

**SPACE PORTAL**  
for enterprise and commerce



# *Economic Readiness Level Considerations for a Robust LEO Economy*



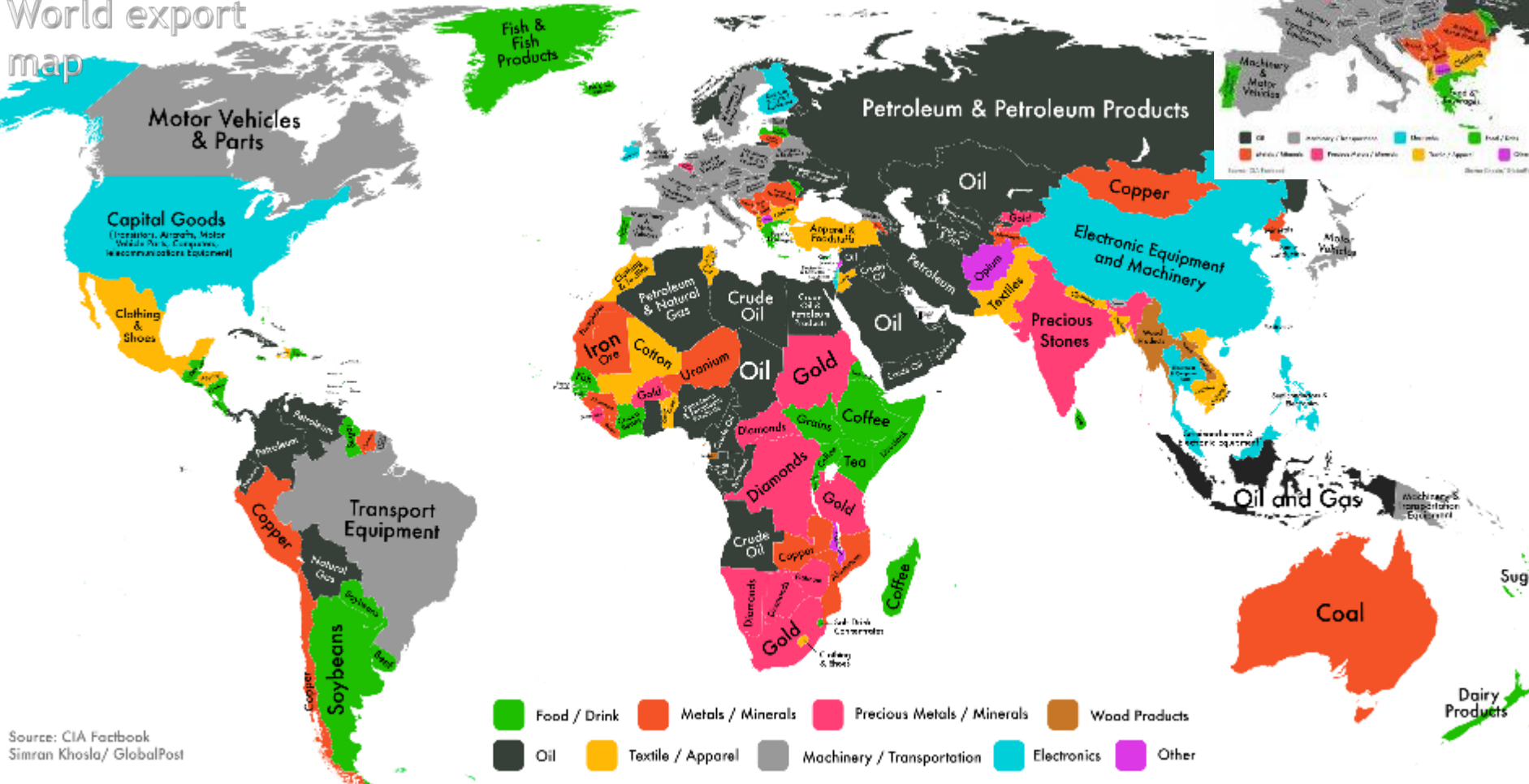
Dr. Ioana Cozmuta  
*Industry Innovation and Microgravity Lead*

Science and Technology Corporation  
Space Portal, NASA Ames Research Center

# TERRESTRIAL ECONOMY



World export map



Source: CIA Factbook  
Simran Khosla/ GlobalPost



## ECONOMY

A country's RESOURCE management through production & consumption

I. Cozmuta, Techsylvania 2016 Keynote, <https://www.youtube.com/watch?v=wdz6Vlcr8KY>

*WHAT HAPPENS AT THE EDGE OF SPACE?*



*ORBITAL ECONOMY*

# ORBITAL ECONOMY



GLOBALIZATION



INTERNET OF SPACE



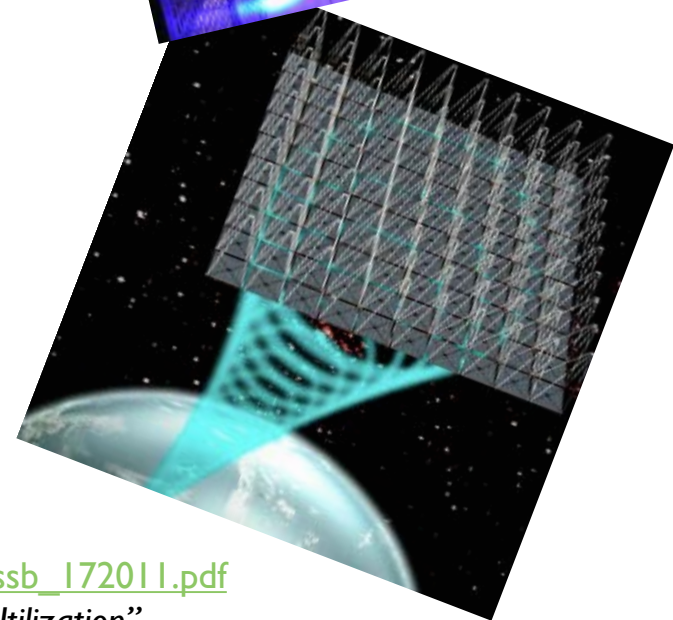
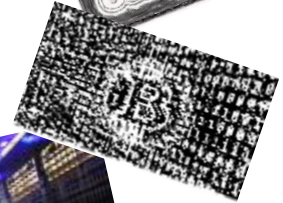
LAW & REGULATIONS



ORBITAL CURRENCY



SPACE RESOURCES



I. Cozmuta, National Academy of Sciences, Leo commercialization day:

[http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb\\_172011.pdf](http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_172011.pdf)

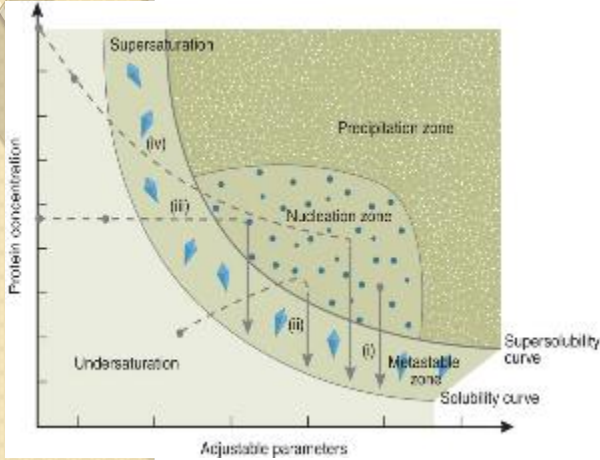
Webinar "On-Orbit Manufacturing: From Orbital Factories to In Situ Resource Utilization"

