

Since it takes a lot of energy to change the equilibrium states of matter and locations of matter, those become our natural separators of distance.

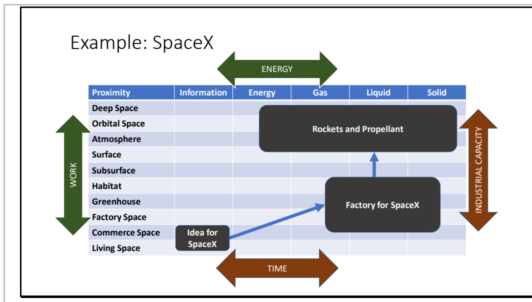
These columns are generic for this chart. Industry-specific charts would have different columns, but put them in this order for consistency.



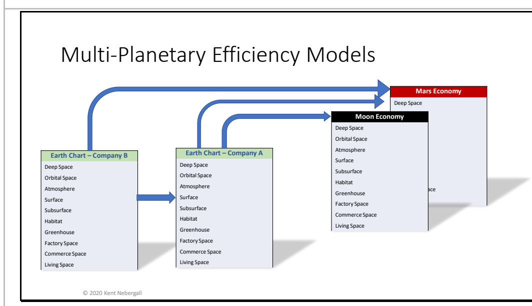
You learn the cost and benefit of each step by plugging numbers into each arrow, with time, energy, industrial capacity, and work as coordinate systems for those vector equations.
Here is Mars Direct propellant production mapped this way.
The original plan called for importing liquid hydrogen from Earth, shown in blue. The more efficient plan calls for mining ice locally from recently discovered buried glaciers, shown in black. We see the path for mining ice locally is much shorter than importing hydrogen from Earth, even before we add energy and distance values to the chart. We also see carbon dioxide mining in orange.



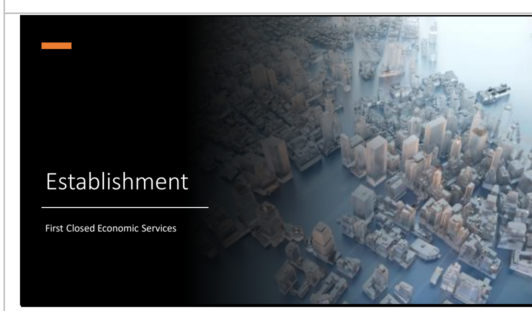
What makes this chart doubly useful is we can map enterprises starting here on Earth to create space settlement in the first place.



Here is a crude approximation of SpaceX. We start with an idea for a company and move onto the actual company, eventually reaching deep space. The top edge is our connector to other worlds.

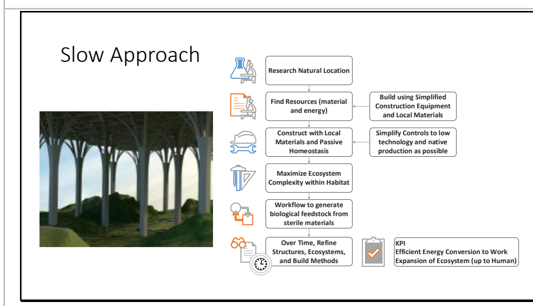


So we can click these business models together like equipment on an assembly line – Across the whole solar system.
An economic, business, and energy model can be run at any scale across worlds to evaluate the most efficient and effective systems for development. They can then be run backwards for exports back to Earth.



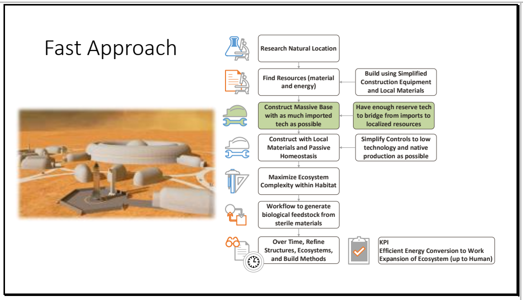
OK, so we have a way to model efficient paths forward. So where are we going, and how fast?

