Nanotechnology Presentation Agenda

7:30	Continental Breakfast	
8:00	Welcome and Review Process, Panel Chair & NRC Staff	
8:15	Introduction by APIO to NASA Capability Roadmapping	Julie Crooke
8:50	Nanotechnology Presentation Agenda	Murray Hirschbein, NASA
9:00	Background: Nanotechnology at NASA	Minoo Dastoor, NASA
9:45 - 10:15	– *Break* –	
10:15	Overview and Summaries of Roadmapping Activity	Minoo Dastoor, NASA
10:45	Nano-Structured Materials	Ilhan Aksay, Princeton (Mike Meador and Len Yowell, NASA)
11:15	Sensors and Devices	David Janes, Purdue (Harry Partridge, NASA)
11:45 - 12:45	– *Lunch* –	
12:45	Intelligent/Integrated Systems	Chih-Minh Ho, UCLA (Benny Toomarian, JPL)
1:15	Summary and Next Steps	Minoo Dastoor
1:30	Closure and Crosswalk (with other Roadmaps)	Murray Hirschbein
2:00	Open Discussion	
3:30	– *Break*/NRC Panel Closed Session –	
4:15	NRC Panel Discussion with NASA	
5:00	Adjourn	

Background: Nanotechnology at NASA

Background: Nanotechnology at NASA

Presentation to the National Research Council

March 8, 2005
Washington, D.C.

Co-Chairs:

M. Dastoor (NASA HQ) M. Hirschbein (NASA HQ) D. Lagoudas (Texas A&M)

Nanotechnology

Advanced Planning & Integration Office

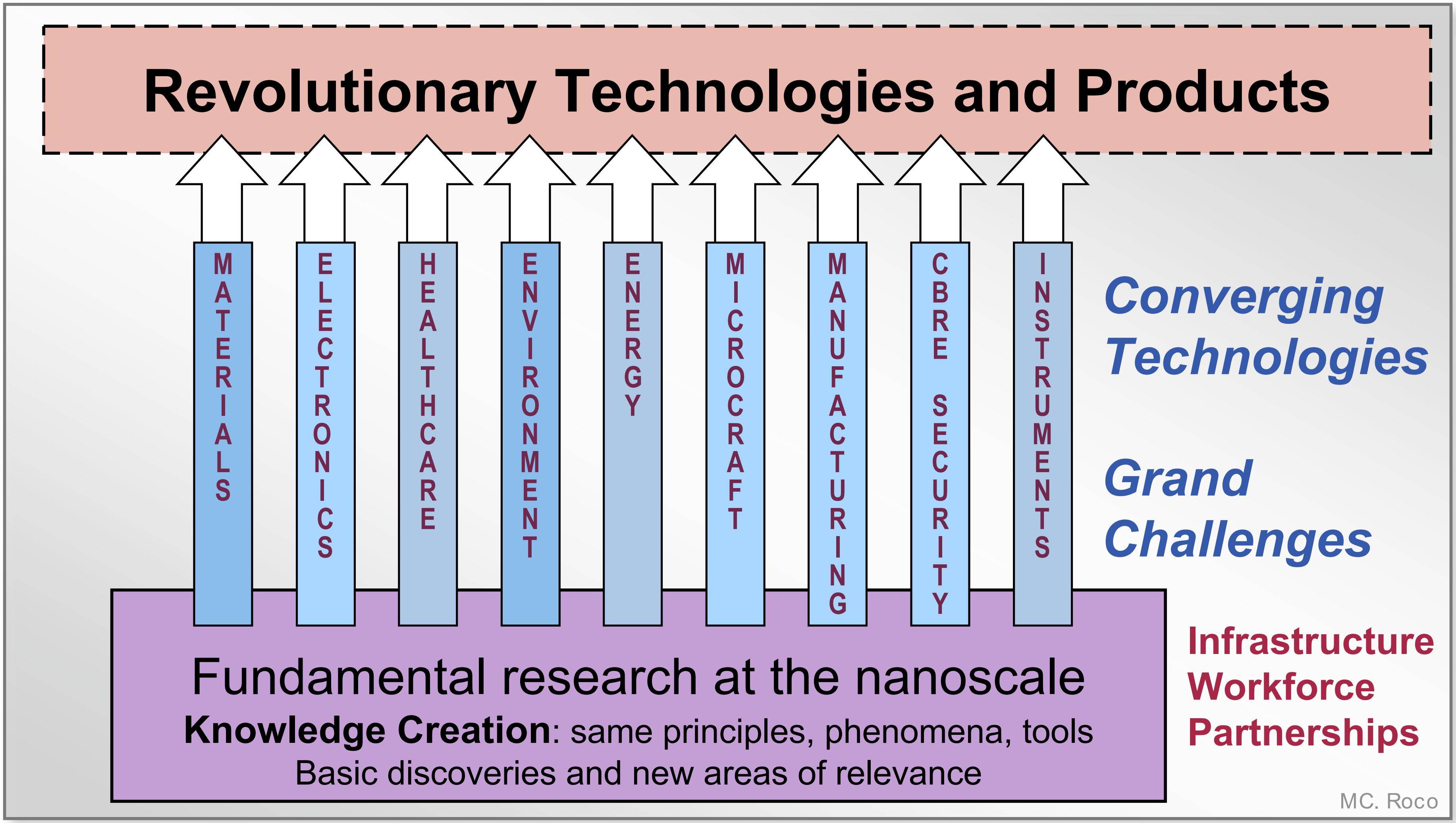
- **Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 *nm* range, in order to understand, create and use materials, devices and systems with fundamentally new properties and functions because of their small structure**

- **NNI definition encourages new contributions that were not possible before.**
  - novel phenomena, properties and functions at nanoscale, which are nonscalable outside of the nm domain
  - the ability to measure / control / manipulate matter at the nanoscale in order to change those properties and functions
  - integration along length scales, and fields of application

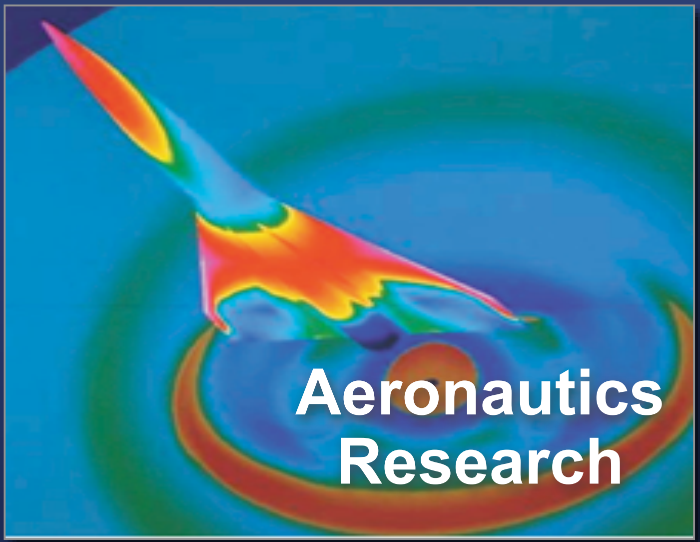
Interdisciplinary "horizontal" Knowledge Creation

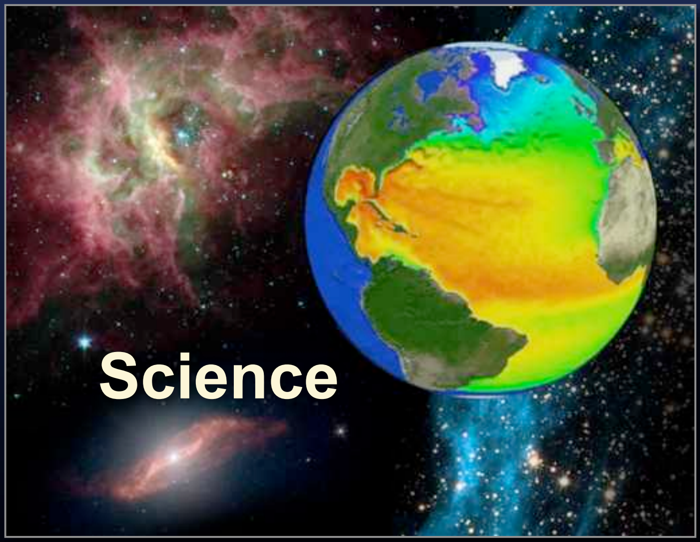
with "vertical" transition from basic concepts to Grand Challenges and technology integration - Converging Technologies

Advanced Planning & Integration Office



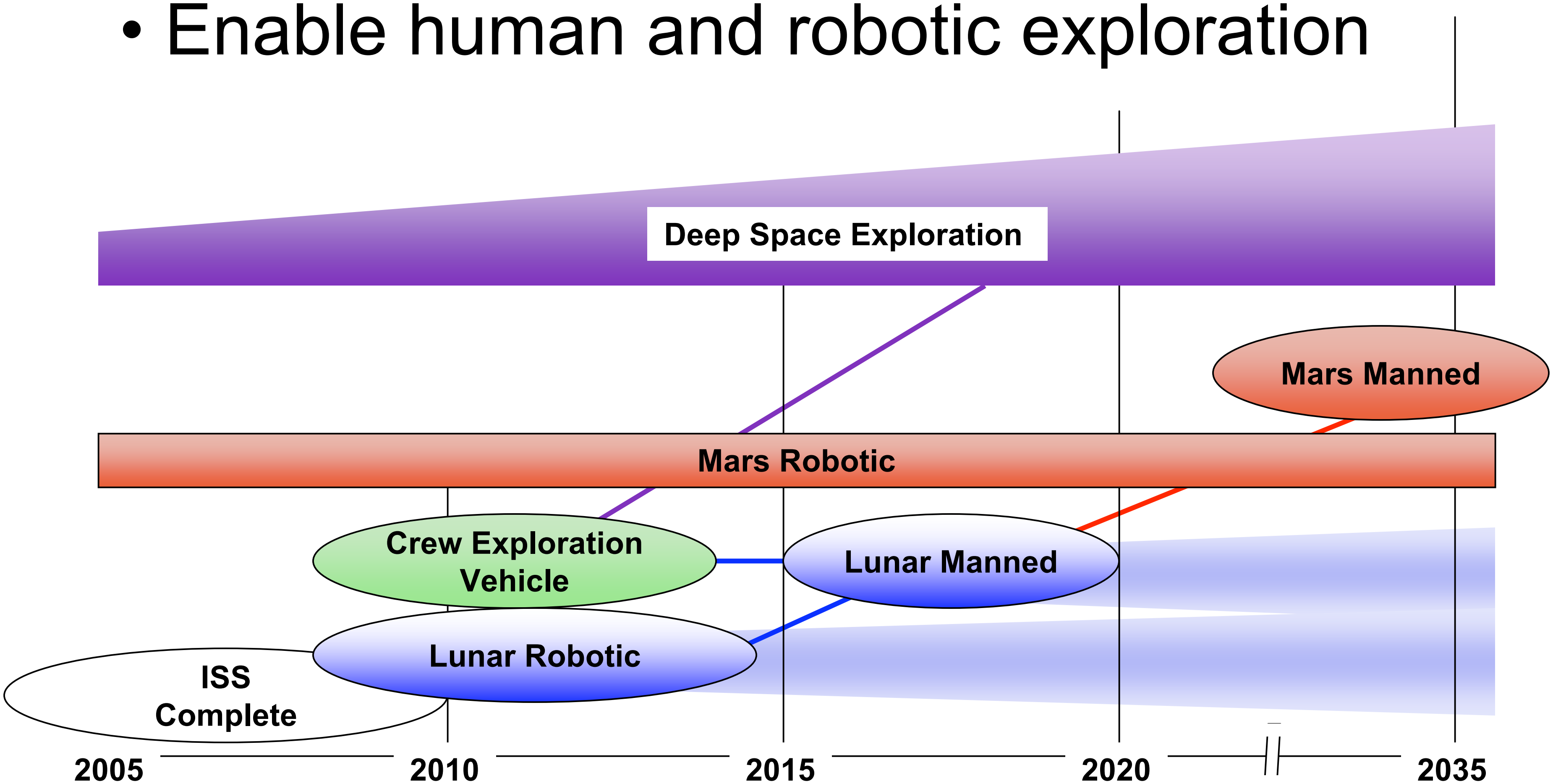
NASA's Strategic Enterprises





The Space Exploration Plan

- Enable human and robotic exploration



Astronaut Health Management

Personal Biomedical Monitoring

- Identification of molecular indicators for onset of conditions
- High sensitivity assays
- Short prep-time assays, no prep-time assays and in vivo monitoring
- Multiple simultaneous assays

Major Medical Operations

- Contrast agents to target specific sites for surgery
- Bio-mimetic or engineered compounds to help wound healing
- Miniaturized electron microscopes for biopsies

Personal Countermeasures

- Timed drug release
- Targeted drug therapy
- Triggered drug release
- Indicators for drugs effectiveness

Life Support

- High surface area materials for CO_2 removal
- Inorganic coatings that catalyze the revitalization of air and water
- Sensors to monitor harmful vapor and gases

Basic Biomedical Research

- The role that forces plays on cell mechanisms (gravitational forces)
- Molecular machines (ATPase, Kinesin, Microtubules, Polymerase, etc.)
- In vivo monitoring of ultra-low concentration proteins and biomolecules

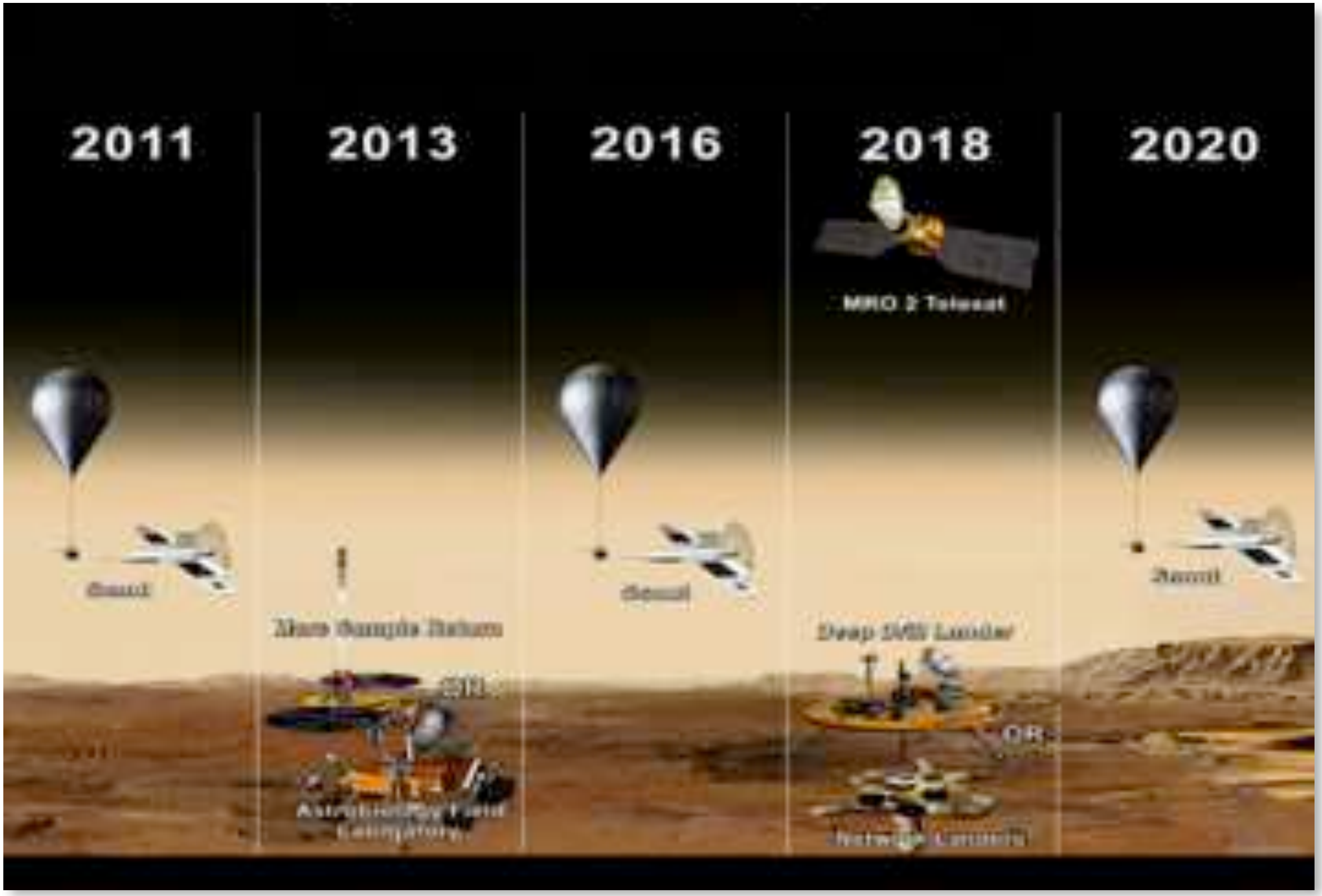
Toxicology & Ethics

- Biodistribution of nanoparticles
- Toxicology of nanoparticles
- Ethical use of information from nanotech devices