<https://attendee.gotowebinar.com/register/5666583135043371522>

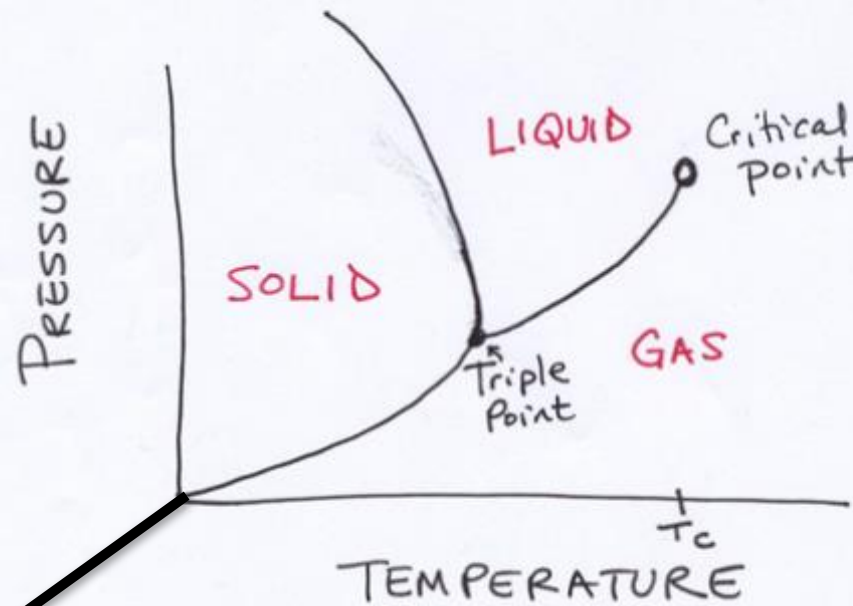
# WHAT IS MICROGRAVITY?

- Microgravity or reduced gravity represents ~6 orders of magnitude reduction in one of the fundamental forces (gravity)
- Gravity is a physical parameter that together with pressure and temperature define the state of a system
- When the force of gravity is removed other forces (surface tension, capillary forces) become predominant and drive a different system dynamics
- Historically, major breakthrough and innovations were achieved when systems were studied, for example, at low temperatures.
- Many of our intuitive expectations do not hold up in microgravity!

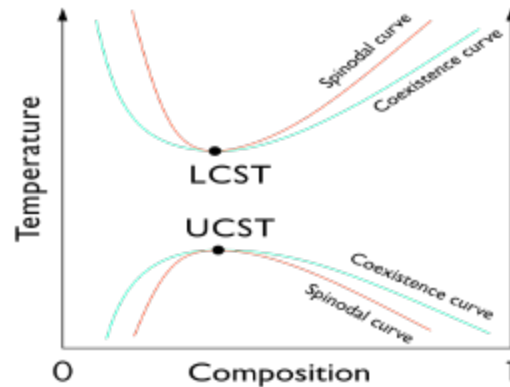
# GRAVITY AND PHASE DIAGRAMS



CRYSTALLIZATION  
PHASE DIAGRAM

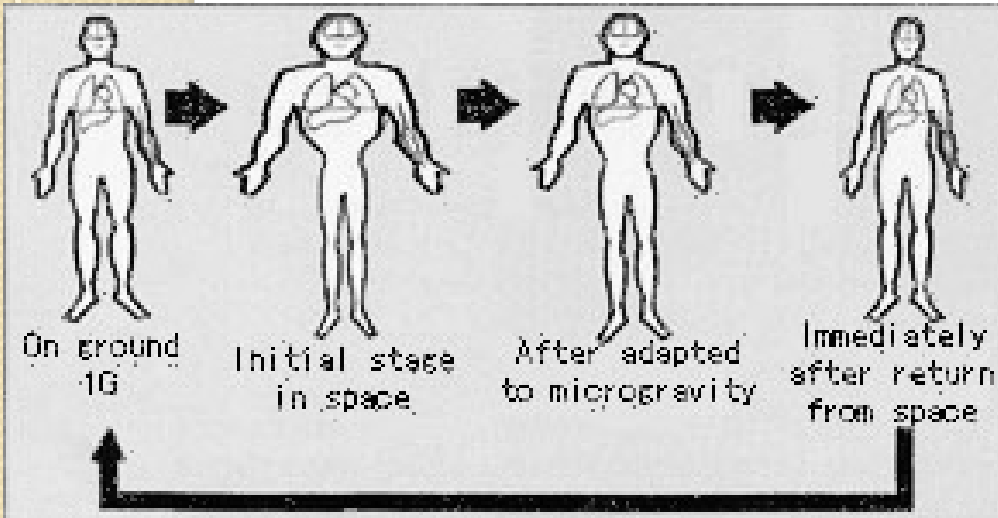


GRAVITY



BINARY COLLOIDS  
PHASE DIAGRAM

# BENEFITS FOR LIFE SCIENCE



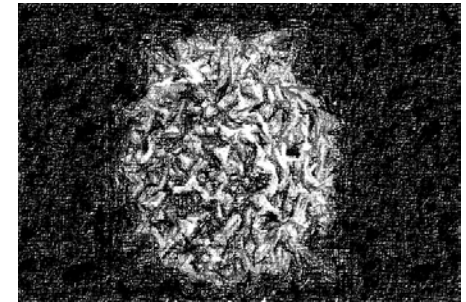
Microgravity is evolutionarily novel and enables new understanding of living systems that can be used for medicine and biotech.

Commercial biosciences and pharmaceutical companies have flown experiments in space since the 1980s.

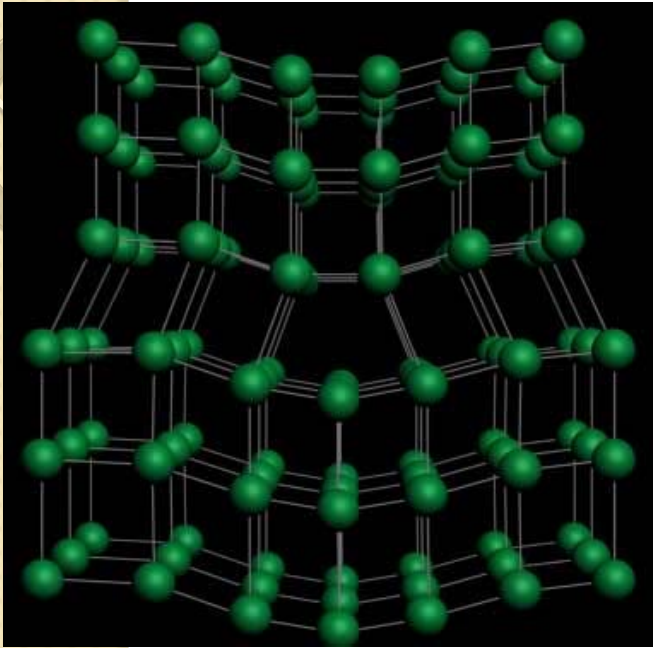
Response to gravity is complex.