For a slow approach, think of terraforming over centuries before attempting human habitation on a large scale. The example here would be how a volcanic island is slowly colonized by birds and plants before becoming a jungle over centuries.

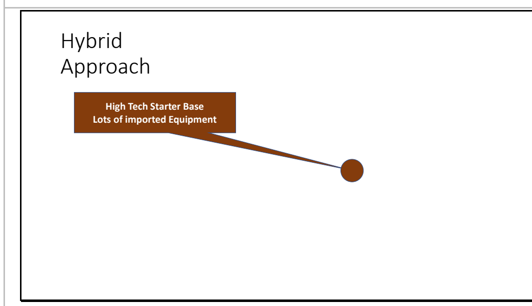


If we break this into a process, we make pocket habitats, then slowly adapt life to fill those spaces, like caves and so on. We keep homeostatic systems like temperature controls as passive as possible.

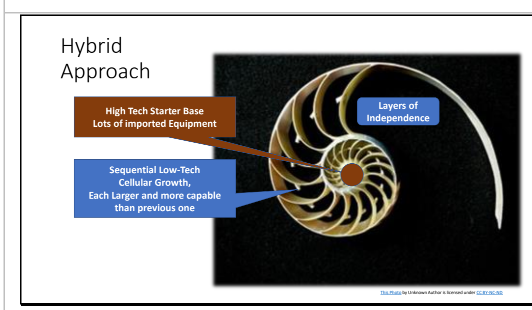
Conversely, here is a fast approach. Thule Air Force Base in Greenland was built by the US Military in four months in 1953 and is considered as big an operation as building the Panama Canal.
So the fast approach is the Mars equivalent, as Elon Musk proposes now, and as Werner Von Braun proposed in the 1960's.



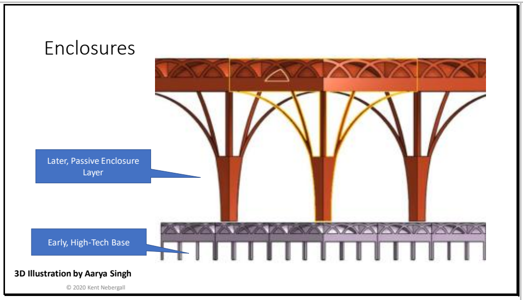
What is interesting here is that this simply adds an accelerant layer to the chart from the Slow Approach. This step is shown in green. All the other elements are non-negotiable in terms of long-term self-sufficiency.



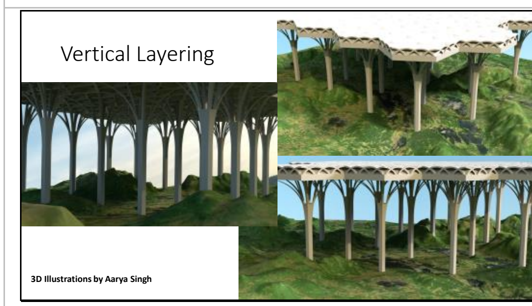
So ultimately, the best approach is a hybrid. We build a core outpost with as much technology capacity as possible…



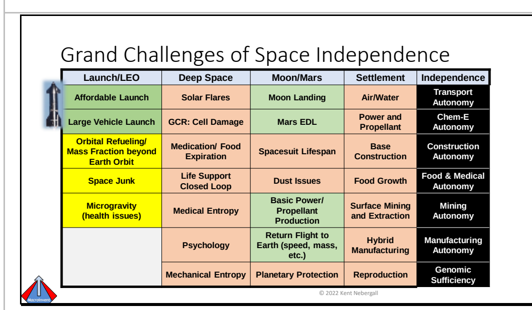
… and then use that to slowly build out a shell of independence-minded efforts over time.