Systems Integration

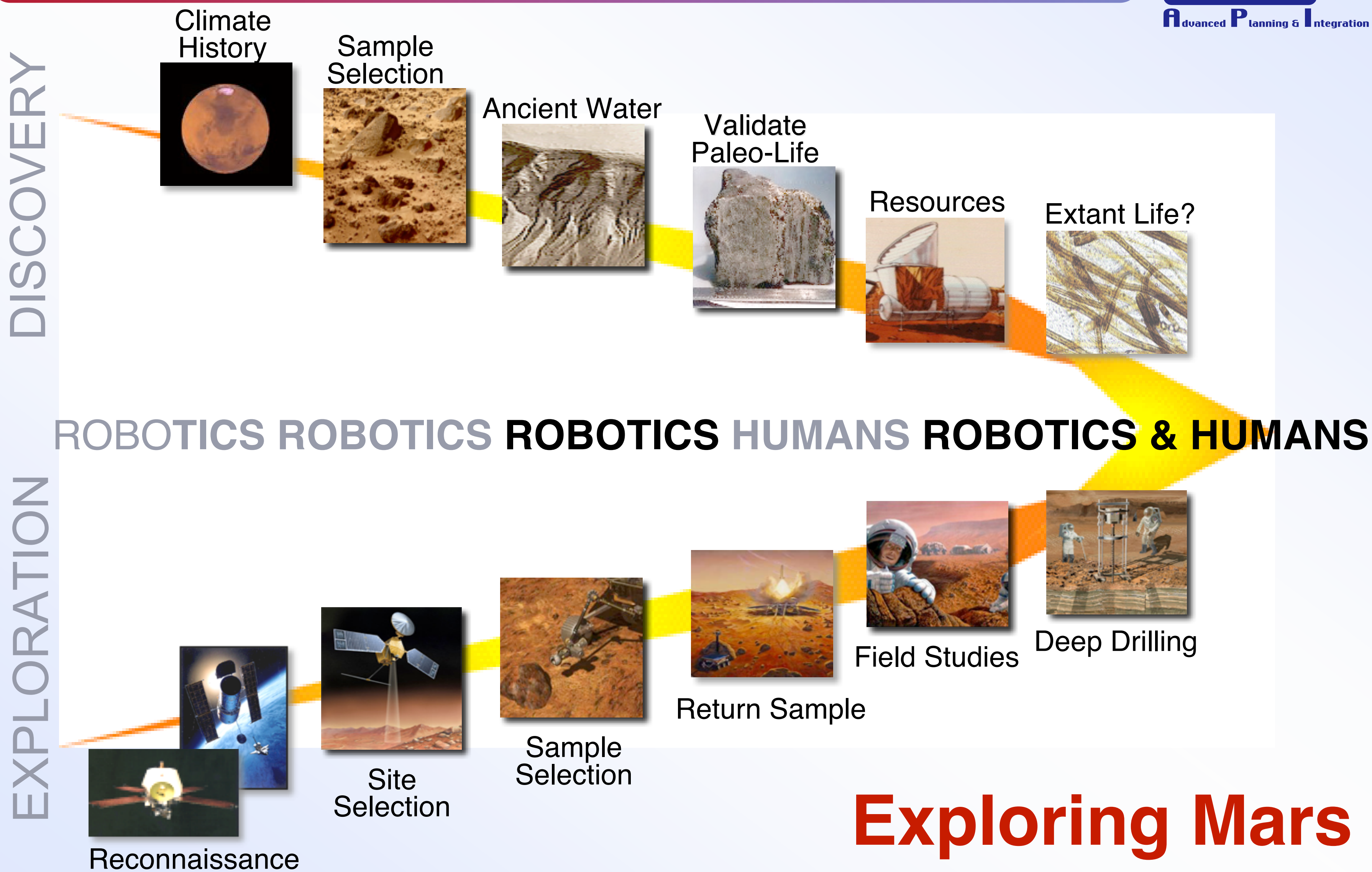
- Develop ‘common toolkit’ for bio-nano chemistry and assembly processes

Mars Exploration Pathway - Next Decade

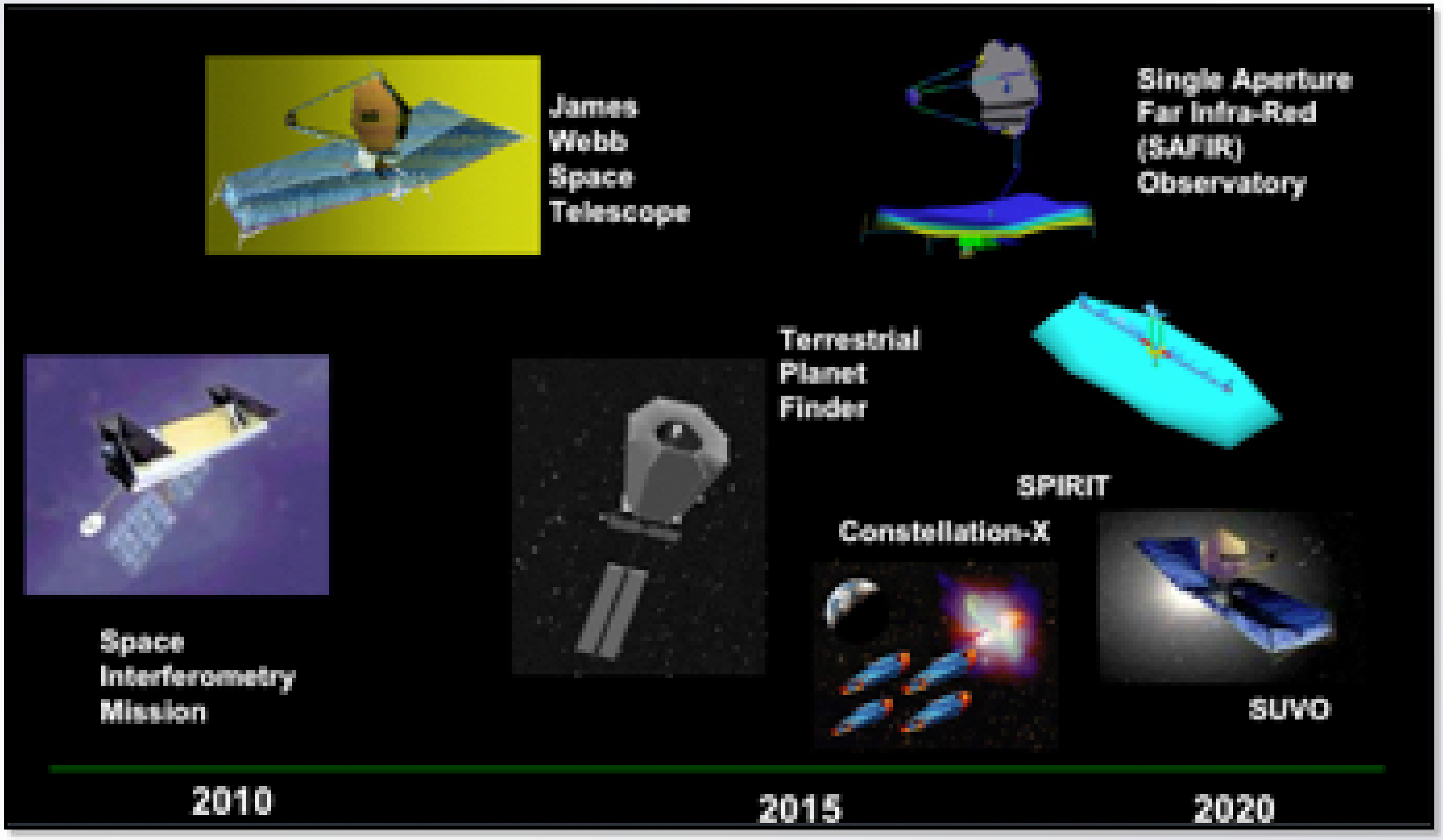


Capability Roadmap: Nanotechnology

Towards Convergence



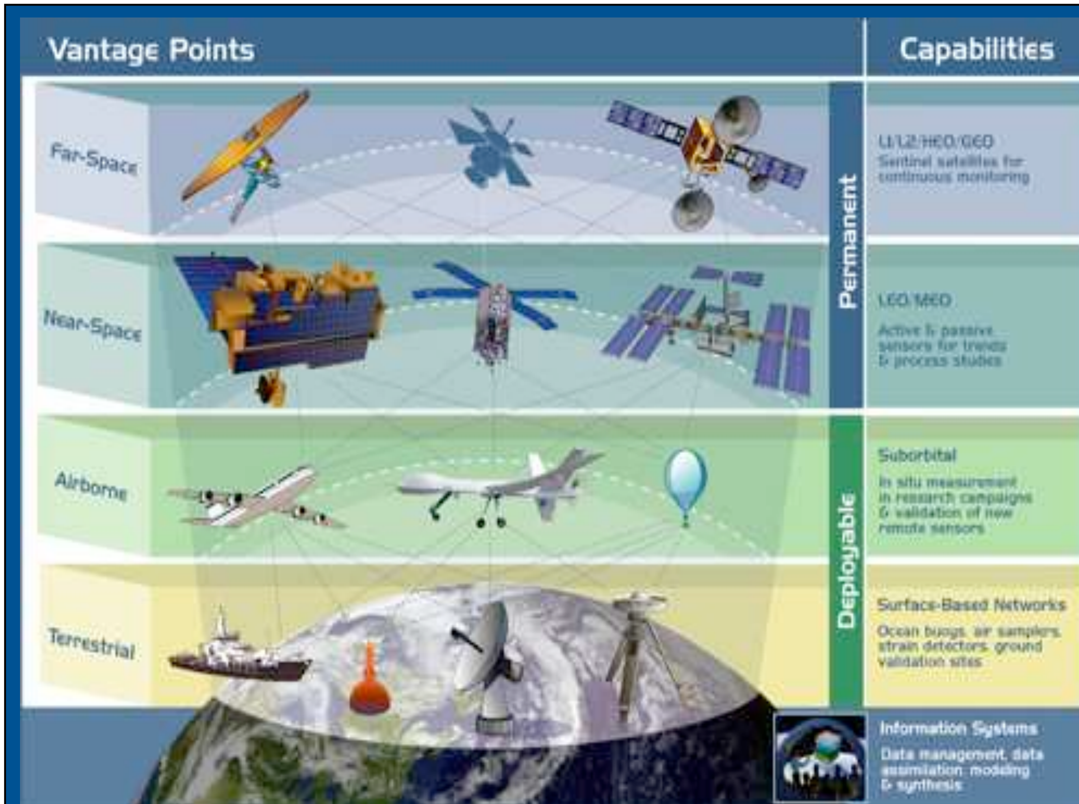
Next Generation of Observatories



Capability Roadmap: Nanotechnology

Observing Sensor Webs: *A System of Systems*

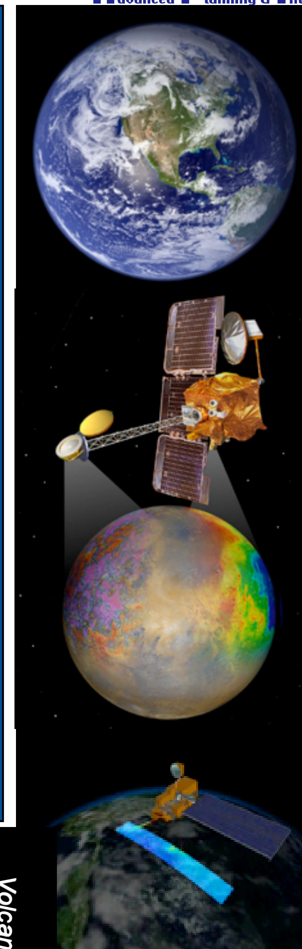
Advanced Planning & Integration Office



Space

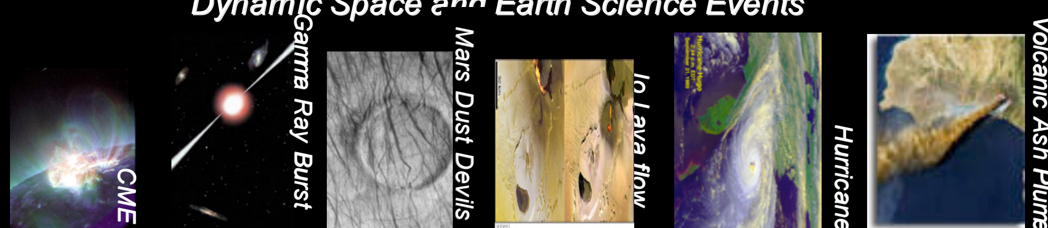
Airborne/ Suborbital

Surface/ Subsurface



The Bigger Picture…

Dynamic Space and Earth Science Events



Aeronautics Challenges

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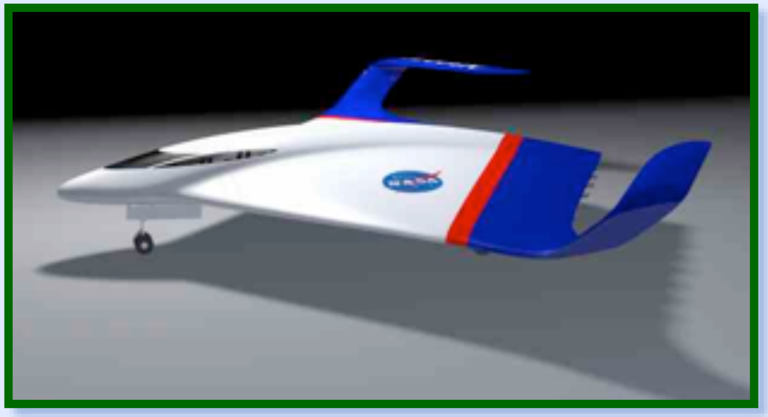
Hydrogen fuel, electric propulsion
– zero environmental impact



Clean and Quiet Aircraft

- Light Weight
- High Strength
- High Reliability
- High Efficiency

High Altitude and Long Endurance (HALE) for….

Science and….

"Perpetual Flight"

Exploration ….

About the Earth and Other Planets

Overarching Needs

- Performance in Extreme Environments (Radiation, Temperature, Zero Gravity, Vacuum)
- Light Weight
- Frugal Power Availability (for Space Systems)
- High Degree of Autonomy and Reliability
- Human “Agents” and “Amplifiers”

Impact of Nanotechnology on NASA Missions

- **New and Powerful computing technologies**
  - Onboard computing systems for future autonomous intelligent vehicles; powerful, compact, low power consumption, radiation hard
  - High performance computing (Tera- and Peta-flops)
    - processing satellite data
    - integrated space vehicle design tools
    - climate modeling

- **Smart, compact devices and sensors**
  - Ultimate sensitivity to analytes
  - Discrimination against varying and unknown backgrounds
  - Ultrasmall probes for harsh environments
  - Advanced miniaturization of all systems

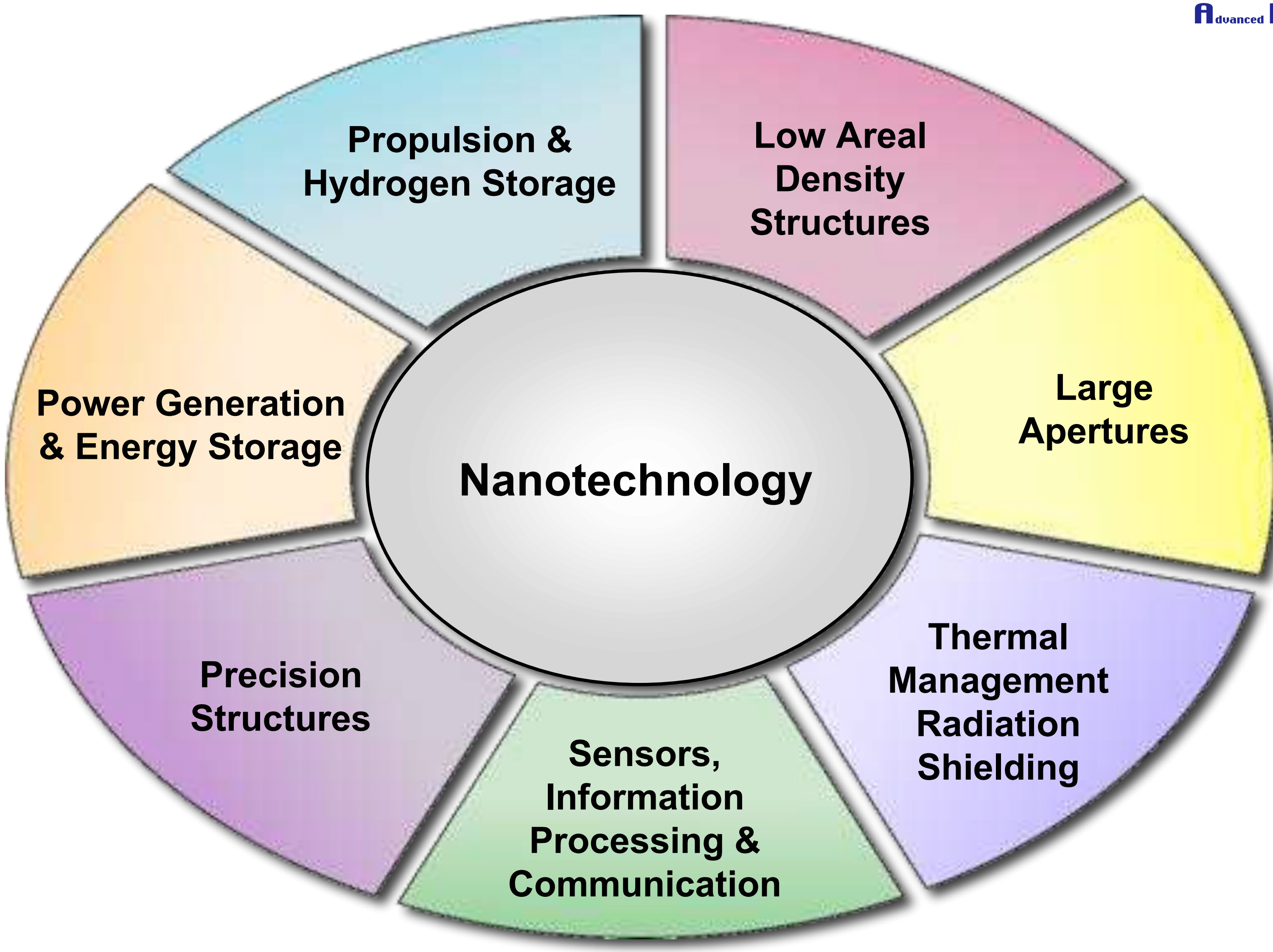
- **Microspacecraft/Micro-Nanorovers**
  - "Thinking" Spacecraft with nanoelectronics/nanosensors
  - Size reduction through multifunctional, smart nanomaterials

Capability Roadmap: Nanotechnology
High Impact Application Areas for Nanotechnology: Exploration Missions