**All levels of biological organization, cells, tissues, organs, organisms, are affected by gravity/microgravity, often in novel and useful ways, sometimes in ways that allow medical problems on Earth to be better studied.**

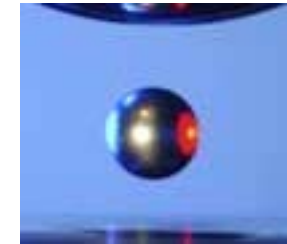
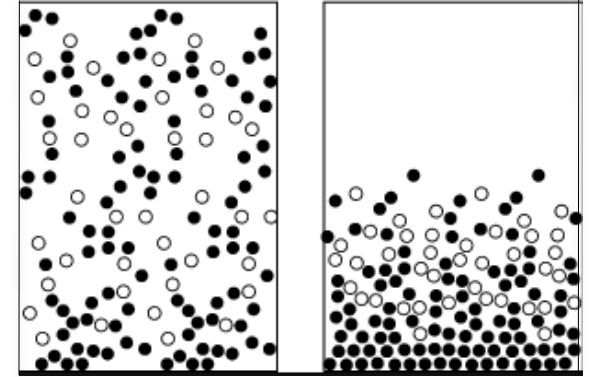
As biotech companies have found, novel environments offer novel biological responses useful for industry, medicine, and agriculture.



# BENEFITS FOR MATERIAL SYSTEMS



- No solute buildup
- No sedimentation
- No convection



- Defect free
- Homogeneous
- Controlled, symmetric growth
- Avoidance of nucleation or single nucleation
- High resolution
- Containerless processing
- Free suspensions
- Perfect spherical shape
- No wetting





# SINCE 1946



- May 10, 1946 – first space research flight (cosmic radiation experiments) –US, V2 rocket**
- February 20, 1947 –first animals into space (fruit flies)–US, V2**
- November 3, 1957 –first animal in orbit (the dog Laika) -USSR, Sputnik 2**
- August 19, 1960 –first plants and animals to return alive from Earth orbit –USSR, Sputnik**
- April 12, 1961 –first human spaceflight -Yuri Gagarin –USSR, Vostok 1**
- 1969 –first Welding experiment in space –Soyuz 6**
- 1971 – composite casting – Apollo 14**
- 1973-1979 – Skylab Materials Processing Facility, Multipurpose Furnace System, Skylab**
- 1980-2000 – Spacelab, etc – Shuttle Era (STS-3 through 87)**
- April 23, 1971 – first space station – USSR, Salyut 1**
- February 19, 1986 –first inhabited long-term research space station -USSR, MIR**
- November 20, 1998 – first multinational space station (ISS)**
- Largest man-made object built in space to date (Russia, USA, Europe, Japan, Canada)**

\$/kg to LEO

≥ \$30,000

~ \$5,000

≤ \$1,500

Frequency

1-2/year

~3-6/year

≤monthly

Orbital



NASA - STS



Cygnus  
Orbital Sciences



Dragon  
SpaceX



Cygnus  
Orbital Sciences



Dragon  
SpaceX



SNC/Dream Chaser



Boeing CST100



NASA/DOD  
SRLV (10min)



Masten  
Xombie



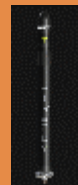
UpAerospace  
SpaceLoft



ARCA  
Haas



Bigelow



Firefly  
Alpha



RocketLab  
Electron



ULA  
DTAL-R



NASA/DO  
D  
KC-135



Zero-G  
Airbus



Virgin Galactic  
Space Ship Two



S3 SOAR



New Shepard  
Blue Origin



S3 A300



World View



Novespace

REGIME

Suborbital

Parabolic

CAPABILITIES:

1990-2010

2010-2015

2015-2020

# BACKGROUND

- Reviewed microgravity findings since 1985: materials, life science, (limited) human medical research
- Reviewed 1000+ papers and reports in 30+ topic areas TO assess potential terrestrial applications
- Reviewed NASA and OGA **spinoffs database** as appropriate
- Reviewed **153 pool of technologies under Flight Opportunities**
- Interviewed 150+ microgravity PI's TO understand implications of their findings and potential success enablers
- Discussed with 400+ industrial lead scientists and technologists TO understand their technical problems caused by gravity
- Discussed with 100+ venture capitalists and financiers (primarily from Silicon Valley) TO understand the risks they perceive for microgravity related applications
- Identified 30+ potential candidates for commercial microgravity feasibility to implement, and company interest.
- Completed 4 in-depth Case Studies (Exotic optical fibers and glasses, Semiconductor materials, Biotech, Solar Power Data Centers)



How is  
**GRAVITY**  
affecting

**YOUR BOTTOM LINE?**

Commercial  
Space



# VERTICALS OF MICROGRAVITY

Future

New Materials

Computers & Communications

Biotech

Medical Devices

Medical Applications

Consumer products



1st Vertical



2nd Vertical



3rd Vertical



4th Vertical



5th Vertical



6th Vertical

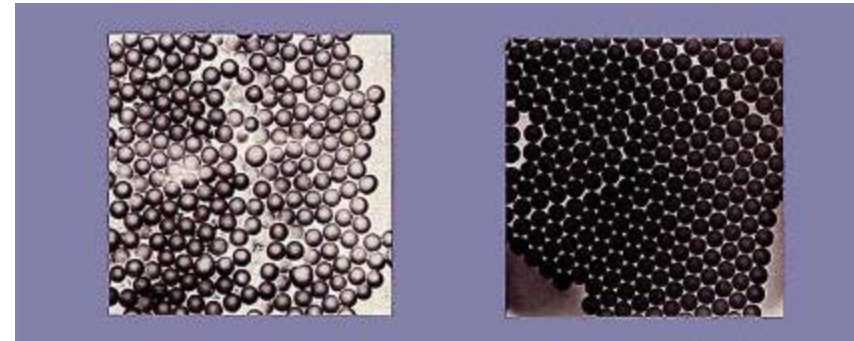
Existing

## MICROGRAVITY

Developed to capture in a compressed manner a mix of very diverse values (knowledge, processing) of the microgravity environment. Emerging from a common background, that of microgravity, the verticals extend from existing companies and their microgravity products, to new players & future partners that could potentially benefit of the microgravity environment.

# SUCCESS STORIES

Despite relatively low funding, relatively few investigators, and great difficulties accessing space (compared with laboratory research on Earth), the success rate from microgravity R&D into applications is remarkably significant.



## Space Beads

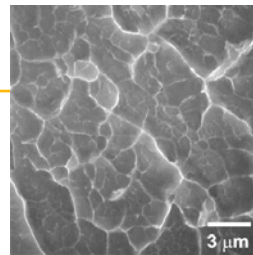
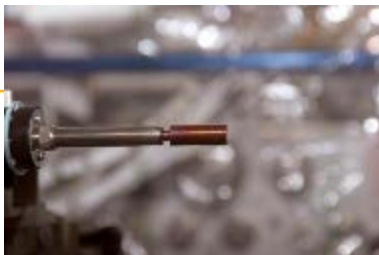
Polystyrene spheres 10 microns in diameter-calibration standard SRM 1965 for NBS

Superior product in terms of (1) sphericity (2) narrowness of size distribution (3) rigidity

## Bulk Metallic Glasses

Hinges, sliders, frames, display frames, miniature camera case, phone cases, golf clubs, surgical tools, SIM eject tool for iPhone