While the sea-shell example is horizontal, we would probably go vertically as well. We use the low-tech habitat as a protection layer for the high-tech core. So imagine an industrial base at one atmosphere, surrounded by an agricultural greenhouse at a half atmosphere.

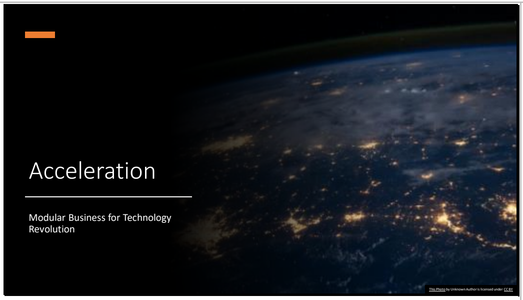


Here are some prettier renderings. The factories are underground. Morlocks not included.

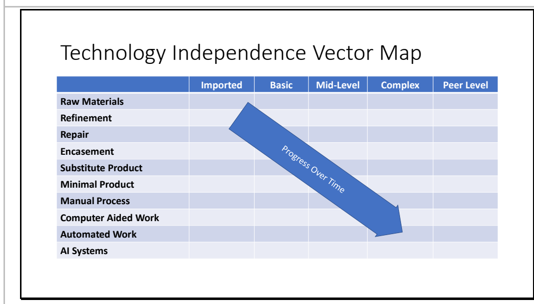


Launch/LEO	Deep Space	Moon/Mars	Settlement	Independence
Affordable Launch	Solar Flares	Moon Landing	Air/Water	Transport Autonomy
Large Vehicle Launch	GCR: Cell Damage	Mars EDL	Power and Propellant	Chem-E Autonomy
Orbital Refueling/ Mass Fraction beyond Earth Orbit	Medication/ Food Expiration	Spacesuit Lifespan	Base Construction	Construction Autonomy
Space Junk	Life Support Closed Loop	Dust Issues	Food Growth	Food & Medical Autonomy
Microgravity (health issues)	Medical Entropy	Basic Power/ Propellant Production	Surface Mining and Extraction	Mining Autonomy
	Psychology	Return Flight to Earth (speed, mass, etc.)	Hybrid Manufacturing	Manufacturing Autonomy
	Mechanical Entropy	Planetary Protection	Reproduction	Genomic Sufficiency

So before we continue, here is a brief revisit of the Grand Challenge Chart – here is the line of autonomy in terms of various industrial and agricultural capacity challenges.. The last state is genomic autonomy, or having enough genetic species-differentiation and capacity to survive indefinitely. A sort of Turing complete ecosystem and farm life. And actually, all of these industries must be Turing complete in the sense that enough parts exist to expand the state of the possible.



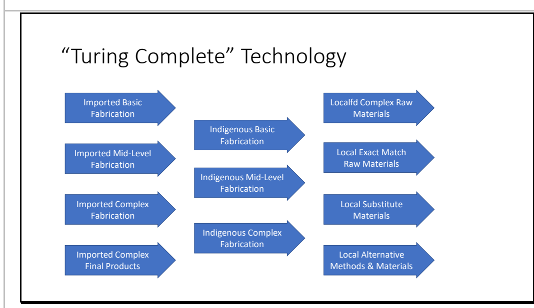
Now we need the human operations to build them. These operations have to be small, cellular, innovative, and adaptive.



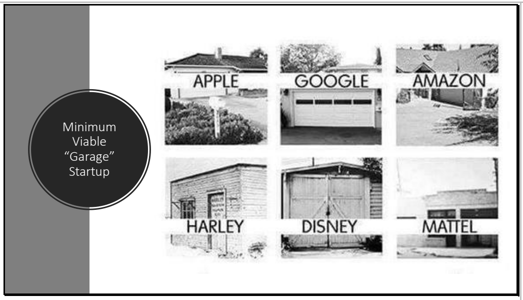
Here is our next analytical chart. The top left are raw materials imported to the planet, or the least independent state. At the bottom right is a fully peer-level civilization in all spheres of technology. Civilizations will grow as boxes from the top left to the bottom right.