Advanced Planning & Integration Office

- **Advanced Materials**
  - High strength-to-weight composites for vehicle primary structures and habitats
  - Hydrogen resistant nanostructured materials for cryotanks
  - High thermal conductivity materials for heat sinks, heat pipes, and radiators
  - High temperature materials for propulsion systems and thermal protection systems
  - High electrical conductivity materials for wiring
  - Self-healing materials for repairing impact damage and wire insulation
  - Space-durable materials resistant to ultraviolet and particle radiation
  - Self-assembling materials for in-space fabrication
- **Power**
  - High energy density batteries and fuel cells
  - High efficiency photovoltaic cells
- **Sensing**
  - Bio-chemical sensors for monitoring environmental contaminants in crew habitats
  - Bio-chemical sensors for detecting the signatures of life on other planets
  - Chemical systems for identifying, processing, and utilizing planetary resources
- **Integral Health Management**
  - Systems that incorporate integral sensors and processors for fault detection and diagnosis
- **High Performance Computing**
  - Fault-tolerant reconfigurable processors, micro-controllers, and storage devices
- **Extreme Environment Electronics**
  - Microelectronic devices that can operate reliably in extreme temperature and radiation environments

Capability Roadmap: Nanotechnology
High Impact Application Areas for Nanotechnology: Science Missions



Focus of NASA Investment

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Nanostructured Materials
- High strength/mass, smart materials for aerospace vehicles and large space structures
- Materials with programmable optical/thermal/mechanical/other properties
- Materials for high-efficiency energy conversion and for low temperature coolers
- Materials with embedded sensing/compensating systems for reliability and safety

Nano Electronics and Computing
- Devices for ultra high-capability, low-power computing & communication systems
- Space qualified data storage
- Novel IT architecture for fault and radiation tolerance
- Bio-inspired adaptable, self-healing systems for extended missions

Sensors and Microspacecraft Components
- Low-power, integrable nano devices for miniature space systems
- Quantum devices and systems for ultrasensitive detection, analysis and communication
- NEMS flight system @ 1μW
- Bio-geo-chem lab-on-a-chip for in situ science and life detection

University Research Engineering and Technology Institutes
- Bio-nano-information technology fusion (UCLA)
- Bio-nanotechnology materials and structures (Princeton)
- Bio-nanotechnology materials and structures (Texas A&M)
- Nanoelectronics computing (Purdue)

Capability Roadmap: Nanotechnology
University Research, Engineering & Technology Institutes (URETIs)

Bio-Inspired Design and Processing of Multi-Functional Nano-Composites (BIMat)

- Design and modeling of hierarchically structured materials capable of bio-sensing catalysis and self-healing

- **Princeton**
- UCSB
- Northwestern
- U of NC
- Nat'l Inst. Aerospace

Institute for Nanoelectronics and Computing (INAC)

- Develop fundamental knowledge and enabling technologies in: ultradense memory, ultraperformance devices, integrated sensors, and adaptive systems

- **Purdue**
- Yale
- Northwestern
- U of Fl
- Cornell
- UCSD
- Texas A&M

URETIs

Institute for Intelligent Bio-Nano Materials and Structures for Aerospace Vehicles (TiiMS)

- Basic and applied research in: the integration of sensing, computing, actuation and communication in smart materials

- **Texas A&M**
- Rice
- Texas Southern
- Prairie View A&M
- U of T-A
- U of Houston

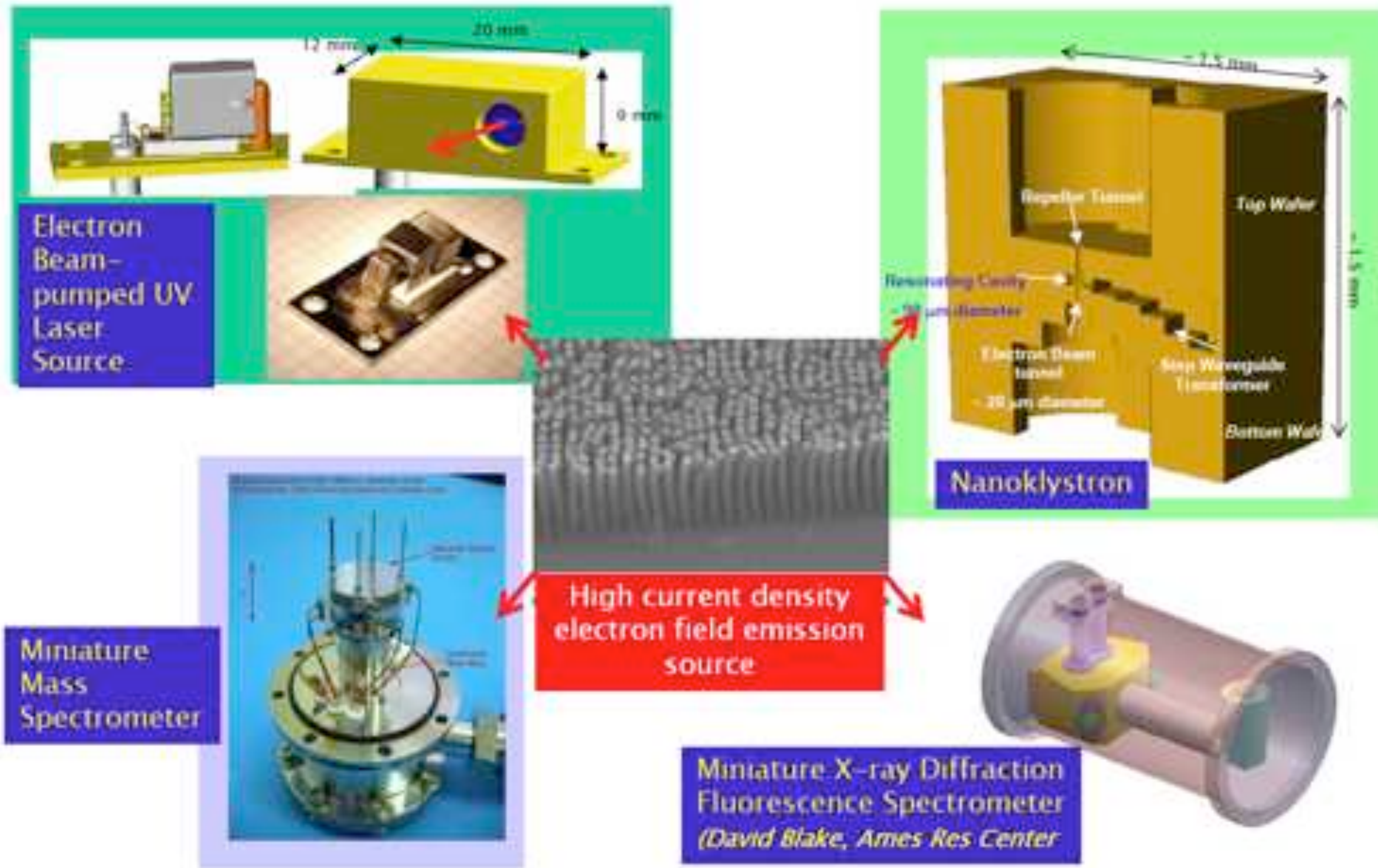
Center for Cell Mimetic Space Exploration (CMISE)

- Bio-informatics for the development of new, scalable nano-technologies in sensors, actuators and energy sources

- **UCLA**
- CIT
- Ariz. St
- UCI

Capability Roadmap: Nanotechnology

Electron Sources - Application Regimes



Future Research Directions

NOVEL PHENOMENA

Present Phase

- Production of Nanomaterials
- Characterization at Atomic/Bulk Scale
- Nanoscale Modeling and Simulation

Next Phase

- Integration of “Nanoworld” with the “Macroworld”
- Integration of Wet World with Dry World
- Emergence of Intelligence from Complexity
- Multi-scale Modeling and Simulation Hierarchy

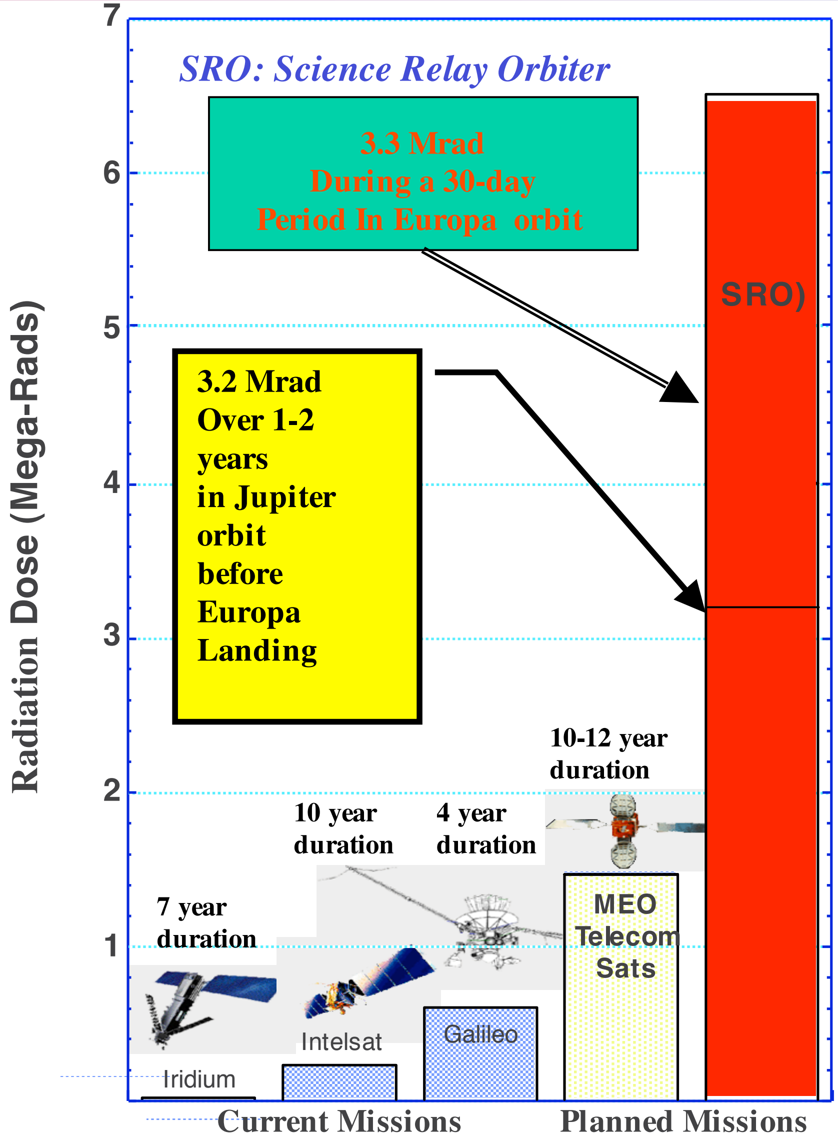
NOVEL PHYSICS (NANOSCALE)

Barriers and Challenges for Nanotechnology

- **Science at the nanoscale**
  - The Physics of the behavior of molecules/atoms at the mesoscale is poorly understood. The full potential of nanotechnology will be realized when such “new” laws are established.
- **Production of nanomaterials**
  - Quantity, quality, control of properties & production in specified forms
- **Characterization at both atomic and bulk scale**
  - Fundamental mechanical, electrical and optical properties
- **Modeling & Simulation**
  - Prediction of physical/chemical properties and behavior from nanoscale to macroscale as well as models for material production

Backup

Europa Lander: Radiation Dose

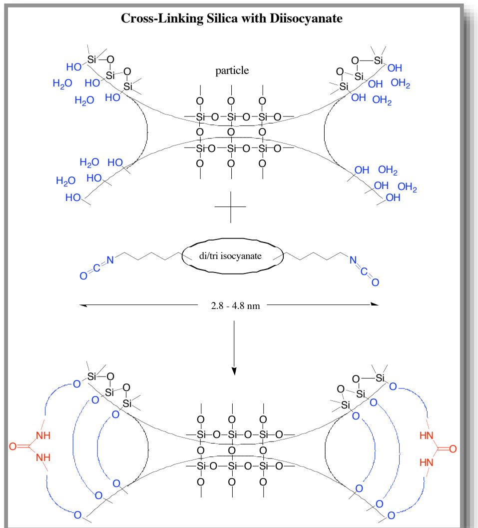


Capability Roadmap: Nanotechnology

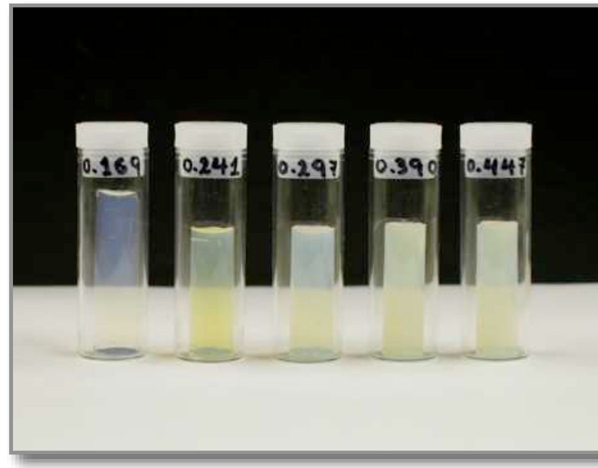
X-Aerogels Have Potential as Structural Materials

Advanced Planning & Integration Office

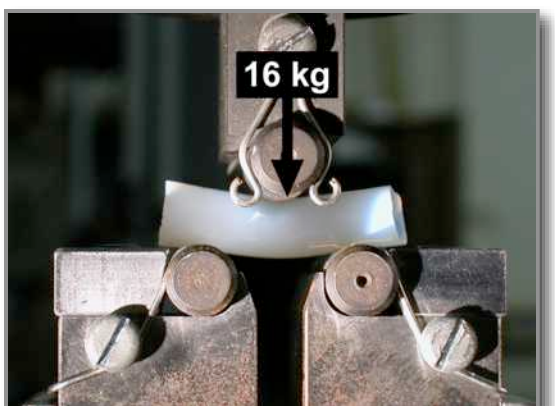
Versatile Cross-linking Chemistry



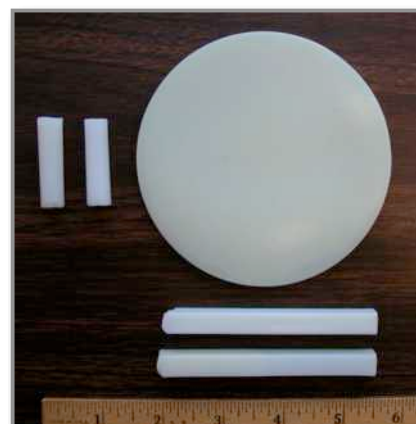
Tailorable Properties



400 Fold Increase in Strength



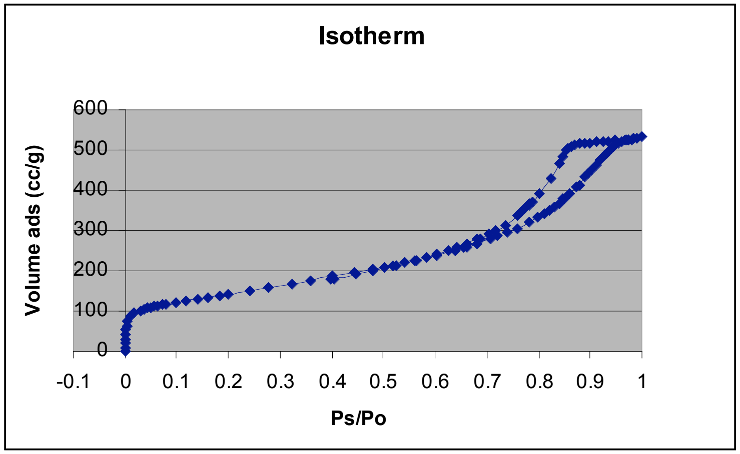
Simplified (Ambient Pressure) Processing, Improved Machinability

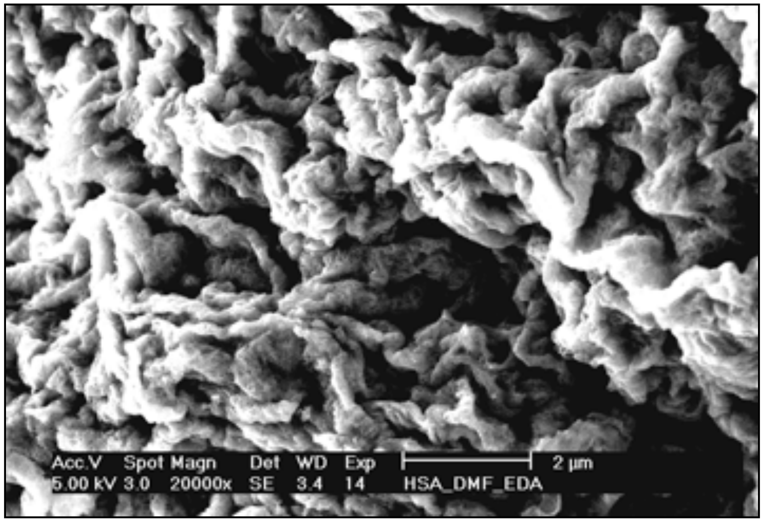


Air Revitalization: Regenerable CO_2 Removal

- Modified Ames process for high/engineered surface area
- Characterization of SWCNT material:
  - BET – Quantitative surface area + pore size
  - SEM – Qualitative surface area characteristics
- **Initial Performance Test:**
  - Solid amine coating: University of Connecticut
  - **Thermogravimetric Equilibrium Experiment**
    - **Pressure Swing**
    - **Temperature Swing**