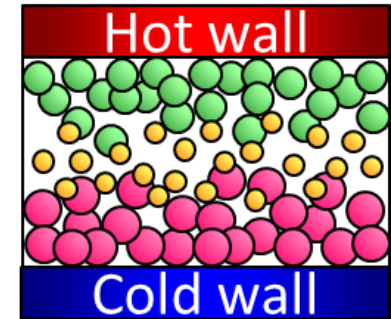
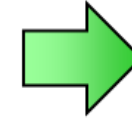
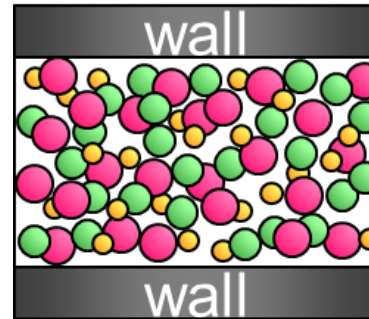
Helped develop BULK (vs thin) metallic glasses by acquiring understanding in microgravity underlying viscosity of



# SUCSESSE STORIES



single crystal area 35mm



## Exp

### Semiconductor crystals

Fabrication of low noise field effect transistors (FET's), analog switch integrated circuits (LCS)

Microgravity-grown crystals have  
 (1) increased single crystal size  
 (2) suppressed impurities and defects  
 (3) higher quality crystals

### Thermal Diffusion Coefficients

Database of Soret coefficients for various mixtures

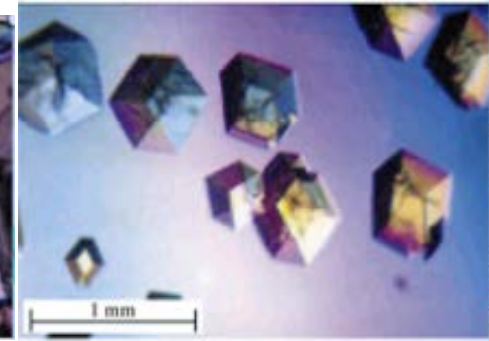
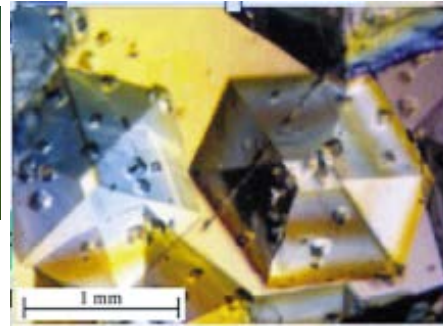
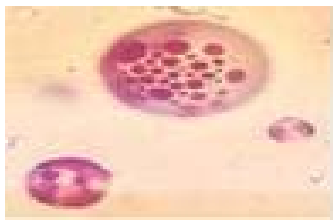
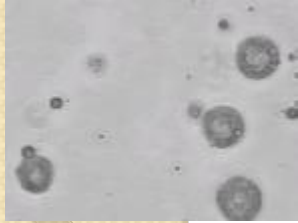
Capturing the diffusive aspect of thermodiffusion (no convection)

### Capillary Flow Experiments

Software for modeling of complex interface configurations.  
 New rapid diagnostic for infant HIV for the developing world,

Capturing fluid and bubbles system dynamics as driven by capillary and surface tension forces in microgravity (in the absence of buoyancy driven convection) has resulted in high performance,

# SUCSESSE STORIES



## Experi

### Microencapsulation

Bright Mark line of tissue site marker for accurate tumor diagnostic devices  
Chemo-FDA approved drugs contained in microcapsules (clinical trials entered in 2012) for local (vs systemic) cancer chemotherapeutic treatment

Pharmaceutical drug and its outer membrane form spontaneously improving ease of drug manufacturing and direct injection into tumoral tissue; controlled layering enables timed delivery of drug.

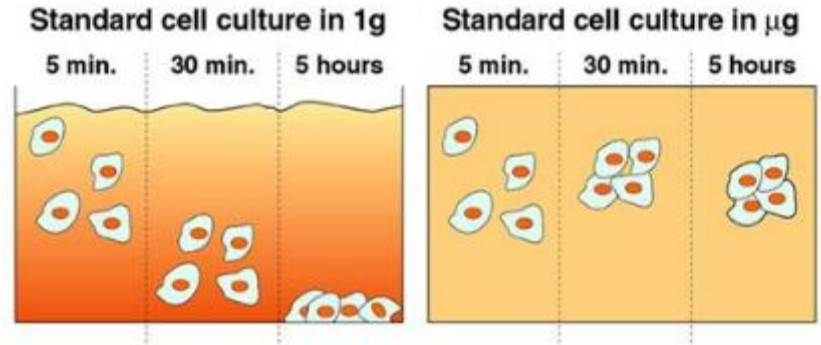
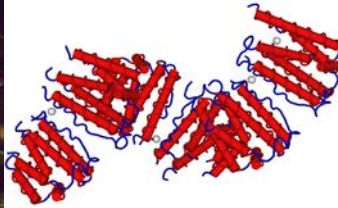
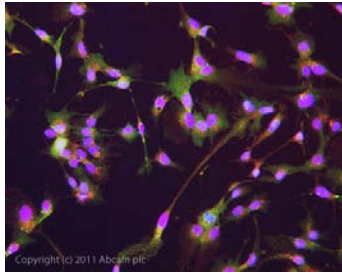
### Insulin crystals

Slow absorption diabetic drug

Well ordered, high resolution crystals of the T3R3 insulin hexamer variant were produced in microgravity resulting in designing a stable form that dissolves at the right rate inside the body<sup>6</sup>.



# SUCSESSE STORIES



## Experi

### Interferon

FDA approved Peg-Intron™, a pegylated alpha interferon formulation, for the treatment of chronic hepatitis C in January 2001.

STS-Microgravity experiments on alpha interferon, Intron A, for the first time provided Schering Plough Research Institute with large quantities of large, high quality crystals. This was a critical stimulus that enabled the company to demonstrate the crystals' suitability as a long lasting formulation, one of its goals.

### 3D cell cultures

39000 Rotating Wall Vessel/Bioreactor units. Synthecon is the manufacturer and distributor. Industry standard for 3D tissue cultures (non-animal origin)

Inspired by characteristics of microgravity, the design minimizes shear and turbulence in the mixing process and produces superior 3-D cell and tissue cultures

# NEAR TERM POTENTIAL

## Topic

ZBLAN optical fibers	Mid-IR lasers, Photonics, Thermal imaging, Sensing, Spectroscopy, Biomedical devices, telecom	Fibers made in microgravity would result in very low broadband attenuation (~100x better than currently used Si fibers)
3D tissue and tumor growth	Growth of patient derived tumor cultures for selection of chemotherapy drugs	Size of tumors grown in microgravity ~10x larger <sup>1</sup> than on ground and of higher tissue fidelity
Freeze cast foams	Bottom-up processing/manufacturing	Solid oxide fuel cells; ISRU; fast dissolving pharmaceutical tablets;
Zeolite crystals	Catalysts, ion exchangers; absorbents/separation; hydrogen storage; “green” household products; Photocatalysts	Growth of large, uniform, high-quality/zeotypes ETS titanosilicate crystals; reduced defect concentrations and types; attunement of chemical formulation, growth&composition
Field-Directed colloidal and nanoparticle self assemblies	Magneto-rheological (MR) dampers for energy absorption (earthquake, automobiles, trucks) Electro-rheological (ER) fluids for haptic controllers and	Knowledge: formation and dissolution of structures for rapid and reversible change of rheological properties. Microgravity offers a unique opportunity to interrogate the structural evolution, pattern formation and aggregation dynamic of dipolar suspensions.