Think of every cell on this chart as a business that moves goods, services, and energy to the cells to the right and below it.

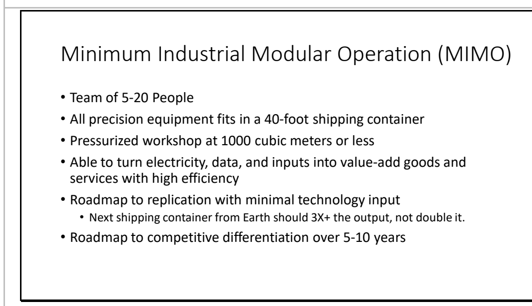
How big are the operations within each market box? And how many operations can fill those roles within a box?



Basically, we need specialized enterprises that fit into the space economy. Naturally, early operations will be entirely devoted to getting stuff from Earth to space settlements. But local operations on Mars need to be built and grow over time to slowly build independence and resilience. We need a common template for small scale operations that can be borne and replaced as needed to maximize the speed of innovation. In short – small and nimble mice, not slow growing dinosaurs.

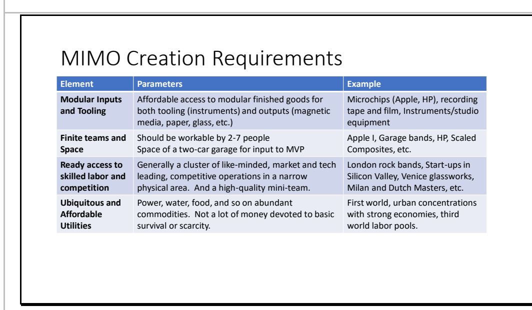


So here is another important question. WHY did these companies start with small teams in small spaces?
We can add the Wright Brothers and the glassworks and machine shops of Europe a few centuries ago to this list.



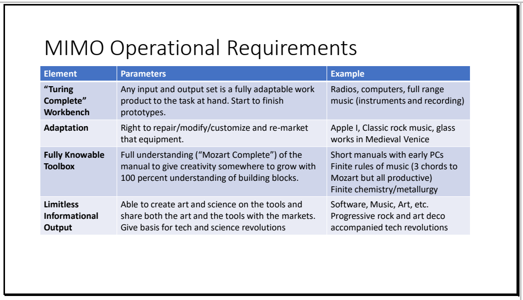
For the sake of time, I'll skip to the end of the story. I'm calling this a Minimum Industrial Modular Operation, or MIMO for now. It's an abstraction of the garage start up that is movable to Mars.

To be considered a MIMO, we need a small team with enough tooling to fill a shipping container and able to operate in a workshop the size of a two-car garage. Second, they must fill some key need of the outpost and do it efficiently. There may be one business in this space or dozens, as supply and demand see fit.


MIMO Creation Requirements

Element	Parameters	Example
Modular Inputs and Tooling	Affordable access to modular finished goods for both tooling (instruments) and outputs (magnetic media, paper, glass, etc.)	Microchips (Apple, HP), recording tape and film, Instruments/studio equipment
Finite teams and Space	Should be workable by 2-7 people Space of a two-car garage for input to MVP	Apple I, Garage bands, HP, Scaled Composites, etc.
Ready access to skilled labor and competition	Generally a cluster of like-minded, market and tech leading, competitive operations in a narrow physical area. And a high-quality mini-team.	London rock bands, Start-ups in Silicon Valley, Venice glassworks, Milan and Dutch Masters, etc.
Ubiquitous and Affordable Utilities	Power, water, food, and so on abundant commodities. Not a lot of money devoted to basic survival or scarcity.	First world, urban concentrations with strong economies, third world labor pools.