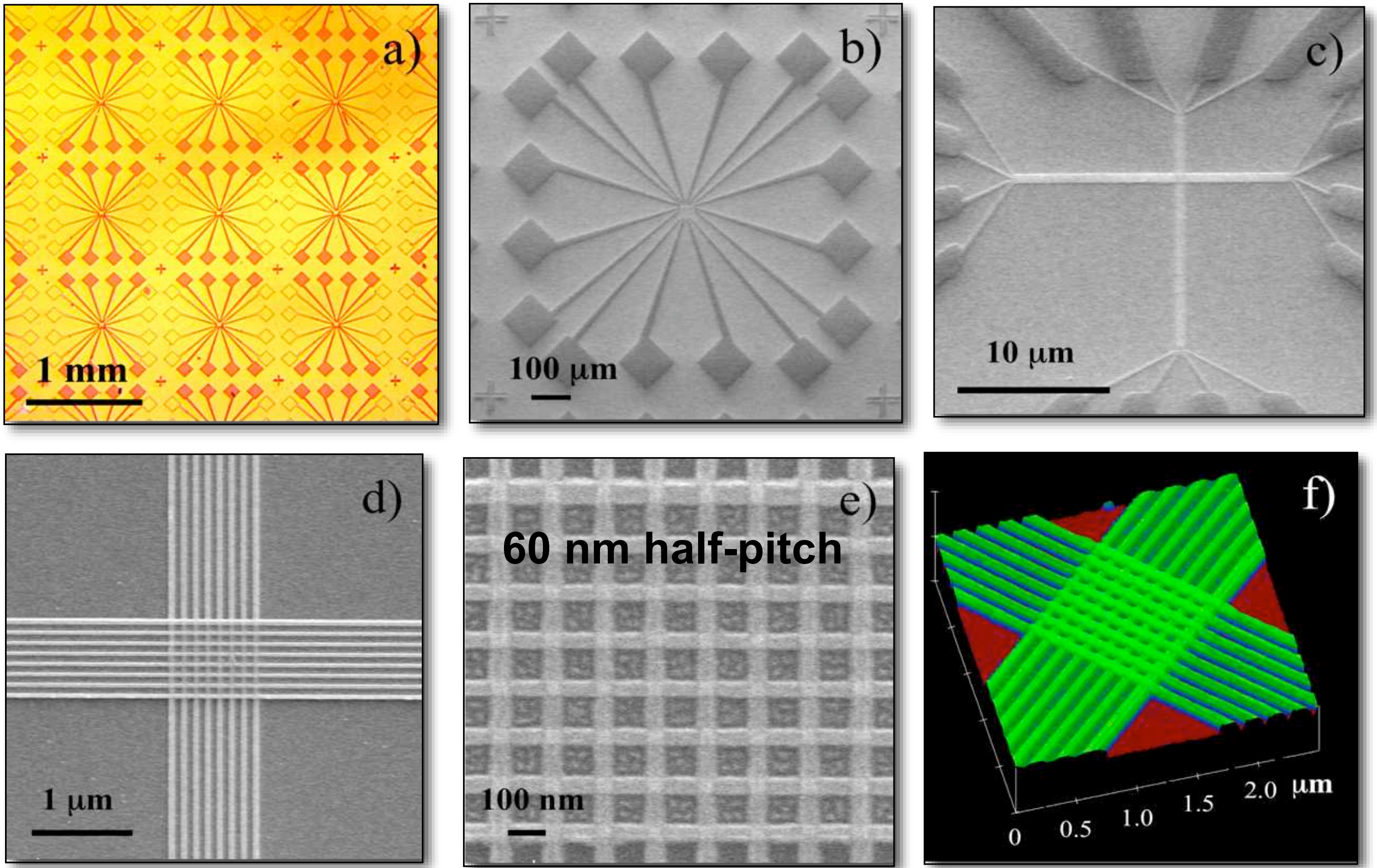
BET Surface area 510 m^2/g





- **Reduce system volume**
- **Increase efficiency**
- **DoE Smokestack application**

Nano-imprinted Crossbar Arrays



Courtesy of Stan Williams, Hewlett-Packard

NASA Grand Challenge Workshop

- **September 2004 Workshop on Micro-Spacecraft and Robotics**
  - NASA-led National Nanotechnology Initiative Grand Challenge area
  - Expanded scope covered elements of President's Exploration Vision
    - Nano-materials
    - Nano-Sensors and Instruments
    - Nano-Robotics
    - Nano-Micro-Macro Integration
    - Microcraft
    - Astronaut Health Management

Charge To Workshop Breakout Sessions

Advanced Planning & Integration Office

Microcraft
Deep Space Probes
Orbiters
Planetary Entry / Surface Probes
Micro/Nano/Pico-craft

Nano-Micro-Macro Integration
Electronics
Sensors / Instrumentation
Actuators
New algorithms
Communications

Nanomaterials
Structural
Power / Energy Storage
Thermal Management
Shielding
Multifunctionality

Executive Summary:
- Goals
- Value
- Hard Problems
- SOA

Nanorobotics
Actuation and Control
Molecular Actuation
Micromachines

Nanosensors and Instrumentation
Biological
Chemical
Radiological
System / Vehicle Health
In-situ Analysis

Astronaut Health Management
Personal Biomedical Monitoring
Personal Countermeasures
Basic Biomedical Research
Major Medical Operations
Life Support

Microcraft & Constellations Summary

Goals

- Reduce mass of microcraft by factor of ~100 in 10 years and ~1000 in 20 years, while maintaining full functional capability at no increase in cost/kg
- Fly "Constellations" of 100s-1000s microcraft and enable them to managed by a few (maybe only one) human operators

Hard Problems

- Systems-level design and integration of nanotechnology into single microcraft and constellations for ≥ 10X performance over SOA: power, propulsion, communications, computing, sensing, thermal control, guidance/navigation, etc.
- Assuring durability and endurance, especially in harsh environments
- Increase on-board computational performance by ~100X for self-directed, intelligent operations

Value to Space Systems

- Much greater capability at much lower cost
- Distributed robust monitoring and inspection for safer operations
- Simultaneous dense sampling of phenomena for exploration and accurate modeling of Earth, planetary, and space environments

State of the Art

- Commercial satellites (e.g. Orbcom) @ 40Kg
- Sojourner Mars Rover @ 11.5 kg
- "Picosats" (some MEMS) 0.27 to 1 Kg flown on expendable and STS vehicles
- Variety of lab prototype vehicles at 10-100 g, all with sensing, computation, communications, and actuation

Capability Roadmap: Nanotechnology

Astronaut Health Management Summary

Advanced Planning & Integration Office

Goals

- To provide medical care (prevent, diagnose, and treat) during long-term transportation and extended presence in Moon and Mars
- The rapid development in the field of nanotechnology and biotechnology will provide significant solutions in the Astronaut Health Management arena during the long-term manned mission to Moon and Mars

Hard Problems

- Biocompatibility, especially toxicity of the nano-derived systems with the humans
- Management of the large volume of data and timely analysis of the data for medical assessment and subsequent treatment
- Integration of different disciplines from product development to clinical maturation
- Requirement for instrumentation autonomy while maintaining reliability

Value to Space Systems

- Screening for Personnel for minimal risk (radiation susceptibility, genetically high risk)
- Monitoring and countermeasure (radiation, bone loss, immune, muscle…)
- Autonomous Medical Care (Non-invasive Diagnostics, non-invasive imaging and Therapeutics, blood replacement therapy)
- Atmosphere monitoring and control (Environmental parameters, contaminants)
- Human Factors (Early assessment of performance quality)
- Antimicrobial coatings, High capacity regenerative adsorbants, Food packaging

State of the Art

In Shuttle and ISS

- Hearing test – EarQ
- Monitoring Heart Rate and Oxygen Consumption during exercise work load.
- Assess neurocognitive function (short term memory, verbal memory, math skills)
- Portable Clinical Blood Gas Analyzer – iStat (measures pH, blood gas, glucose…)
- Intra-vehicle radiation monitor to track crew exposure
- Ultrasound for research purposes only

Overview and Summaries of Roadmapping Activity

Overview:
Nanotechnology Capability Roadmap

Presentation to the National Research Council

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Content

- Capability Roadmap Team
- Capability Breakdown Structure
- Roadmap Approach
- Top Level Assumptions
- Top Level Mission Sets
- Roadmap Schedule
- Capability Presentations by Leads under Roadmap (Repeated for each capability under roadmap)
  - Capability Description, Benefits, Current State-of-the-Art
  - Capability Requirements and Assumptions
  - Roadmap for Capability
  - Maturity Level - Technologies
  - Metrics
- Summaries of Top Level Capabilities

Capability Roadmap Team

Co-Chairs

NASA: Murray Hirschbein (Headquarters)
NASA: Minoo Dastoor, (Headquarters)
External: Dimitris Lagoudas, (Texas A&M, URETI Director*)

Government (NASA/JPL)

Mike Meador (Glenn Research Center)
Harry Partridge (Ames Research Center)
Mia Siochi/Mike Smith (Langley Research Center)
Benny Toomarian (Jet Propulsion Laboratory)
Len Yowell (Johnson Space Center)

Industry

Dan Herr, (SRC)
John Starkovich, (Northrop-Grumman)
Stan Williams (Hewlitt-Packard)

Academia

Wade Adams (Rice, Center for Nanoscale S&T)
Ilhan Aksay (Princeton, URETI* Director)
Supriyo Datta/David Janes (Purdue, URETI* Director)
Chih-Ming Ho (UCLA, URETI* Director)

Coordinators

Directorate: Harley Thronson (Science)
APIO: Julie Crooke (GSFC)

• **University Research Engineering and Technology Institute**

Capability Breakdown Structure

NASA Co-Chair: Minoo Dastoor

16.0 Nanotechnology

NASA Co-Chair: Murray Hirschbein

External Co-Chair: Dimitris Lagoudas

16.1 Nano-structured Materials

External Lead: Ilhan Askay
NASA Lead: Mike Meador
Len Yowell

- 16.1.1 Structural Efficiency
- 16.1.2 Efficient Power and Energy
- 16.1.3 Thermal Protection and Management
- 16.1.4 Radiation and EM Protection
- 16.1.5 Life Support/Health Management
- 16.1.6 Sensing and Actuating

16.2 Sensors and Devices

External Lead: David Janes
NASA Lead: Harry Partridge

- 16.2.1 Sensing
- 16.2.2 Electronics
- 16.2.3 Mechanisms/Actuators
- 16.2.4 Modeling and Simulation

16.3 Intelligent Integrated Systems

External Lead: Chih-Ming Ho
NASA Lead: Benny Toomerian

- 16.3.1 Multi-Scale Modeling
- 16.3.2 Multi-Scale Manufacturing
- 16.3.3 Interconnectivity
- 16.3.4 Utilization of Nano-Scale Properties
- 16.3.5 Information Representation

Roadmap Approach

- **Build on 5+ years of similar activity including prior roadmaps and involvement in the National Nanotechnology Initiative (NNI)**
  - Recent planning for the second 5 years of NNI
  - NASA NNI workshop Microcraft and Robotics
  - Recent workshop among the four NASA University, Research, Engineering and Technology Institutes in nanotechnology (URETI)
  - Utilize existing informal NASA team, including URETIs, that has evolved over the past several years
- **The scope will include both aeronautics and space**
  - Both near and mid-term opportunities and long-term vision
  - Tie development of capability to enabling higher level applications
  - Key demonstrations and quantifiable milestones to guage progress
- **<u>Focus on fundamental underlying technological capability</u>, such as**
  - Theory and analysis from the nano-scale to the macro-scale to predict properties and behavior
  - Materials processing for desired properties and behavior
  - Design and development of devices and systems based on nano-scale technology
  - Integration of nano-scale devices and systems into micro- to macro- systems
  - Training and Education

Roadmap Approach

(Continued)

- Continue active participation in the National Nanotechnology Initiative to enhance broad government coordination and cooperation
- NASA will work closely with….
  - NIH in matters of astronaut health
  - DOD across broad common interests in aeronautics and space
  - DOE in materials, especially energy related
  - NIST on fabrication and manufacturing (NASA fabricates, but does not manufacture)
  - Semiconductor industry (ITRS) for electronics and system integration

Top Level Assumptions

- Nanotechnology is a "push" technology driven by breakthroughs and opportunities
  - No mission currently "requires" nano-scale technology
  - All planned and future missions can significantly benefit from advances in nano-scale technology
- The most significant breakthroughs in nano-scale technology likely have not yet occurred – predictions beyond a few years are very speculative
- Most advances benefiting NASA will come from external sources
- The target level for the nanotechnology roadmap is about Technology Readiness Level 4 (fully demonstrate/validate functionality)
- Leveraging Commercial/Academia developments is essential
- NASA will have unique needs and requirements not met by external sources
- A strong internal emphasis and highly competent internal talent is essential to benefit from external sources and satisfy unique needs and requirements

Mission Needs/Opportunity Timeline for Nanotechnology

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1st Generation:
Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.

Radiation Protection, Advanced TPS

2nd Generation
Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.

Humans to the Moon

Crew Exploration Vehicle

Mars Transfer Vehicle

Humans to Mars

High Strength, Lt. Wt./ Multifunctional Structures

Lightweight Fuel Tanks, Radiators (Nuclear Prop.)

High Strength/ Multifunctional Structures

Lunar and Mars Robotics Precursor

Mars robotic missions (every 2 years)

Greatly miniaturized robotic systems:1 kg-sats/robots with the capability of today's 100 kg systems (Mars and other planetary bodies: in orbit, atmospheres. surfaces, sub-surfaces)

Robotic Missions to Extreme Environments After Mars
(Outer Solar System, Venus …)

Sun-Earth Observing Constellations

Deep Space Constellations
(X-Ray Telescope, Earth's Magnetosphere,..)

Extremely large, lightweight, highly stable optical and RF apertures and metering structures (~10-100 m)

Large, lightweight highly stable optical and RF apertures and metering structures (~10m)

Large Scale Interferometry
(Planetary Finding)

Very Long Baseline Interferometry
(Planetary Imaging)

Thermal control; lightweight, low power radiation hard/tolerant electronics and avionics; advanced active/detection; lightweight high efficiency power systems; high strength-to-weight structures and thermal protection systems

High Altitude Long Endurance Aircraft

"Planetary Aircraft"
(e.g. Mars)

1st Generation Zero Emissions Aircraft

Lt. Weight High Strength Structures
Low Power Avionics
Lightweight, High Efficiency
Electrical Power Systems (Solar Arrays, Regenerative Fuel Cells)

2005 — 2015 — 2025 — 2035

– Draft –

Roadmap Schedule

- Team established in November
- First team meeting December 14-15, 2004
  - External perspectives
  - Organized sub-teams
  - Focused on what should NASA do in nanotechnology and why
- Second team meeting February 1-2, 2005
  - Developed final capability breakdown structure
  - Focused on how and when NASA could achieve Agency needs/benefits in nanotechnology
  - Initial draft of roadmaps including state-of-the-art, metrics and timelines

Roadmap Schedule (continued)

Advanced Planning & Integration Office

- NRC review March 8, 2005
  - Integral part of nanotechnology roadmapping plan
  - "Mid-term" assessment of assumptions, scope, direction and overall technical content
  - Early enough in the process to affect final product

- Third meeting in March
  - Incorporate NRC feedback
  - Finalize content

Nano-Structured Materials

Capability 16.1 Nanostructured Materials

Presenter/Team Lead:

Ilhan Aksay

Co-Leads:

Mike Meador-GRC

Leonard Yowell – JSC

Team Members:

Wade Adams – Rice University

Mike Smith - LaRC

John Starkovich – Northrop Grumman

Capability 16.1 Nanostructured Materials

Advanced Planning & Integration Office

- Nanotechnology is producing materials with properties, processing and durability far exceeding that of conventional materials. These materials will have a significant, pervasive impact on all NASA missions:
  - Reduced mass, improved structural efficiency
  - Extreme environmental performance
  - Efficient power (frugal consumption, efficient generation, storage and management)
  - High reliability
  - Human safety

Requirements /Assumptions for Capability 16.1 Nanostructured Materials

- Critical drivers for all NASA Missions:
  - Weight
  - Performance
  - Power and Energy
  - Safety
- Benefits and improvements identified by theoretical and laboratory based experimental results are achievable at scales required for NASA missions
- TRL 4 includes scale-up to appropriate size/quantity
- Resources will be available to develop technologies to TRL4
- Nanotechnology Roadmap assumes that technology will be developed to TRL4, other CBS and WBS Roadmaps will :
  - Identify opportunities for insertion of nanotechnology
  - Develop roadmaps for insertion and maturation to higher TRLs

Benefits of 16.1 Nanostructured Materials

Advanced Planning & Integration Office

Why Nanotechnology

Mechanical	
Strength	nano length scales below Griffith criteria
Toughness	distributed deformation at nanolength scales
Damping	efficient energy dissipation at nano-interfaces, nanomorphology, increased viscoelasticity with nanoparticle addition
Hardness	supermodulus effect - nanoscale inclusions
Modulus/Stiffness	enhanced molecular alignment- more perfect structures - achieve theoretical limits
Recoverable strain	quantum level nanoeffects,
Compressive	toughened interfaces through nanoscale particles, nanovoids
Impact /Dynamic Loading	nanomorphology effects on energy dissipation
Friction and Wear	tailored nanostructures to fit asperities
Thermal	
Conductivity/Insulation	geometry and size effects at a wide range of temperatures (cryo to reentry)
CTE	nanoscale morphology (voids) effects, phonon coupling, enables tailorable CTE
Emissivity	enhanced surface area/roughness,possible quantum effect

Benefits of 16.1 Nanostructured Materials

Advanced Planning & Integration Office

Why Nanotechnology

Electrical	
DC Conductivity	nanoscale design/defects, enables ballistic conductivity
Semiconductive	nanoscale tailoring of bandgaps
Dielectric Constant	nanopores
Current Density	enables ultra-high current densities, eliminates/controls defects, size effects, gating of nanowires
Percolation Threshold	high aspect ratios
Field emission	high aspect ratio
Thermoelectric	larger density of states, more phonon scattering
Optical	
Transparency	size effects (clearly)
Color/Absorption	size effects
Photonic Band Gap	tailored bandgaps through nanostructures, size effects (lambda/10)
Left-Handed	size effects
Surface Area	size, radius of curvature and geometry effects, tailorability
Porosity	heirarchical distribution, functionalization

Benefits of 16.1 Nanostructured Materials

Advanced Planning & Integration Office

Why Nanotechnology

Mass Transport/Permeability	nanoscale morphology (voids) effects,length scale effects on diffusion mechanisms
Density	nanomorphology (inclusion of nanopores)
Environmental	
Radiation	electronics (smaller cross-section, redundancy,spintronics), human (size effects on energy dissipation??, design flexibility)
Temperature Stability/Performance	nanoscale morphology (new interfaces), inhibits degradation (diffusion)
Corrosion	surface area, interface tailoring
Magnetic	size effect
Piezoelectric	size effect
Chemical Reactivity	surface area, interface tailoring
Materials Interactions	surface area and tailoring, interface tailoring