# NEXT GENERATION

Topic		
Amyloid fibrils	Neurodegenerative diseases (Alzheimer, Parkinson)	Understanding disease mechanism
3D DNA	DNA nanotechnology, DNA based computing	DNA self-assembly crystals to control inter-molecular contacts
Nanoclays	Flammability inhibitors, rheological modifiers, gas absorbents, liquid crystal displays, drug carriers	More uniform clay-polymer mixtures generated in the microgravity environment with reduced mixing time.
Plant Cells	Essential oils, scents, flavors, biodiesel (Jatropha Curcas)	Breeding and genetic improvement by comparing cell differentiation and regeneration through gene-wide expression profiling in space and on Earth
Ultra thin coatings	Biocompatible coatings for implanted batteries&devices; photovoltaic coatings; semiconductor components manufacturing; storage systems; photoresist microelectronics	Gravitational forces create shear stresses in the flow introducing 3D instabilities (waves, ribs, streaks) in the film, directly altering device performance. In microgravity the surface tension&viscous forces in the meniscus region lead to smooth&uniform thin films.
Hollow bearings	Load-bearing machines with moving parts tribology	High sphericity, narrow size distribution, hollow: multimaterials multilayered

# SELECTED PUBLICATIONS

67<sup>th</sup> International Astronautical Congress, Toronto, Canada. Copyright ©2014 by the International Astronautical Federation. All rights reserved.

IAC-14A2.6.1

## MICROGRAVITY FOR ECONOMIC GROWTH AND PUBLIC BENEFIT

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Alexander C MacDonell  
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Two major objectives were foundational to President Obama's recent decision to extend operation of the International Space Station (ISS) to 2024: enable a broader flow of societal benefits from microgravity research on the ISS; and allow more time for NASA to fully transition the transportation to low-Earth-orbit to the commercial space industry. These objectives are intrinsically related. The recent successes achieved by the Commercial Orbital Transportation Program (COTP) Program offer new opportunities for affordable commercial Microgravity Research, which in turn helps fuel a new market sector for reentry...

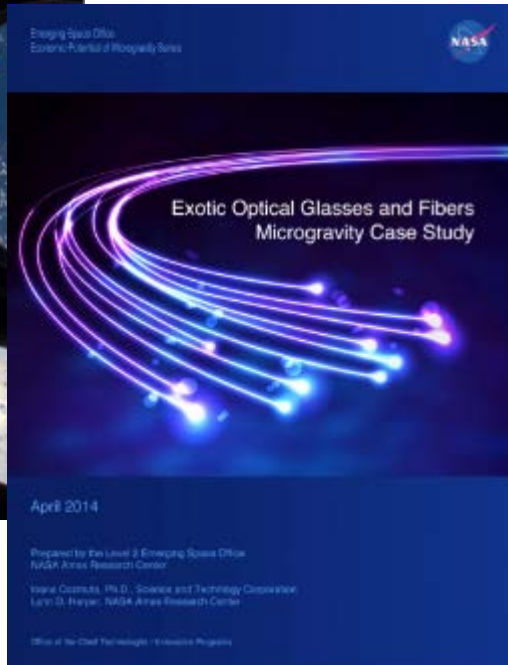
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Hewitt, Ma...  
Technology

IAC 14 08



## Microgravity session to support Degenerative Diseases – SBMT World Congress



## Building a robust commercial microgravity economy in Earth's orbit: Economic Readiness considerations

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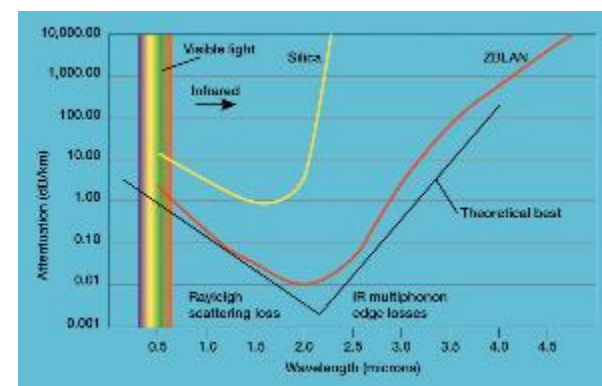


Our understanding of...  
in the science applicat...  
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rial benefit of commercial...  
applications ranges from...  
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is complexity can easily...  
... side with branding and...  
... types of added value that...  
... them, lessons learned from...  
... their successes, they have to...

Nanoscientific, Fall 2015

Ioana Cozmuta, et al; "Innovation at the Edge of Space: Commercial Microgravity Science" webinar: <https://attendee.gotowebinar.com/register/8328957085888480516>

# ZBLAN OPTICAL FIBERS



<b>ZBLAN optical fiber</b>	<ul style="list-style-type: none"><li>• Heavy metal fluoride glasses have been studied for ~35 years</li><li>• <math>\text{ZrF}_4\text{-BaF}_2\text{-LaF}_3\text{-AlF}_3\text{-NaF}</math> (ZBLAN) showed the most promise as optical fiber</li></ul>
<b>ZBLAN Properties</b>	<ul style="list-style-type: none"><li>• Most stable fluoride exotic glass and excellent host for doping</li><li>• Broad optical transmission window extending from ~0.3 microns UV out to ~5 microns IR</li><li>• Theoretical loss coefficient is 0.001 dB/km at 2 microns (~100x better than Si fibers)</li></ul>
<b>ZBLAN limitations and applications</b>	<ul style="list-style-type: none"><li>• Theoretical loss has not been achieved to date due to intrinsic and extrinsic processes</li><li>• Intrinsic and Extrinsic processes limit light propagation<ul style="list-style-type: none"><li>• Intrinsic: band gap absorption, Rayleigh scatter, multiphonon absorption</li><li>• Extrinsic: impurities such as rare-earth ions and crystallite formation</li></ul></li><li>• Applications: fiber amplifiers, fiber lasers, nuclear radiation resistant links</li></ul>