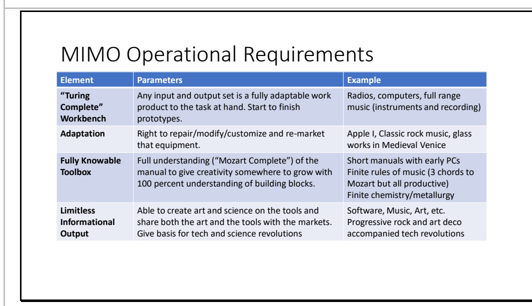
Technology hot spots throughout history have attracted small teams with affordable hardware and big ideas. They had ready access to skilled talent, energy, tooling, and commodities. This was true with the Venice Glassworks that made the first lenses and is true now. It's also true of early rock bands and movie studios.



Element	Parameters	Example
"Turing Complete" Workbench	Any input and output set is a fully adaptable work product to the task at hand. Start to finish prototypes.	Radios, computers, full range music (instruments and recording)
Adaptation	Right to repair/modify/customize and re-market that equipment.	Apple I, Classic rock music, glass works in Medieval Venice
Fully Knowable Toolbox	Full understanding ("Mozart Complete") of the manual to give creativity somewhere to grow with 100 percent understanding of building blocks.	Short manuals with early PCs Finite rules of music (3 chords to Mozart but all productive) Finite chemistry/metallurgy
Limitless Informational Output	Able to create art and science on the tools and share both the art and the tools with the markets. Give basis for tech and science revolutions	Software, Music, Art, etc. Progressive rock and art deco accompanied tech revolutions

Another key factor is finite and fully understood tools. With early microcomputers, the whole manual could be read in a couple days. Then the talented person thought, "OK, what can I create with this new language?" It was "Turing complete". For a rock band it's the first three chords learned on guitar from which they build a whole album catalog.

When the knowledge base gets too big, the creator doesn't hit the transition they stop learning other people's systems and are free to build their own. The smaller the required knowledge base, the more masters you have of the art.



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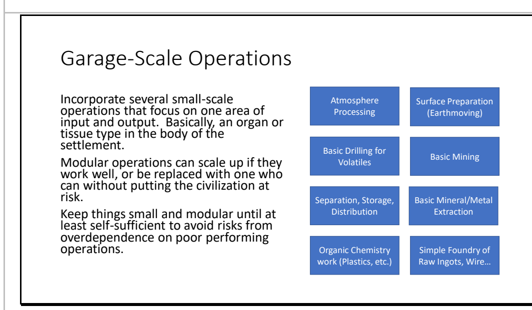
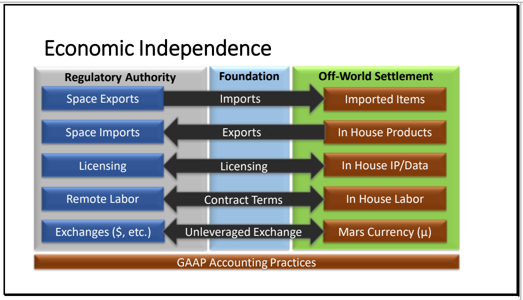
Limitless Informational Output	Able to create art and science on the tools and share both the art and the tools with the markets. Give basis for tech and science revolutions	Software, Music, Art, etc. Progressive rock and art deco accompanied tech revolutions

All startups have the right to modify and repair systems. This can be the products but also the tooling that makes them. Any culture where right to repair and modify dies will become a slave to a smaller and smaller number of post-doctoral experts, who will then die off and leave lost arts. We must democratize the most technical aspects of creating tooling and materials. This is harder and harder as civilization advances, but remains a key requirement for civilizations to continue, let alone reproduce on new worlds.