Future Exploration Missions Requirements Cannot Be Met with Conventional Materials

Satellites and rovers

- Reduced mass and volume
- Reduced power requirements
- Increased capability, multifunctionality

Vehicles and habitats

- Reduced mass
- High strength
- Thermal and radiation protection
- Self-healing, self-diagnostic
- Multifunctionality
- Improved durability
- Environmental resistance (dust, atmosphere, radiation)

EVA Suits

- Reduced mass
- Increased functionality and mobility
- Thermal and radiation protection
- Environmental resistance

Nanostructured Materials Can Impact Science Missions and Exploration

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NanoTechnology

NORTHROP GRUMMAN
Space Technology

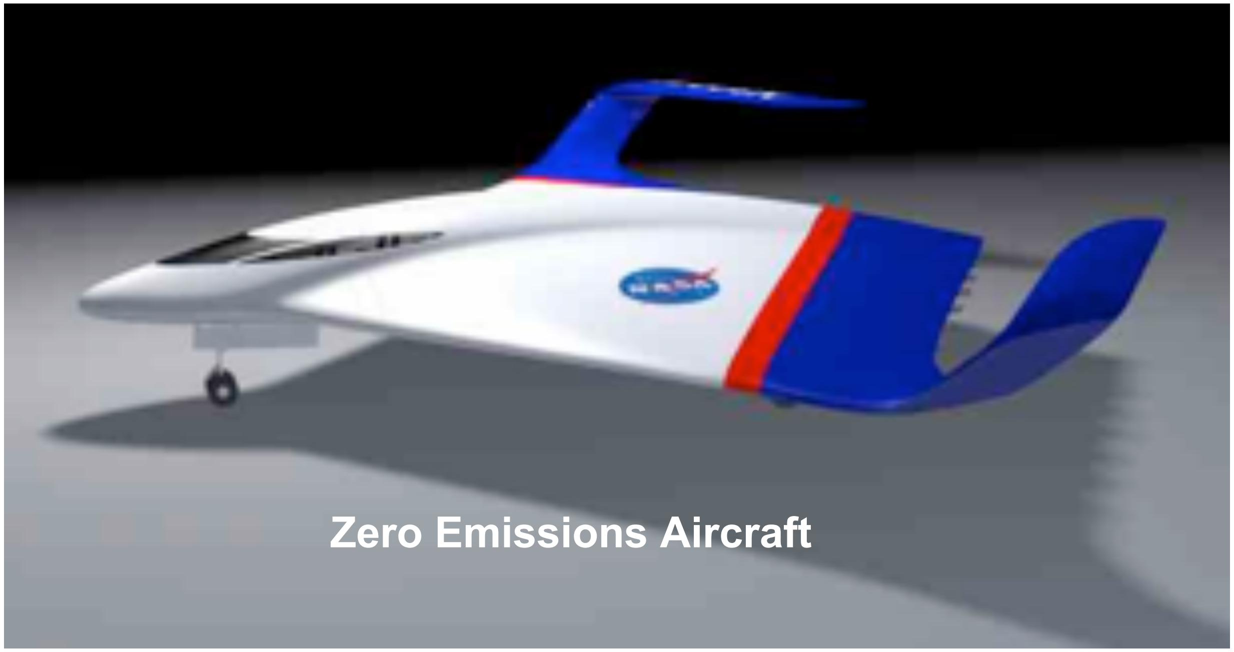
The Vision & The Challenges

- N+2 generation civil space missions require spacecraft and payload instruments with Order-of-Magnitude greater scale, resolution, and precision than present systems afford
- Revolutionary designs and breakthrough technologies will enable development of such systems
- NanoTechnology, particularly NanoEngineered materials may be key to realizing this vision

Very Large Membrane Reflectors · Orbital Transfer Vehicles · Large Deployable Structures

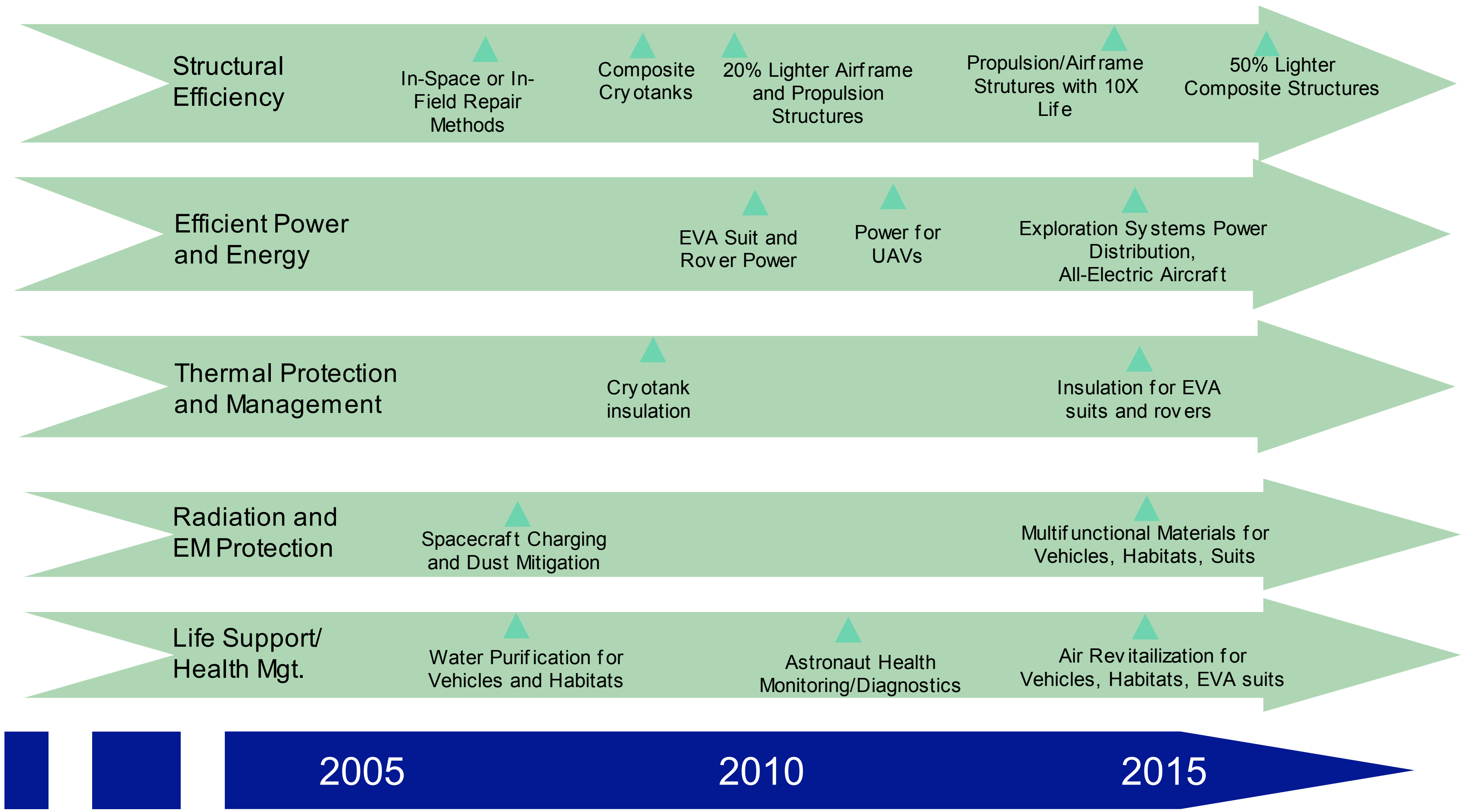
Relocatable Power Beam Stations · Dynamically Stable Platforms / Instruments · Space Based Radar & Comsats

Nanostructured Materials are Critical for Future Aeronautics Demonstrators

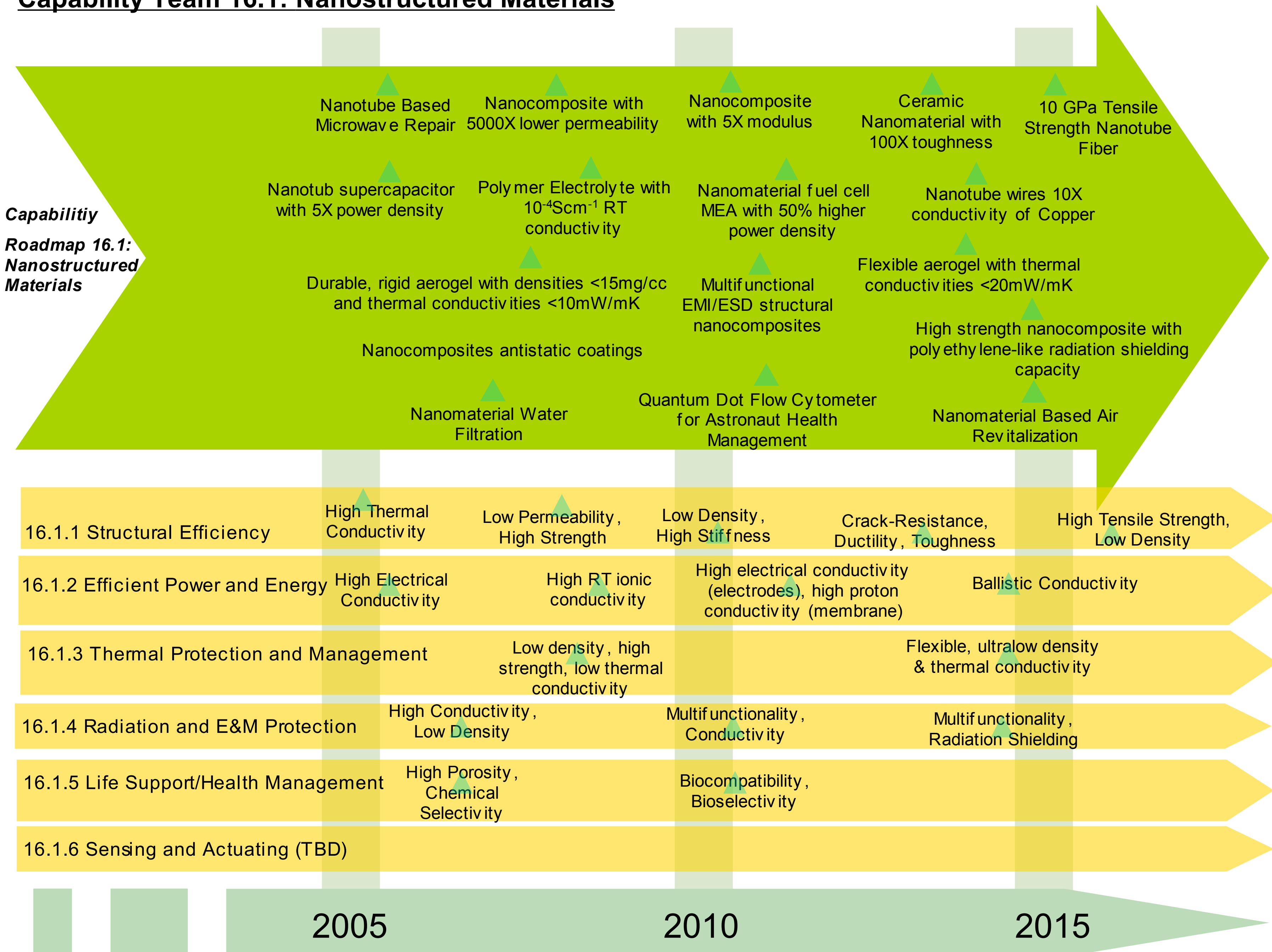


- Airframe – ultralightweight, high strength, multifunctional nanocomposites
- Cryopropellant Tanks – low density, durable aerogel insulation & ultralow permeability nanocomposites
- Fuel Cell Power – nanostructured electrode materials
- Electric Motors – high conductivity, lightweight nanocomposites, nanolubricants

Key Assumptions: Potential NASA Applications



Capability Team 16.1: Nanostructured Materials



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Key Assumption: Potential NASA Applications

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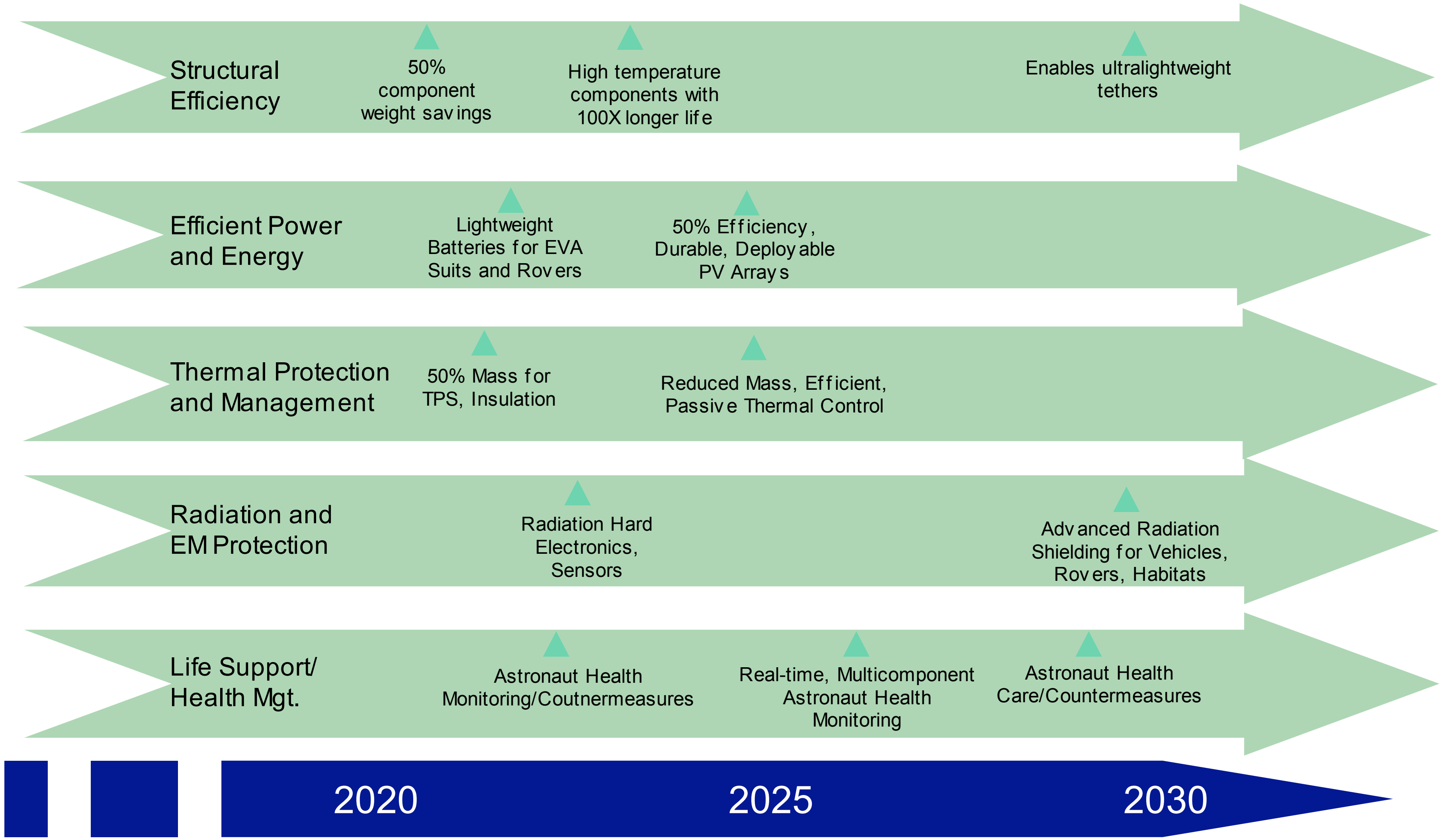

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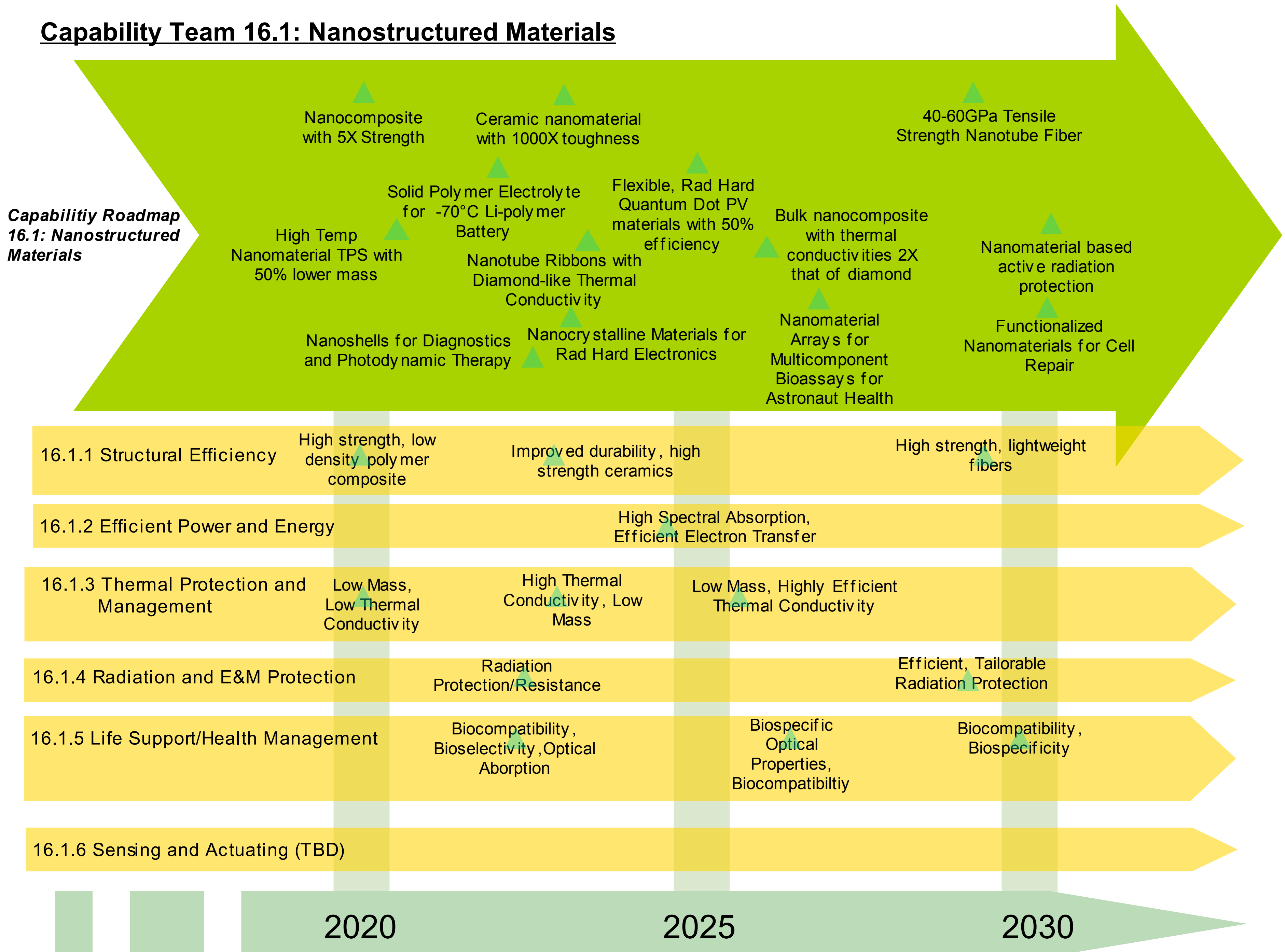
Capability Team 16.1: Nanostructured Materials