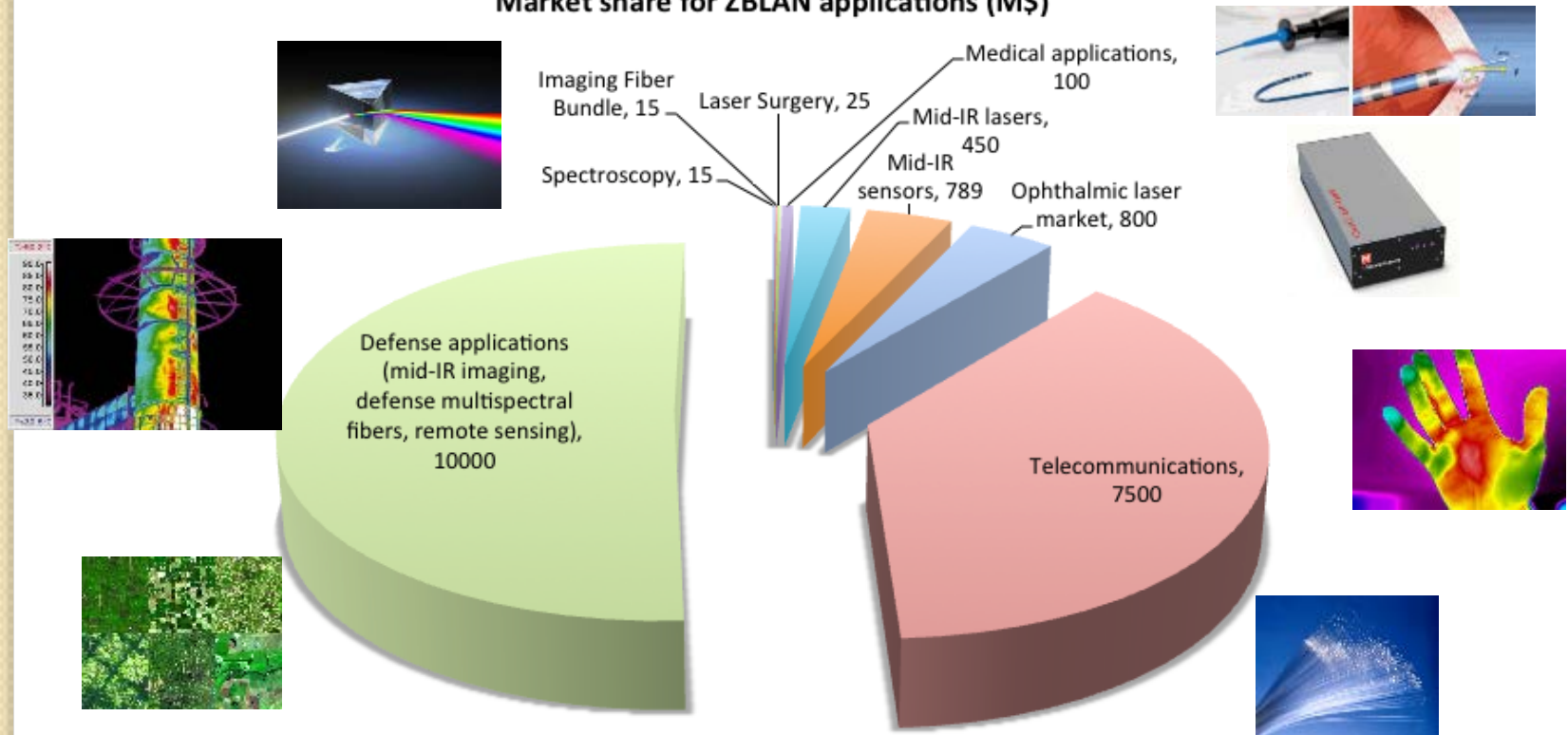
# MICROGRAVITY EXPERIMENTS

<b>Hardware and Procedure</b>	<ul style="list-style-type: none"><li>• ZBLAN fibers obtained from Infrared Focal Systems, Inc. and Bell Laboratories</li><li>• Fibers were stripped of coating and placed in evacuated quartz ampoules</li></ul>
<b>Parabolic Flights</b>	<ul style="list-style-type: none"><li>• Fibers first flown on NASA's KC135 Reduced Gravity Aircraft</li><li>• KC135 produces ~25 sec. of reduced gravity per parabola</li><li>• One week of flights led to ~200 total parabolas</li><li>• Fibers were heated to the crystallization temperature during reduced gravity and compared to unit gravity for the same amount of time</li></ul>
<b>Sub-orbital Flights</b>	<ul style="list-style-type: none"><li>• Fibers were flown on board Conquest sub-orbital rocket</li><li>• This flight gave 6.5 minutes of reduced gravity</li></ul>

# MICROGRAVITY FABRICATION

- Microgravity suppresses the effect of nucleation and crystallization – directly underlying attenuation-broadband properties
- No limit to the length that can be produced in space without need to adjust payload size (no need for drop towers)
- 1lb of preform would produce ~8 km ZBLAN fiber
- Nominal selling price range on Earth for space manufactured fibers: \$175k/km to \$1,000k/km ~ROI: 90-300x (w/o amortization costs)

Market share for ZBLAN applications (M\$)



# HISTORY & FUTURE STEPS TOWARDS ZBLAN COMMERCIALIZATION

## ZBLAN Investigation

Dr. Dennis Tucker

20 sec of  $\mu\text{g}$  (total 6.5 .....)

20+ samples



## SPACE PORTAL

Assessment of technical and commercial value  
CASIS engaged

Ground: Develop technology to make ZBLAN preform

ISS: Validate technology to make ZBLAN preform

ISS: Develop and validate technology to make other exotic fiber preform



1998

2012

2014

2015

2017

2020

Space made ZBLAN spools



## BURST OF PHOTONICS INDUSTRY

## PAYLOAD TESTED AT AF KIRKLAND

Dr. D. Starodubov/Physical Optics Corp

Preform reprocessing & fiber drawing in  $\mu\text{g}$

Few cm of fiber D-100 $\mu\text{m}$



## PAYLOAD DEVELOPMENT: Automated manufacturing

2015

2017

2020

ISS: One time operation  
15m of  $\mu\text{g}$  ZBLAN fiber  
100 $\mu\text{m}$  diameter

ISS: Multiple automated ops  
100m  $\mu\text{g}$  ZBLAN fiber  
100 $\mu\text{m}$  diameter  
MID-IR lasers

ISS: Multiple  
100m  $\mu\text{g}$  ZBLAN fiber  
20 cm diameter  
Telecommunications