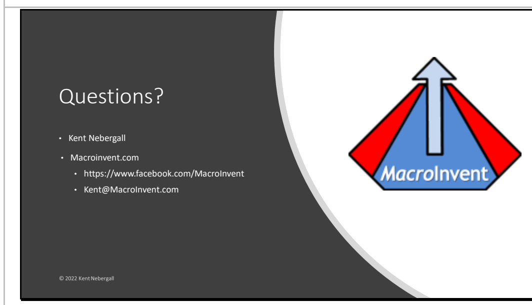


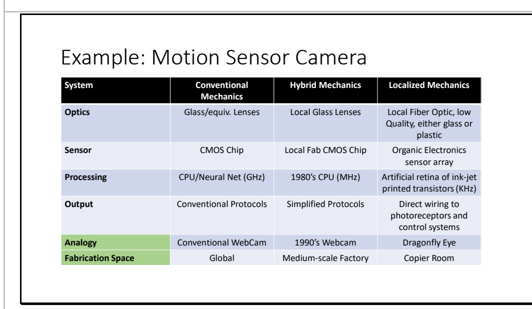
So imagine a Starship landing on Mars. In the cargo bay are a dozen employees of a startup and a shipping container of tooling. They will move themselves and the container into a dome and integrate into the local utilities. They will then make something we take for granted on Earth, like glass or machine parts, using local resources an upstream companies like themselves next door.

They would use the charts we discussed earlier to find their paths in this new frontier.



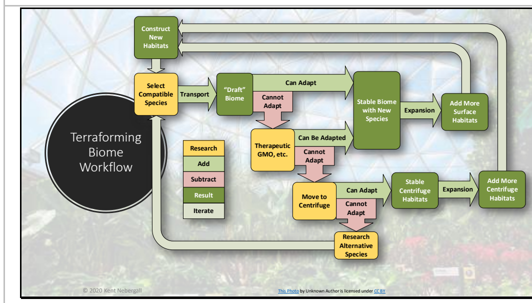
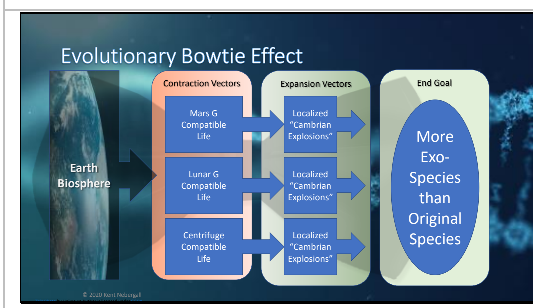
As with any new biology, we need to keep the lab clean from contamination.
We would need a space settlement foundation to act as a buffer between space and earth economies. Since Earth governments will never be perfect, the foundation is a compromise that allows space to evolve separately while still having trade with Earth. It's like the autoclave airlock that prevents contamination from entering the lab.




Example: Motion Sensor Camera

System	Conventional Mechanics	Hybrid Mechanics	Localized Mechanics
Optics	Glass/equiv. Lenses	Local Glass Lenses	Local Fiber Optic, low Quality, either glass or plastic
Sensor	CMOS Chip	Local Fab CMOS Chip	Organic Electronics sensor array
Processing	CPU/Neural Net (GHz)	1980's CPU (MHz)	Artificial retina of ink-jet printed transistors (KHz)
Output	Conventional Protocols	Simplified Protocols	Direct wiring to photoreceptors and control systems
Analogy	Conventional WebCam	1990's Webcam	Dragonfly Eye
Fabrication Space	Global	Medium-scale Factory	Copier Room

One last example. Here is a concept for a Mars-sourced motion sensor camera for industrial use. Since we can't make glass yet, we draw polyethylene into filaments and use it like fiber optics. We connect it to organic transistor sensors printed on an ink jet system the size of an office copier. We use transistor arrays modeled after the retinas of dragonflies. We do this because we need efficiency despite the hardware being as slow as computers from 1965. We get an acceptable result with a technology stack that fits in a garage. We use ideas from history and biology to localize novel solutions.
These solutions look nothing like Earth solutions, but they are hyper-efficient and democratized because they have to be to exist on Mars at all. Technology will evolve quickly with thousands of people able to design circuits rather than a few isolated experts. When a thousand people can design circuits, the bell