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Remaining Work

- Review milestones and metrics for comprehensiveness
  - Fill in gaps – have we left out important needs?
  - Looking for expertise within and outside the Agency for validation of existing roadmaps and help with Sensing and Actuating Subcapability

- Coordinate Roadmaps with other CRM teams:
  - High Energy Power and Propulsion
  - Advanced Telescopes and Observatories,
  - Science Instruments and Sensors
  - Advanced Modeling, Simulation and Analysis

Detailed Challenges and Roadmaps

NASA NNI Grand Challenge Workshop (2004) Reliable Production of Nanomaterials

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Grand Challenge: Develop the ability to reliably and consistently control functional material synthesis and assembly from nano to macro scales

Barriers/Needs:

- Integration of physical and chemical forces with external fields to get desired properties during processing and use (> 10 years)
- Inexpensive production (terrestrial and other planets) of highest quality nanomaterials (>10 years)
- Control of processes over all length scales (>10 years)
- Adaptable synthesis, processing and characterization methods to efficiently utilize resources on other planets (>10 years)
- Lack of fundamental understanding of synthesis, growth, nano-macro structure development mechanisms (5-10 years)
- Lack of real-time methods to characterize structural development during processing and/or synthesis (5-10 years)
- Lack of predictive models/simulations to guide materials and processing design (<5 years)
- Control of interfacial properties and processes (<5 years)
- Lack of approaches that draw upon previous experiences from other disciplines (bio, electrical engineering) (<5 years)
- Failure detection and prediction tools (<5 years)
- Lack of high throughput experimentation and characterization techniques (<5 years)

NASA NNI Grand Challenge Workshop (2004)
Long-Term Durability

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Grand Challenge: Demonstrate that materials, devices and systems based on nanotechnologies can reliably execute prolonged (DECADE +) Human and Robotic Exploration Missions .

- Radiation (space environment & propulsion radiation sources)
- Chemical/reactive environments
- Thermal swings (-120 C to 600 C)
- Fatigue
- MMOD Impact
- Mechanical and launch/entry loads
- Electrostatic charging
- Abrasion
- Synergistic effects.

Barriers/Needs:

- Accelerated life testing for issues listed above
- End-to-end test capability
- Lack of fundamental understanding of materials and interactions with radiation
- Simulation effects from Nano-micro-meso scale is imperative
- In Space repair and regeneration
- Integrated system health management
- Self-repair

16.1.1 Structural Efficiency

- Includes:
  - Low Density
  - Strength
  - Stiffness
  - Toughness
  - Vibration/Acoustic Damping
  - Permeability
  - Dimensional and Dynamic Stability
  - Environmental Durability
  - Impact Resistance
  - Self-Healing
- SOA:
  - Polymer/clay nanocomposites with 100X lower permeability than base resin
  - Nanocomposites with strength equivalent to conventional carbon fiber
  - Ceramic nanocomposites have toughness 10X that of best ceramic
  - Vibration damping - ?
  - Impact Resistance
  - Self-healing ionomers demonstrated that can heal 1 cm diameter cut, not space compatible

16.1.1 Structural Efficiency

- Metrics:
  - Nanocomposites with 5000X lower H2 permeability
  - Composite materials with 5-fold increase in specific strength and stiffness over conventional composites
  - Ceramic nanocomposites with 100 to 1000x better tougness
  - Vibration damping – (Will get information from Starkovich)
  - Impact resistance- Nanocomposite bumbers and self-healing foam support to improve performance 10-100X
  - Nanotube based microwave active repair materials
- Barriers:
  - Lack of fundamental understanding of synthesis, growth, nano-macro structure development mechanisms
  - Reliable and affordable scale-up methods
  - Interface design, functionalization, control and characterization
  - Predictable structural control (dispersion and alignment) over all length scales
  - Lack of robust modeling tools across all length scales
  - In-situ characterization and diagnostic techniques are limited

Capability 16.1 Nanostructured Materials Roadmap

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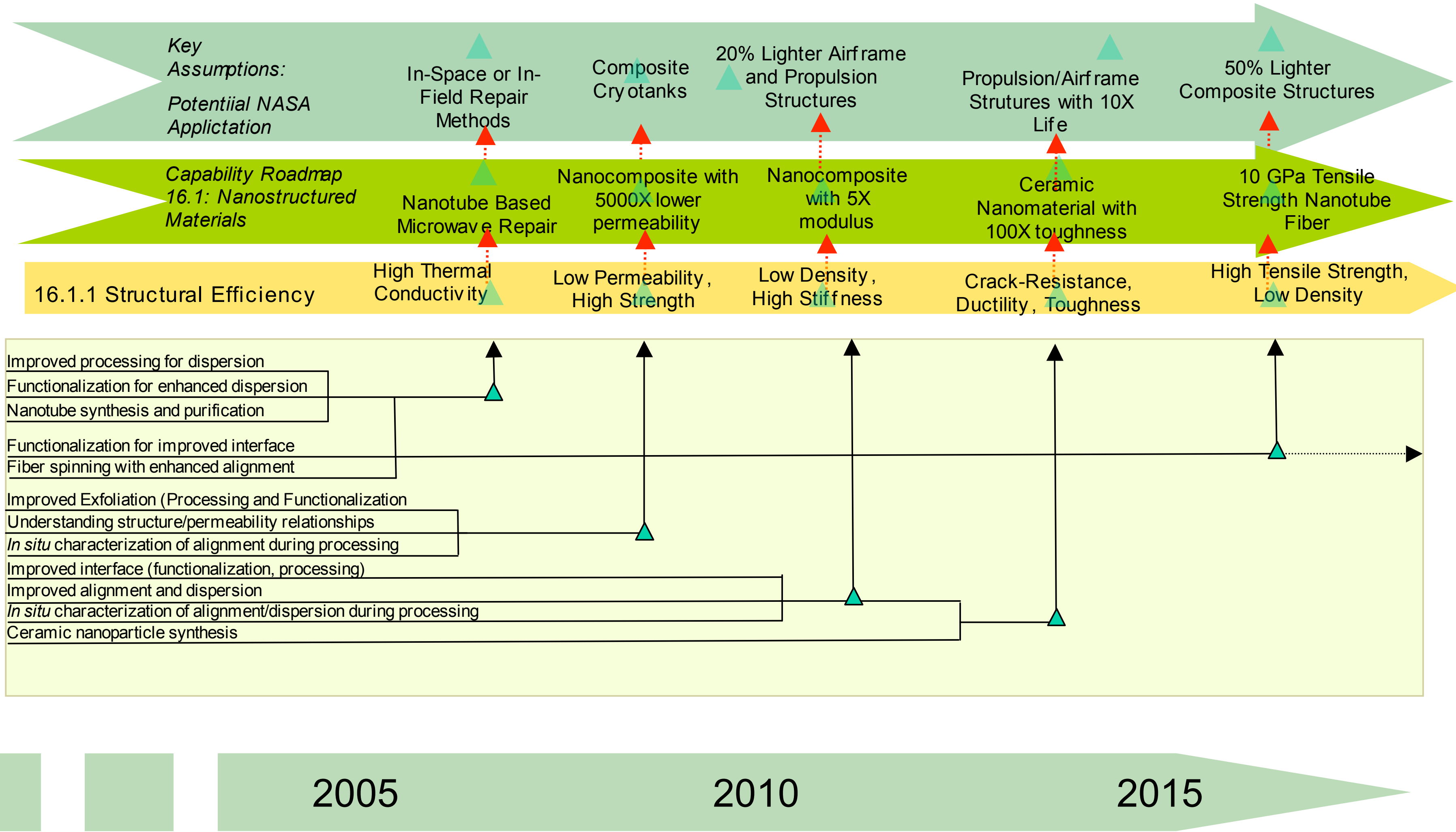
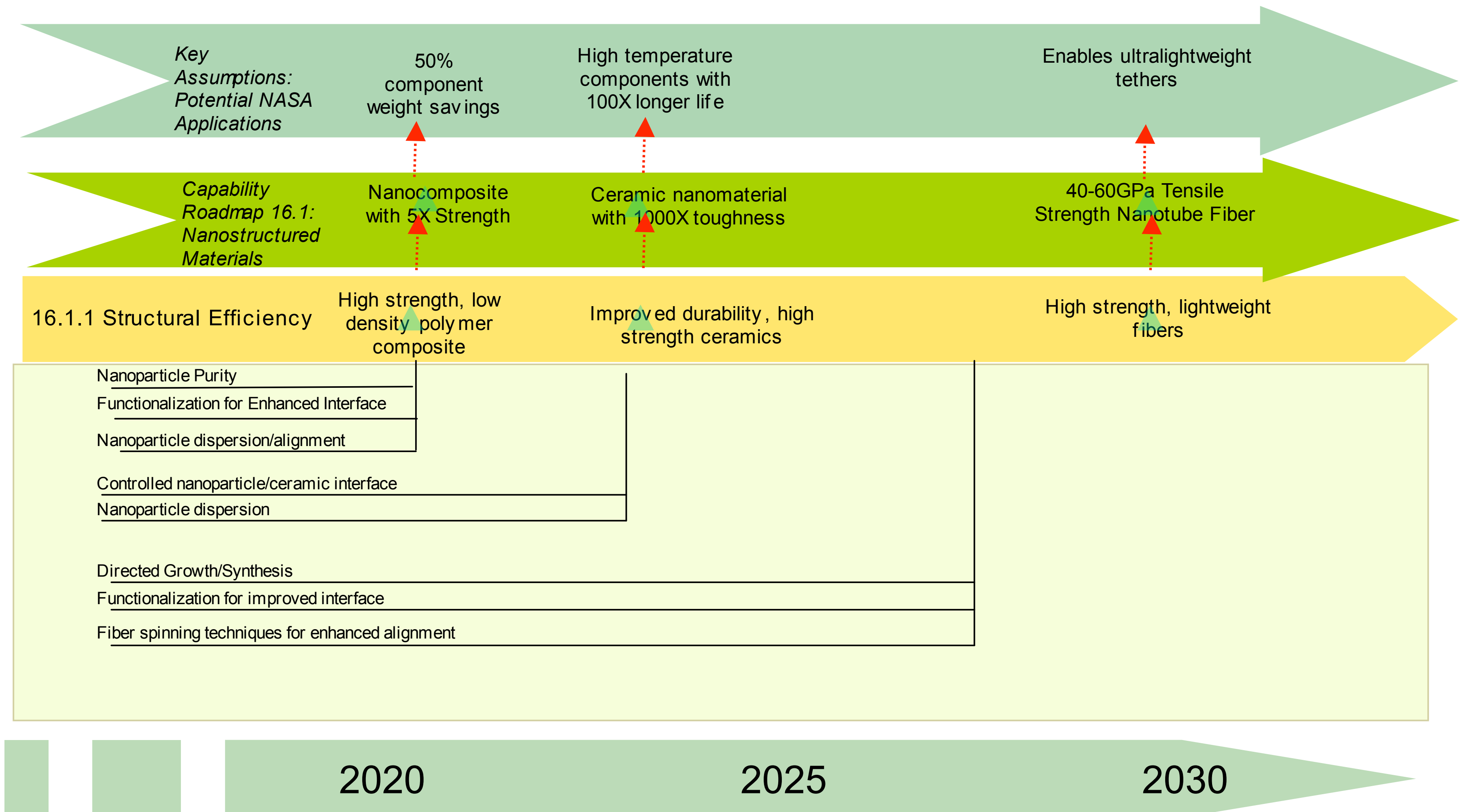


Capability 16.1 Nanostructured Materials Roadmap

Advanced Planning & Integration Office



16.1.2 – Power and Energy Density

- Includes:
  - High Specific Power
  - High Specific Energy
  - Low Loss Power and Energy Distribution
- SOA:
  - Quantum dot/nanotube based photovoltaics with XX% efficiency
  - Nanotube double layer supercapitor with 5x power and 30x specific power of conventional supercapitors
  - Self-assembled polymer electrolyte with 10X ionic conductivity of conventional electrolyte at room temperature
  - Aerogel based membrane with Nafion-like conductivity but at 200°C and no need for external humidification
  - Wires??
- Metrics:
  - Material system capable of power generation, storage and self-actuation total aerial weight of 0.8Kg/m2 and capable of 1.0 kw/kg power generation
  - Solid polymer electrolytes with ionic conductivities >10-4 scm-1 at -70°C and structural capabilities
  - Multifunctional electrode materials for reversible fuel cells
  - Flexible, photovoltaic materials with 50% PV efficiency
  - Membranes?
  - Arm chair nanotube-based wires with 10X conductivity of copper at 1/6th the weight

Capability 16.1 Nanostructured Materials Roadmap

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Key Assumptions: Potential NASA Applications

- Shuttle, ISS Power
- EVA Suit and Rover Power
- Power for UAVs
- Exploration Systems Power Distribution, All-Electric Aircraft

Capability Roadmap 16.1: Nanostructured Materials

- Nanotube based supercapacitor with 5X power density
- Polymer Electrolyte with 10^{-4} Scm^{-1} conductivity at RT
- Nanomaterial fuel cell MEA with 50% higher power density
- Nanotube wires with 10X higher conductivity than Copper

16.1.2 Efficient Power and Energy

- High Electrical Conductivity
- High RT ionic conductivity
- High electrical conductivity (electrodes), high proton conductivity (membrane)
- Ballistic Conductivity

Functionalization for improved interface

Controlled nanotube synthesis and purification

Chirality selective nanotube synthesis , purification

Nanostructured membrane development

Nanostucturd catalyst development

High surface area nanoparticle support

Understanding of structure/conductivity relationships

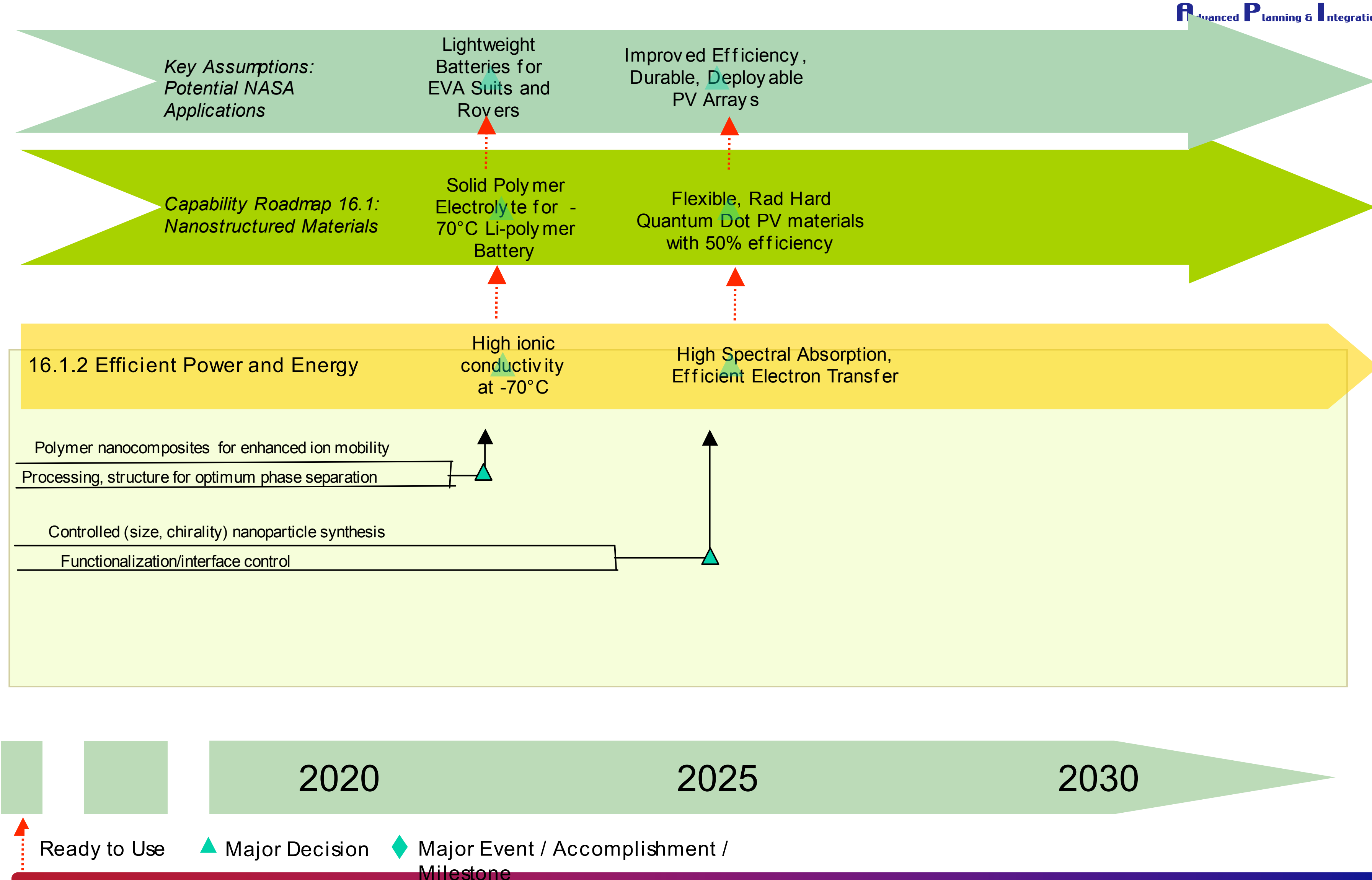
Polymer and processing for optimized phase separation

In situ characterization of phase separation during processing

Enhanced phase separation

2005 2010 2015

Capability 16.1 Nanostructured Materials Roadmap



16.1.3 – Thermal Protection & Management

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- Includes:
  - Thermal Conductivity
  - Insulation
  - Emissivity
- SOA:
  - Flexible silica aerogel insulation with thermal conductivities below 20mW/mK
  - Zirconia/carbon nanotube TBC insulation with 50% lower thermal conductivity
  - Magnetically aligned nanotube ribbon conductors with metal-like thermal conductivities (200W/mK)
  - Emissivity
- Metrics:
  - Durable, aerogel insulation with densities below 15mg/cc and thermal conductivities below 10mW/mK
  - Nanotube ribbons with diamond-like thermal conductivities (1000-2000W/mK)
  - Emissivity?