**2024: BROADEN MANUFACTURING TO OTHER EXOTIC FIBERS**



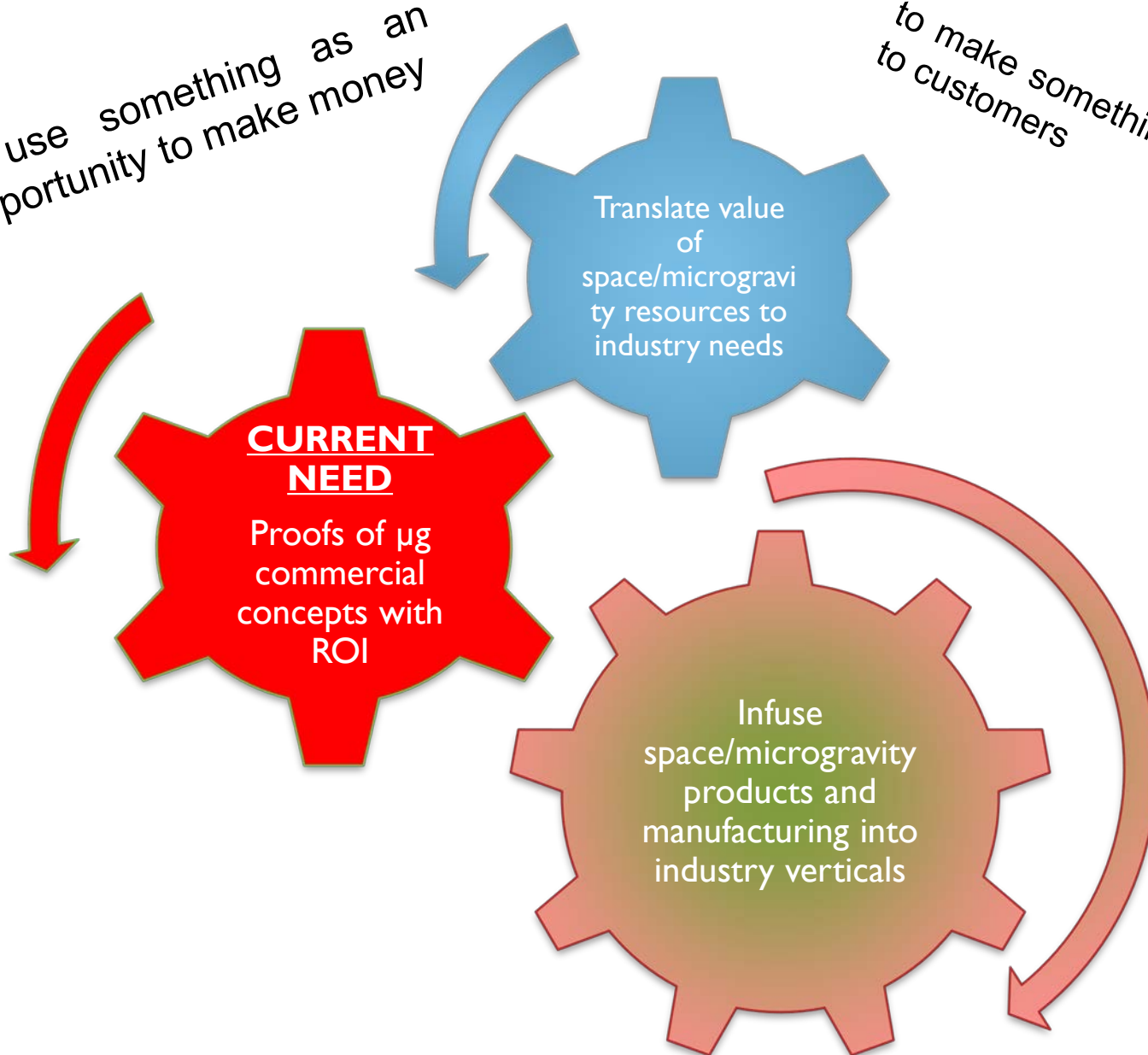
# ECONOMIC READINESS ASSESSMENT

- *Combines technology readiness, market need and investment risk*
- *Bridges between supply, demand and capital in a systematic, standardized manner.*
- *To advance on a Economic Readiness Level the technology itself may not necessarily need to mature but the understanding of its economic potential does.*
- *The ultimate goal of the TRL is to mature a technology from a fundamentally new idea (research) to incorporation and efficient use into a system by optimizing a program's performance, schedule and budget at key points of its life cycle.*
- *Commercializing a technology or “taking a technology to market” builds upon the alignment of the technological push with the business development and the market and economic pull*

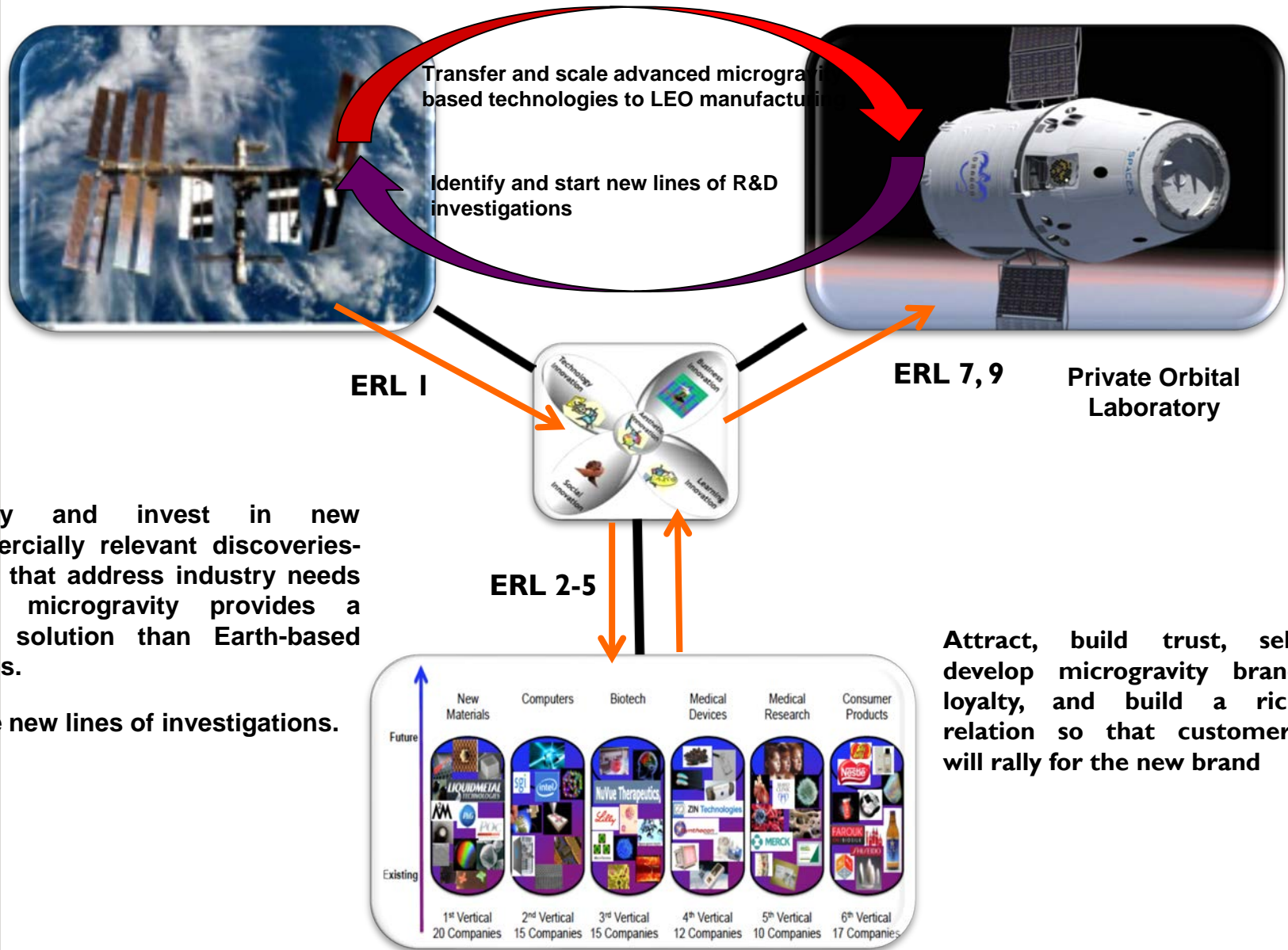
# THE MACHINERY OF COMMERCIALIZATION

to use something as an opportunity to make money

to make something available to customers



# COMMERCIAL MICROGRAVITY LEO BASED PRODUCT CYCLE



Identify and invest in new commercially relevant discoveries—topics that address industry needs where microgravity provides a better solution than Earth-based options.

Create new lines of investigations.

Attract, build trust, sell, develop microgravity brand loyalty, and build a rich relation so that customers will rally for the new brand

# PROTOTYPE LABORATORY FOR COMMERCIAL MICROGRAVITY

**BUILD A COALITION TO:**

- 1. DESIGN AND INTEGRATE THE COMPONENTS OF A MODULAR FREE FLYING COMMERCIAL INCUBATOR**
- 2. DEVELOP AN ATTRACTIVE BUSINESS VALUE PROPOSITION FOR PRIVATE SECTOR UTILIZATION OF COMMERCIAL MICROGRAVITY**