<table>
<tr><td></td><td>curve will select the highest talents to equal or surpass those on Earth.</td></tr>
<tr><td>
</td><td>We have a similar flowchart here for adapting Earth species to space settlement, with similar logic gates. Some species will adapt to surface gravity easily and some will be stressed.
Some stresses can be compensated for with diet or possibly adapting plant species to fill nutrition gaps. It would be a work in progress for many generations. Ones that cannot adapt to surface gravity can move to the centrifuges.
That said, there may be species like migrating birds that cannot adapt to either.</td></tr>
<tr><td>
</td><td>Not all species will adapt well to space settlement, which will narrow the selection range from what we have on Earth. But different environments and the stresses of those environments will bring epigenetic gene expression to the forefront. We will not only see what the silent genes have hidden, but what they can be adapted to do in various environments. And this is independent of any artificial gene editing. The combination will differentiate the species that do adapt to various space environments. In the end, there– exo-species will be more species off of earth, than on our home world.</td></tr>
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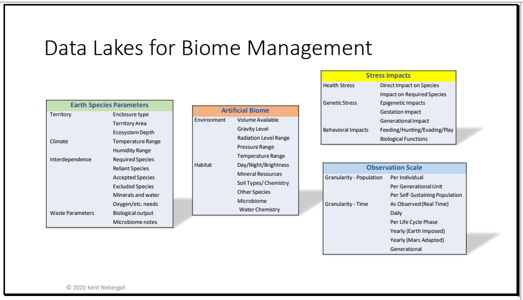
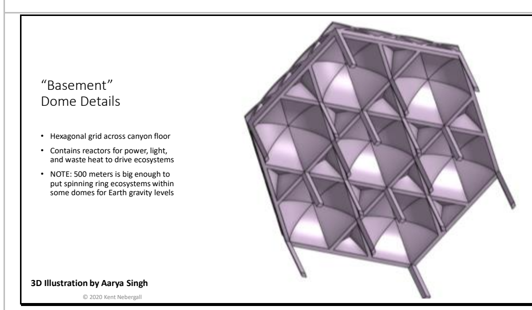


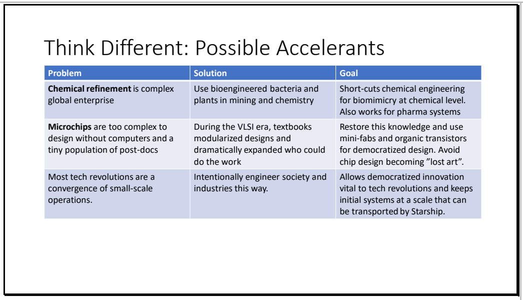
While this **seems** far off, creating a **database** of life **parameters** on Earth can start **now**. From there, future **space** settlers can **select** species with the **highest chance** of success and **work** their way **down** the list until they **hit** the **limit** of technology for **that** generation.

Remediation Method	Description
Natural Selection	Percentage of poorly-adapting creatures that do not breed in the ecosystem naturally.
Artificial Selection	Active farming of generations to promote most beneficial traits for the artificial ecosystem.
Genetic Modification	Can the species be modified and can the traits be passed to future generations?
Food Chain Modification	Can GMO foods be engineered to overcome issues and can those species be added to the ecosystem over generations?
Nutrient Modification	Can the environment itself be supplemented with higher oxygen levels, more calcium in soil, etc. to offset ill effects of artificial system? Will these resources need to be replaced periodically from outside or are they recycled in the food chain?
Habitat Modification	Can new artificial habitats be built that offset the effects and the species be transplanted there?
Replacement	Find another species from Earth (or another habitat) that adapts to this niche better and test.

So in more detail, this is our **toolbox** for adapting **any species** to be multi-planetary. There are a lot of **tools** one can use **without resorting** to genetic engineering. **Most** of these would be the **food-chain** and **gravity modification** versions of what is **done** on the **ISS** to keep **crews healthy** with **diet, medication, and exercise**.