Capability 16.1 Nanostructured Materials Roadmap

Advanced Planning & Integration Office

Key Assumptions: Potential NASA Applications

Cryotank insulation

Insulation for EVA suits and rovers

Capability Roadmap 16.1: Nanostructured Materials

Durable, rigid aerogel with densities <15mg/cc and thermal conductivities <10mW/mK

Flexible aerogel with thermal conductivities below 20mW/mK

16.1.3 Thermal Protection and Management

Low density, high strength, low thermal conductivity

Flexible, ultralow density & thermal conductivity

Nanotemplated coating development

Controlled nanoporous morphology

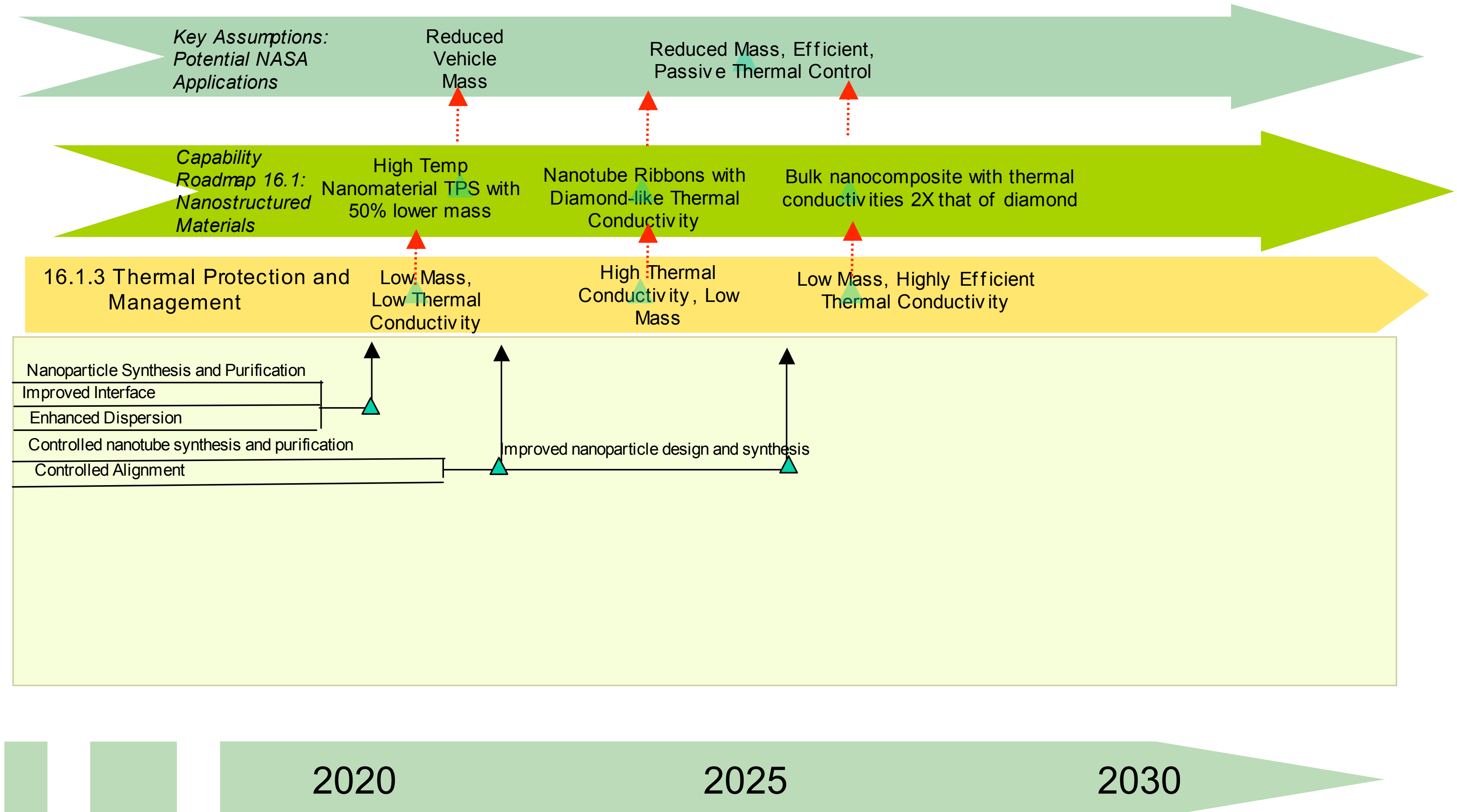
Aerogel & Nanocoating optimization

2005

2010

2015

Capability 16.1 Nanostructured Materials Roadmap



16.1.4 – Radiation Protection and E&M

- Includes:
  - Radiation Protection
  - EMI Shielding
  - Electrostatic Control
  - Active (Magnetic) Shielding
- SOA:
  - Nanotube based anti-static coatings
  - Polyethylene (non-nano) shielding
- Metrics:
  - Nanostructured materials with polyethylene-like radiation protection and structural capability

Capability 16.1 Nanostructured Materials Roadmap

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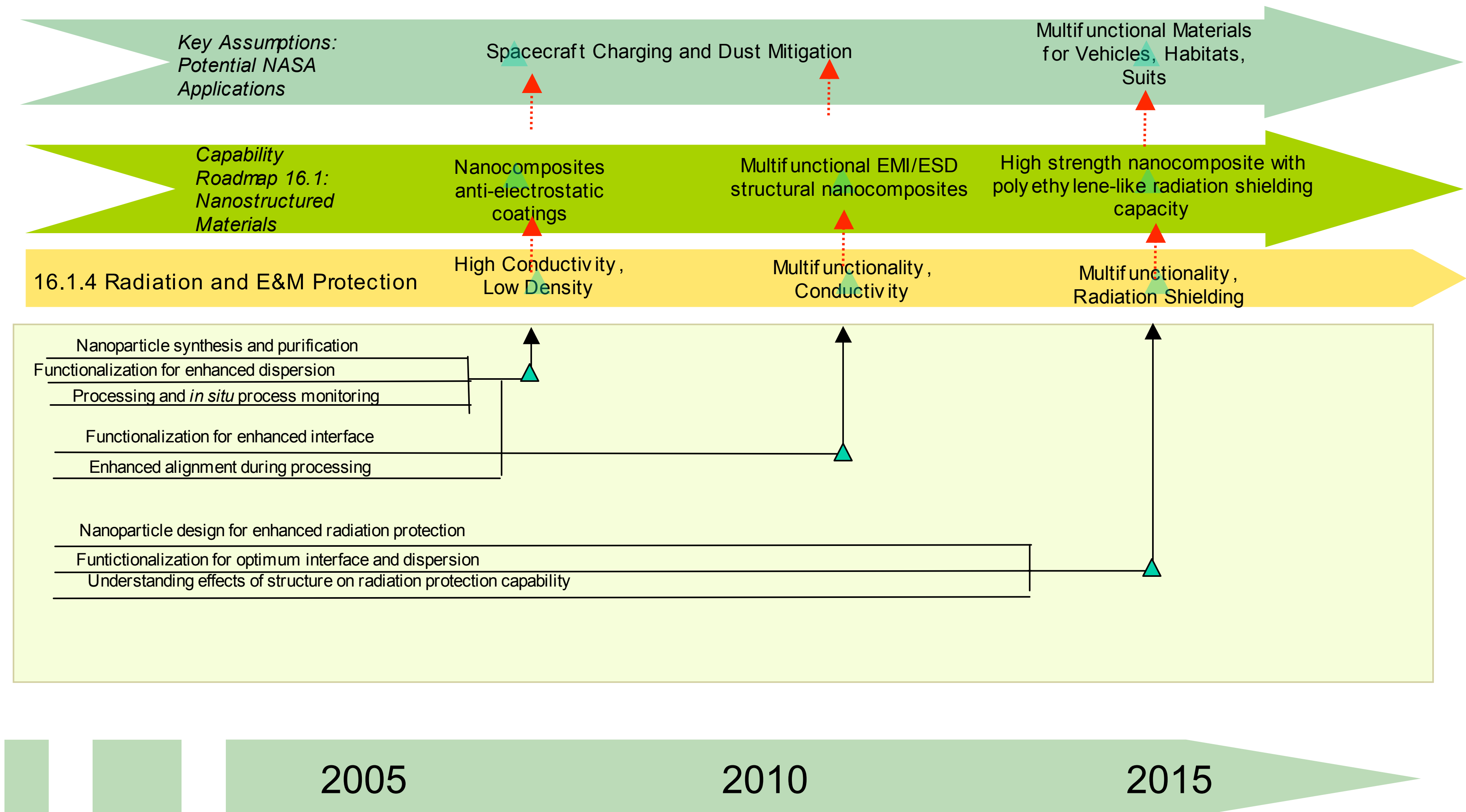
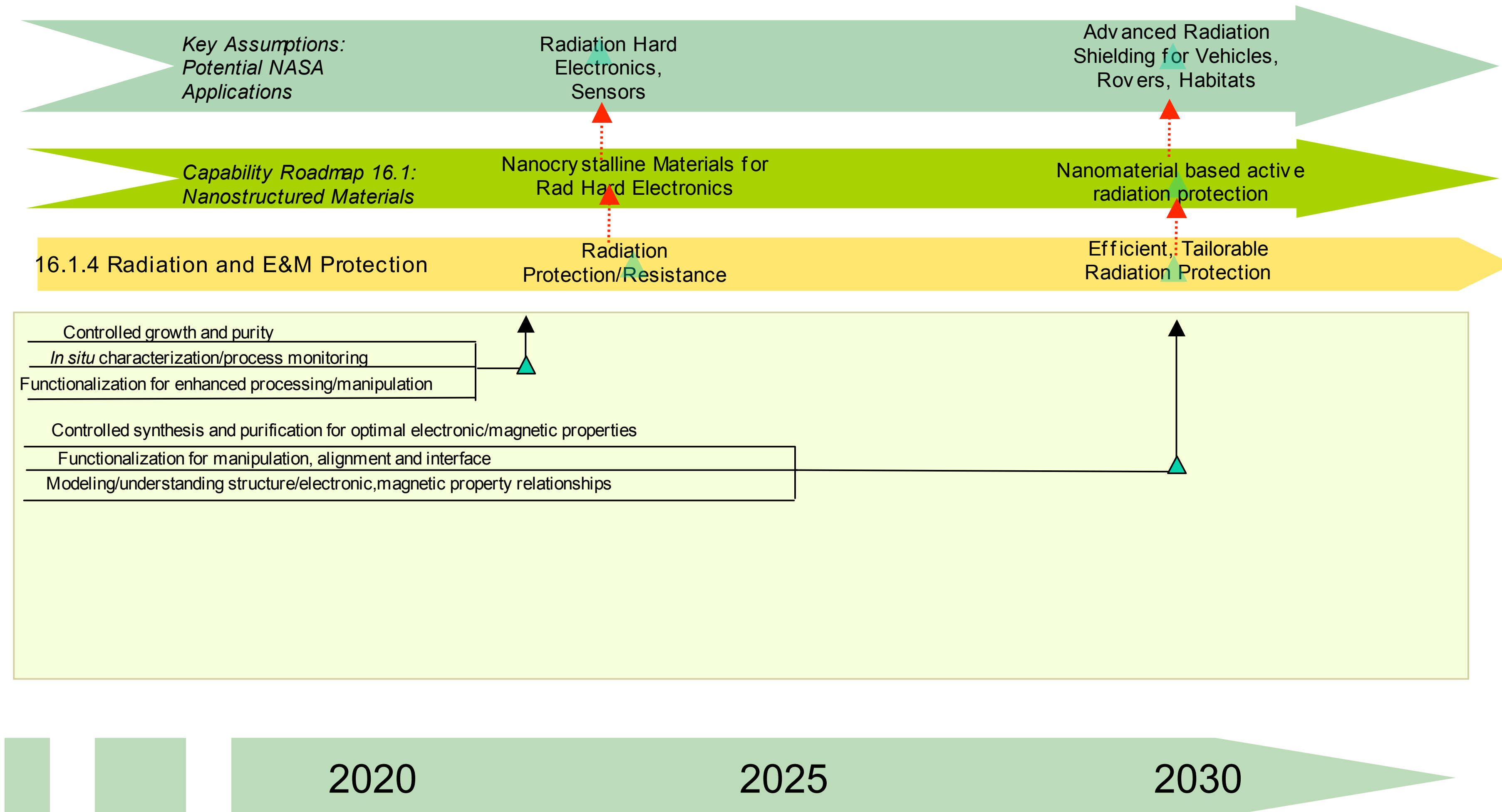


Capability 16.1 Nanostructured Materials Roadmap

Advanced Planning & Integration Office



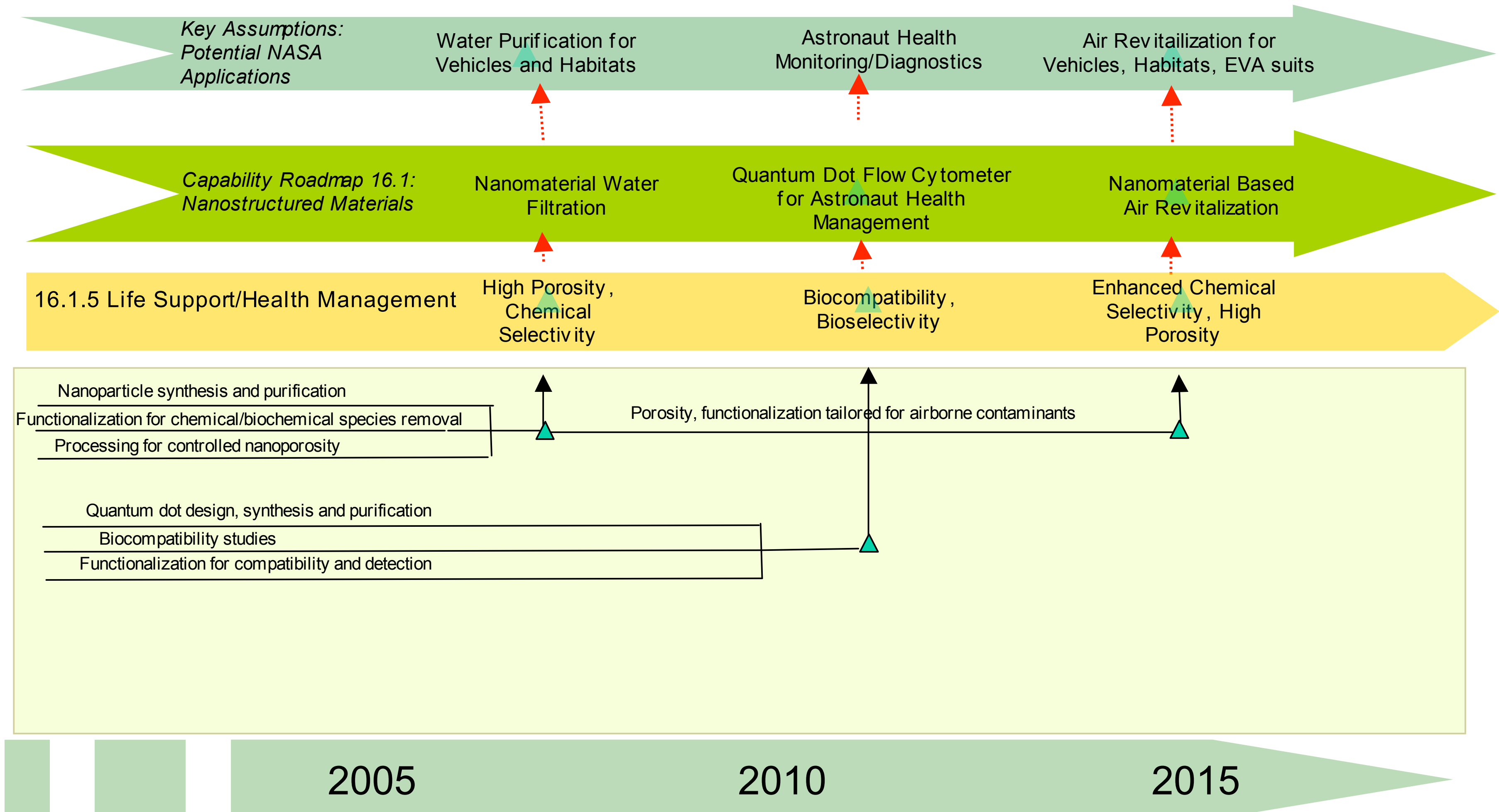
16.1.5 – Life Support – Health Management

- Biocompatability
- Selectivity (Separation and Filtration)
- Monitoring
- Counter-measures