**EXOTIC OPTICAL FIBER  
MANUFACTURING UNIT**

**MODULAR BIOTECH&INDUSTRIAL  
MICROBIOLOGY**

**MATERIALS  
GROWTH&  
REPROCESSING UNIT**

**ROBOTICS &AUTOMATION**

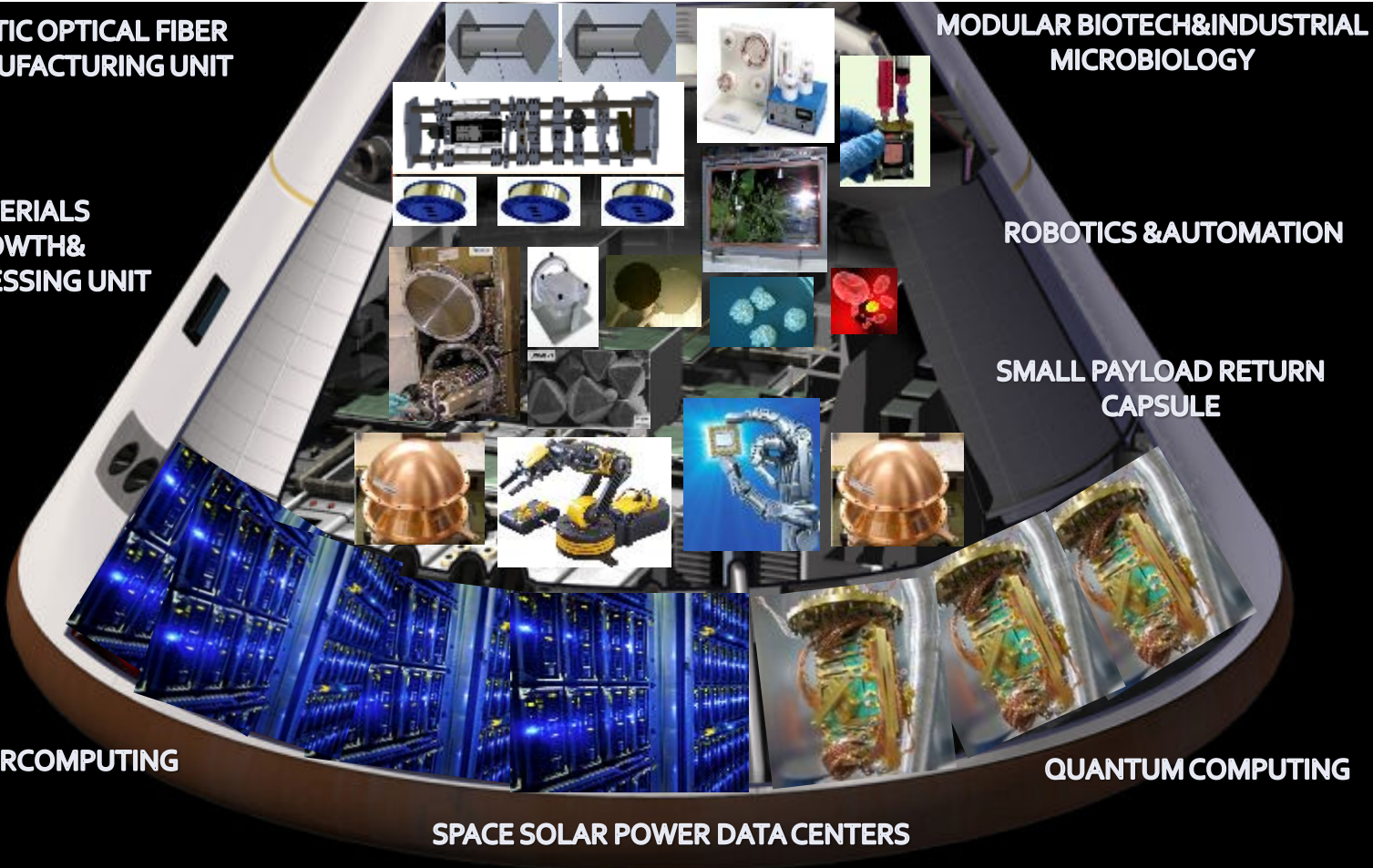
**SMALL PAYLOAD RETURN  
CAPSULE**

**SUPERCOMPUTING**

**QUANTUM COMPUTING**

**SPACE SOLAR POWER DATA CENTERS**

**PATENT PROVISION**



*Thank you!*

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# OBJECTIVE

## Assess the potential of microgravity for public benefit and economic growth over the next decade.

1. Potential	<p>What are the benefits of microgravity for material and life sciences?</p> <p>How deep is the understanding of the microgravity phenomenon?</p> <p>How can microgravity products or insights affect the state-of-the-art on Earth?</p> <p>What is their value/relevance in the current landscape of applications?</p>
2. Credibility	<p>How credible are the microgravity based results?</p> <p>What is the current appreciation and value of the microgravity based applications that have previously returned value to the tax payers?</p> <p>Are there revenue generating companies from a microgravity based product?</p>
3. Accessibility & Awareness	<p>Who is aware of microgravity and to what extent?</p> <p>How structured/accessible is the scientific and commercial value of microgravity?</p> <p>When challenged by a technical problem caused by gravity, do scientists in either the academic or the private sectors think of using microgravity to solve it?</p>
4. Interest	<p>To what extent is there interest in pursuing microgravity based investigations for new knowledge and product innovation?</p> <p>What are the target areas that would benefit most from R&amp;D in microgravity?</p> <p>What is the industry specific infusion point for microgravity driven discoveries?</p>
5. Commercialization	<p>What are generic challenges for commercialization? What are challenges specific to microgravity/space commercialization?</p> <p>What are commercialization challenges specific to a certain sector of the industry?</p> <p>What are driving incentives across the various sectors of the industry?</p>

# STRATEGY

## **Commercial Microgravity Products**

- Online research reviewing the entire ISS database (including the one behind the firewall), selected scientific literature, and spinoff databases to identify microgravity products for specific application areas.
- One-on-one interviews with PI's of microgravity investigations
- Discussions with industry scientists, chief technology and executive officers and venture capitalists from the private sector (mostly Silicon Valley)
- Summarized scientific publications, patents and spinoffs per application

## **Potential Microgravity Benefits and Solutions**

- Microgravity seminars at major universities across the US
- One-on-one discussions with faculty and students of various disciplines relevant to microgravity R&D.
- In-depth examination of promising topic areas, especially comparison and validation against current SOA on ground
- Technical exchanges among experts in microgravity research, PIs, microgravity commercial service providers, recognized scientists at the cutting edge of terrestrial SOA and potential commercial users of microgravity R&D .



# APPROACH

1. Identify products originating from microgravity research, describe their known technological advantages over Earth-manufactured counterparts, and provide clear traceability from microgravity R&D through product development.
2. Organize results with relevance to a specific application (across disciplines); results from most microgravity investigations branch out in a wide (sometimes unexpected) variety of areas
3. Identify potential microgravity-based technical solutions for commercial applications and their possible infusion points into the product development cycle, using results from step (1) and survey of existing market values to provide realism.
4. Evaluate potential commercial benefits from microgravity R&D over the next decade through the lens of the current state-of-the-art of analogous processes on the ground and anticipated industrial high-tech trends.
5. Select topics for in-depth case studies and obtain independent review and validation of findings by both technical and business experts for selected case studies and selected potential products.

# MICROGRAVITY PER DISCIPLINE

<b>Fundamental Physics</b>	<b>Fluid Physics</b>	<b>Material Science</b>	<b>Combustion science</b>
Test basic scientific theories	Perfect shape (surface tension)	Relationship: structure, properties, processing	Ignition
Thermodynamics	Surface tension driven flow	Production of alloys and composites	Flame spreading
Atomic physics	Welding	Dendrites	Flame extinction
Relativistic physics	Dynamics of liquid drops	Ceramics and glass experiments	Role of soot formation
Low-temperature physics	Microfluidics	Optical engineering	Air flow, heat transfer
Heat energy	Dynamics of gases	Containerless processing	
New forms of matter			