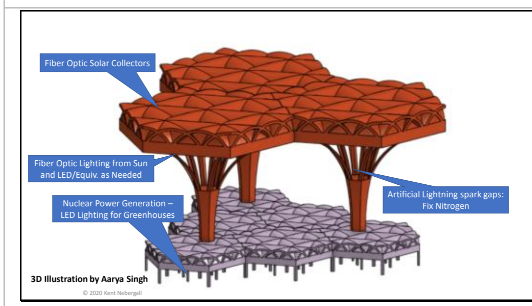


We would first **mine** anything **useful** from the **floor** material and **level it**, using it in **agriculture** to add **organics** to the **soil**. We **build** a series of hexagonal **domes 500 meters** in diameter as a sort of **basement** across the **surface**. Each **one** of these hex **domes** can house a **Eureka-sized centrifuge**. **Air pressure** would help **support** the load.

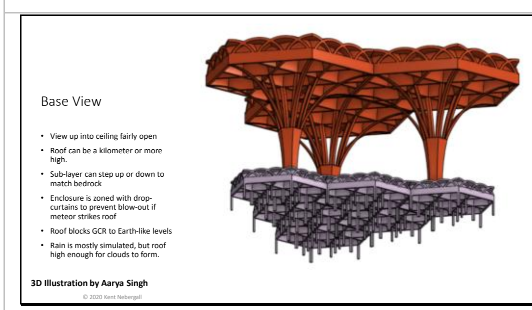


Problem	Solution	Goal
Chemical refinement is complex global enterprise	Use bioengineered bacteria and plants in mining and chemistry	Short-cuts chemical engineering for biomimicry at chemical level. Also works for pharma systems
Microchips are too complex to design without computers and a tiny population of post-docs	During the VLSI era, textbooks modularized designs and dramatically expanded who could do the work	Restore this knowledge and use mini-fabs and organic transistors for democratized design. Avoid chip design becoming "lost art".
Most tech revolutions are a convergence of small-scale operations.	Intentionally engineer society and industries this way.	Allows democratized innovation vital to tech revolutions and keeps initial systems at a scale that can be transported by Starship.

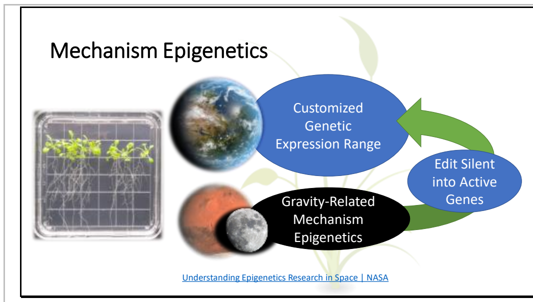
So how would this look? Here is a complex set of technology platforms that took two centuries to build. Chemistry, microchips and bioengineering. We can leverage different platforms to build new systems effiecn



The basement **gray** section then becomes the space for **heating**, **transport**, **power** generation, and so on. We landscape terrain both on **top of** and **underneath** the basement layer. **Heat** from power generation at that layer keeps the **system warm** and can **power** any artificial **light** needed during dust storms.



We can even set **spark gaps** in the **tree structures** to fix nitrogen like **thunderstorms**.



All **life**, particularly **plants**, have many **silent genes** that carry traits that are **only activated** under **unusual stresses** such as **drought**. The **behavior** of the **plant** is altered even if the **genetic code** is **not**. **Some** of these **stresses** are brought out in **microgravity** on the **International Space Station. These** have been found useful in making **crops** that are **not actually gene spliced** with other **species** as with **current** GMO plants, but **simply activating genes** that were **there** to **begin** with. This has the **beginnings** of an **agricultural revolution** that avoids the **controversies** of **GMOs**.

We dramatically **expand** ways to make **food**, **clothing**, and shelter **everywhere**, including **Earth**.