- SOA:
  - Quantum dot bioassays for medical diagnostics/health monitoring
  - Functionalized nanotube membranes for water and air revitalization
  - Surface modified C60 anitioxidants
  - Silica/metal nanoshells for diagnostics and photodynamic therapy and tissue welding
- Metrics:

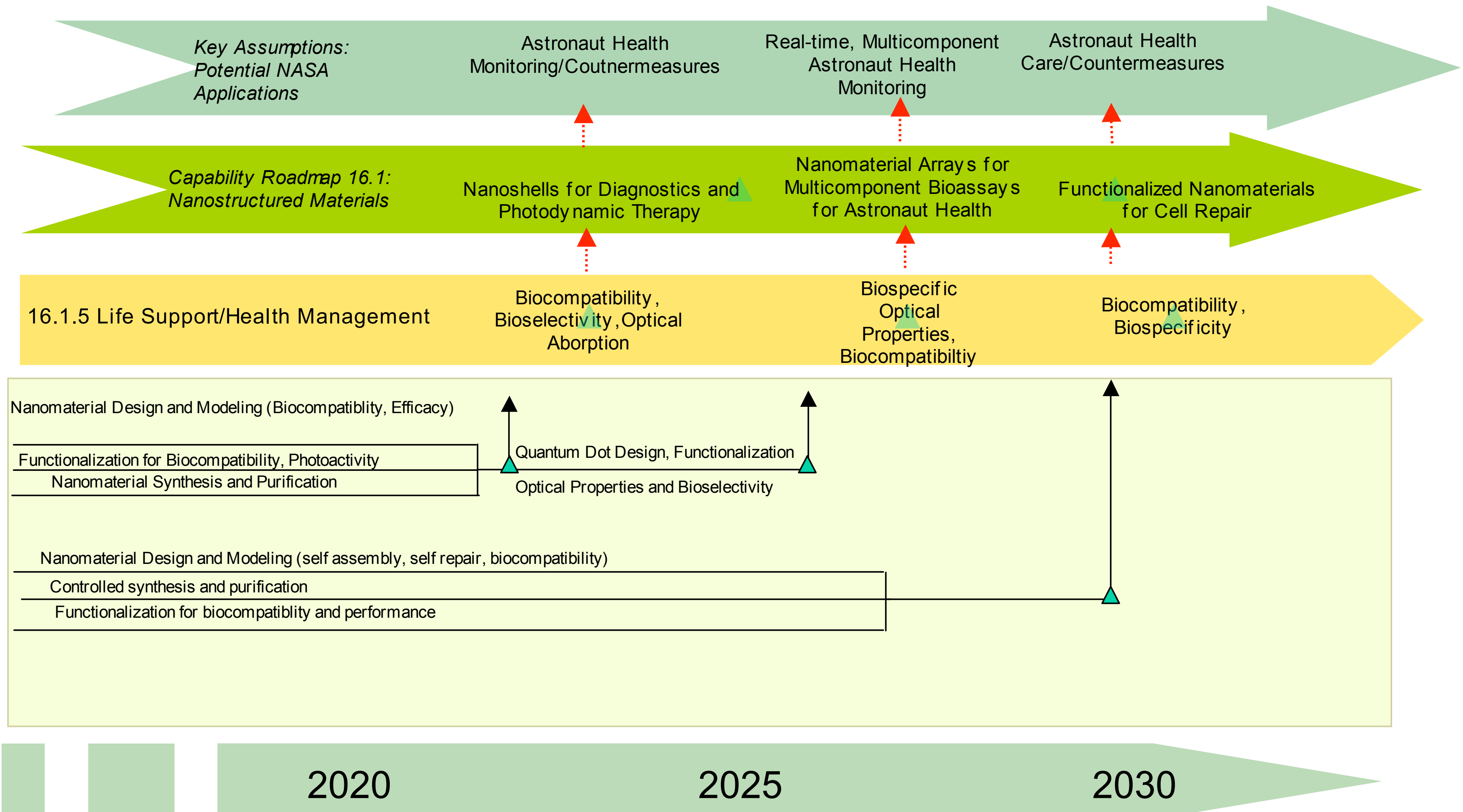
Capability 16.1 Nanostructured Materials Roadmap

Advanced Planning & Integration Office



Capability 16.1 Nanostructured Materials Roadmap

Advanced Planning & Integration Office



Capability 16: Nanotechnolgy

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Capability 16.2 Sensing and Devices

Presenter/Team Lead:
David Janes
NASA Co-Leads:
Harry Partridge

- Scope of Sensing and Devices

Provide the ability to detect, process data, communicate and interpret information, as well as manipulate or control this environment on a common platform by combining capabilities of nano/micro scale sensors and computing

- Why Nano Sensing and Devices?
  - Unparalleled sensitivity, selectivity, multi-functionality and integration
  - Devices suitable for highly integrated systems
  - Considerable reduction in power consumption
  - Enabling multi-point monitoring and enhanced functionality from multi-node system (eg health management and microcraft)
  - Redundancy for fault-tolerance and elimination of false positives
  - Potential performance improvement in extreme environments (radiation, temperature (min/max & swings, pressure, zero gravity, etc.)
  - Bottom-up engineering of materials for device properties through independent control of physical parameters at nano-scale are becoming feasible.

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- Why NASA?
  - Unique environment in space
    - **radiation, temperature, micro-gravity, low power, resource limited**
  - Operation/Vehicle Safety
    - **environmental management, systems status and health monitoring**
  - Astronaut health and environment monitoring and countermeasures
    - **on-board and highly autonomous medical diagnosis and response capabilities with minimal resource requirement**
  - Unique measurements
    - **Low photon counts, long wavelength, extreme temperatures and pressures, harsh chemical environment, detect biomarkers in remote environments**
  - Isolation from Earth
    - **Need for low power, and high redundancy for increased autonomy because of communication delay**
    - **unique shelf life and reliability** requirements for decades in radiation fields.
    - **Materials with low outgas and devices with closely matched thermal expansion for thermal swings**
  - Intelligent, extremely small robotics systems for monitoring and science

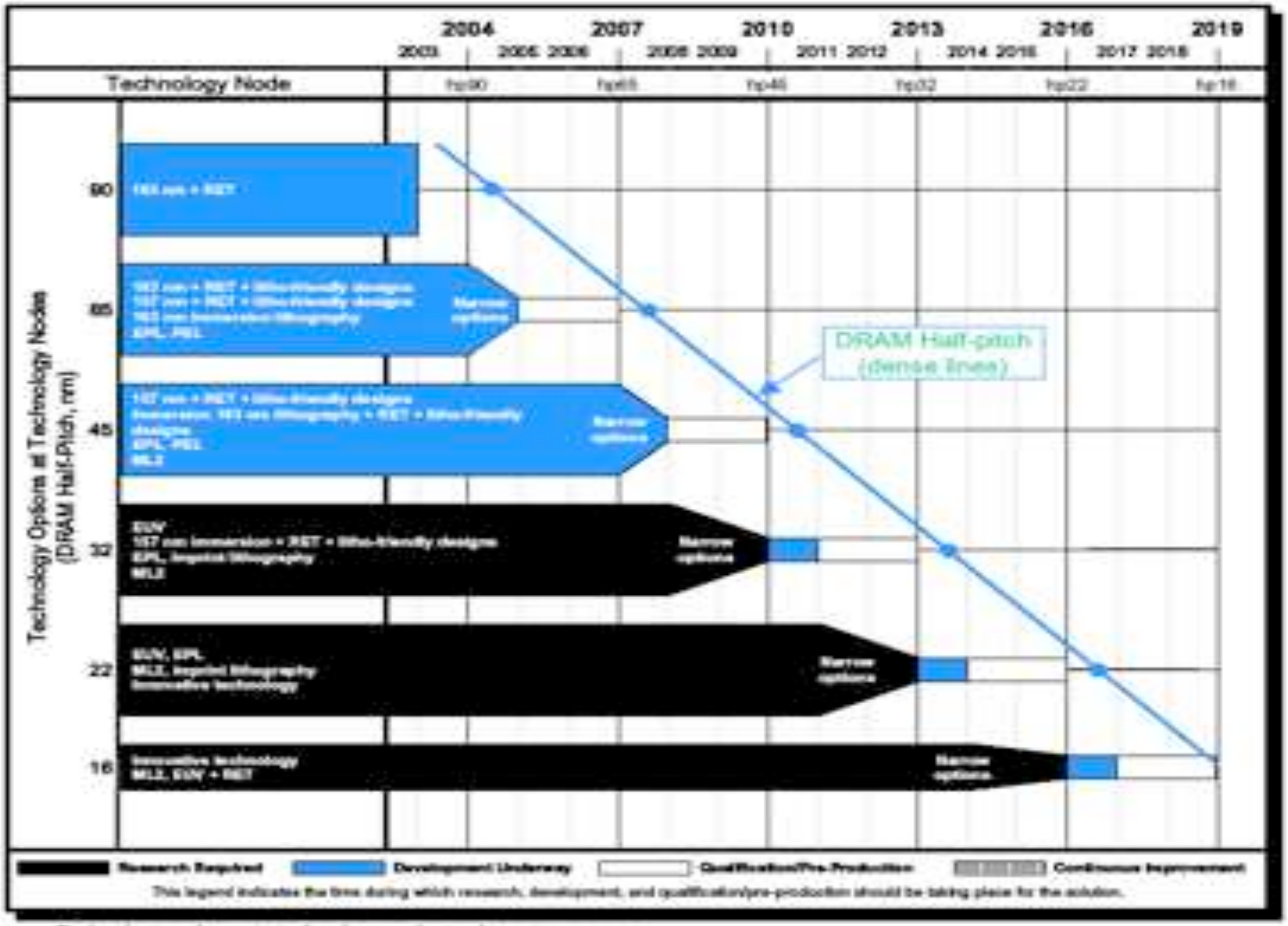
    (NASA is the NNI lead agency for microcraft)
  - Highly specialized and low volume manufacturing requirements not met by commercial development

Capability 16.2 CBS Sensing and Devices

Key Assumptions:

- Developments under National Nanotechnology Initiative, and other funded nanotechnology research, will continue to advance state of the art
- Sensor community is very dynamic and will continue to develop new nano-scale technologies
- Path available to transition from TRL 4 to mission insertion
- Predictions of the state of nano-scale technology beyond about 2010 are highly speculative
- Wireless technology available for integration of sensors and devices
- Electronic device downscaling as per International Technology Roadmap for Semiconductors (ITRS).

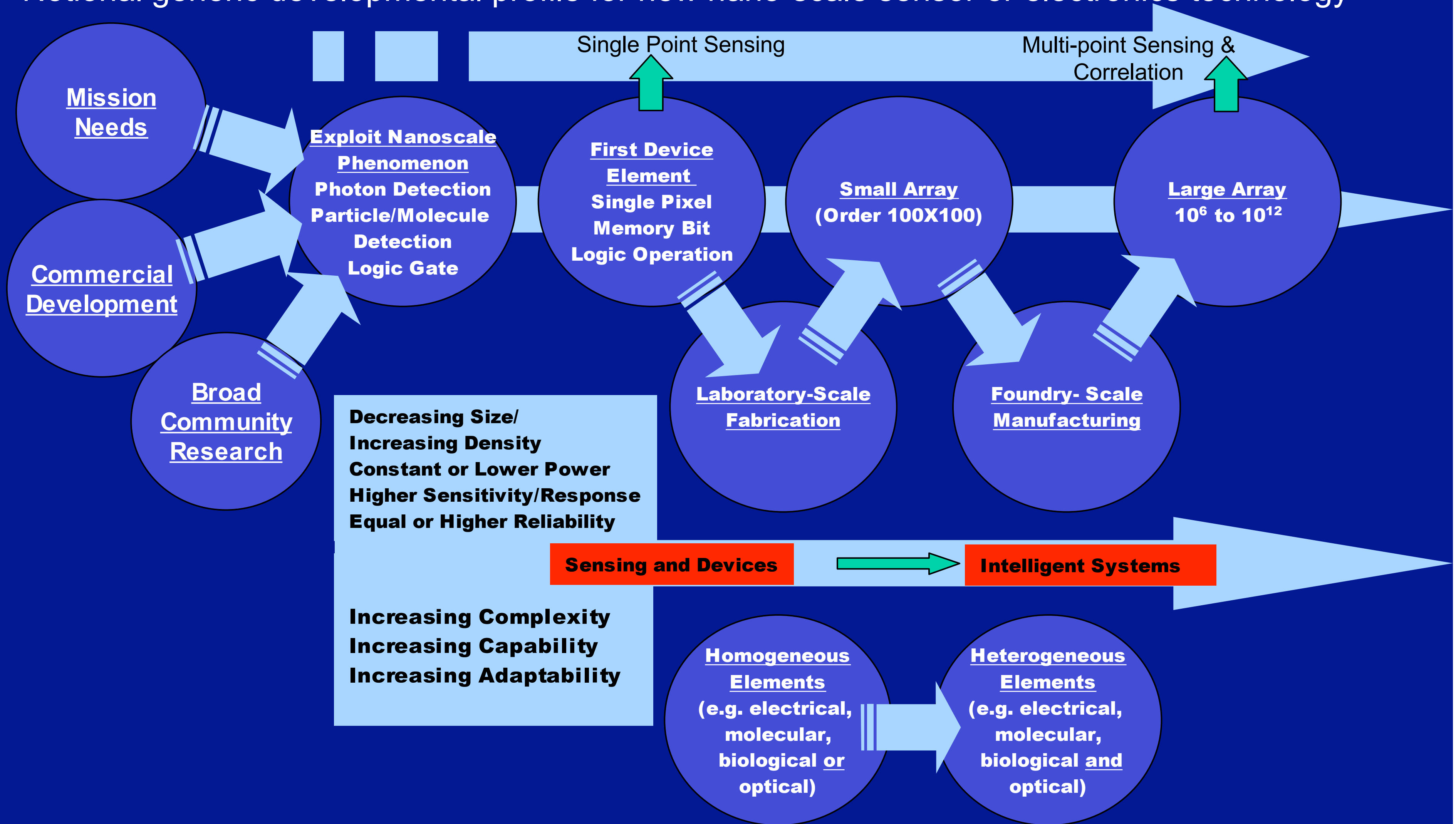
International Technology Roadmap for Semiconductors (ITRS): Opportunity



Technologies shown in italics have only single region support.
RET—resolution enhancement technology EUV—extreme ultraviolet EPL—electron projection lithography
ML2—maskless lithography PEL—proximity electron lithography

Capability 16.2 CBS Sensing and Devices

Notional generic developmental profile for new nano-scale sensor or electronics technology



Capability 16.2 CBS Sensing and Devices

Key Relationships:

- Nanomaterials (16.1):
  Material developments will enable device improvements
- Nano Systems (16.3):
  Sensors/Devices will support development of Systems

- Sensors and Instrumentation (Capability 12):
  - Sensor component developments for In-Situ Sensing (12.6) and Direct Sensing of -- Fields, Waves and Particles (12.5)
  - Improved optical sources/detectors – for Multi-Spectral Imaging / Spectroscopy (12.2) and LASER/LIDAR Remote Sensing (12.4)
  - Principle source of relevant sensor priorities and metrics

- Autonomous Systems & Robotics (Capability 10)
- Human health and Support Systems (Capability 8
- Robotic Access to Planetary Surfaces (Capability 6)
- Advanced Modeling, Simulation and Analysis (Capability 14)

Capability Breakdown Structure

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12.0 Science Instruments and Sensors

Chair: Richard Barney NASA/GSFC
Co-Chair: Maria Zuber
Deputy: Juan Rivera NASA/GSFC

12.1 Active and Passive Microwave Remote Sensing

Chair: Soren Madsen /JPL
Co-Chair: Chris Ruf/UM

- 12.1.1 Radar Altimetry
- 12.1.2 Real Aperture Radar
- 12.1.3 Synthetic Aperture Radar
- 12.1.4 Interferometric SAR
- 12.1.5 Radar Subsurface Sounding
- 12.1.6 Passive Microwave Real Aperture Imager
- 12.1.7 Passive Microwave Synthetic Aperture Imagers
- 12.1.8 Passive Microwave Sounder
- 12.1.9 GPS – Radio time-of-flight triangulation
- 12.1.10 Other Technology

12.2 Multi-Spectral Imaging/Spectroscopy (vis-IR-FIR)

Chair: Craig McCreight/ARC
Co-Chair: Ron Polidan/NGST

- 12.2.1 Visible Imagers, Photometers, Radiometers, Sounders
- 12.2.2 Visible Spectrometers / Interferometers
- 12.2.3 Visible Spectral (& hyperspectral) Imagers
- 12.2.4 IR/FIR Imagers, Photometers, Radiometers, Sounders
- 12.2.5 IR/FIR Spectrometers / Interferometers
- 12.2.6 IR/FIR Spectral (& hyperspectral) Imagers

12.3 Multi-Spectral Imaging/Spectroscopy (UV-Gamma)

Chair: Brian Ramsey/MSFC
Co-Chair: David Chenette/LM

- 12.3.1 UV Imaging and Spectrometry
- 12.3.2 X-Ray Timing and Polarimetry
- 12.3.3 X-Ray Interferometry
- 12.3.4 Gamma Ray Imaging and Spectrometry

12.4 Laser/LIDAR Remote Sensing

Chair: Maria Zuber/MIT
Co-Chair: Richard Barney/GSFC

- 12.4.1 Altimeters
- 12.4.2 Transponders
- 12.4.3 Atmospheric LIDARS
- 12.4.4 Spectrometers
- 12.4.5 Interferometers

12.5 Direct Sensing of Fields, Waves, and Particles

Chair: Dick McEntire/APL
Co-Chair: Carl Stahl/GSFC

- 12.5.1 Energetic Particle and Plasma Imagers and Spectrometers
- 12.5.2 High Energy Particle Detector Systems
- 12.5.3 Magnetometers
- 12.5.4 Electric Fields and Waves Instruments
- 12.5.5 Gravitational Waves and Fields Instruments

12.6 In Situ

Chair: Tim Krabach/JPL
Co-Chair: Rich Dissly/BATC

- 12.6.1 Imaging/Microscopy
- 12.6.2 Mineralogical/Elemental Analysis
- 12.6.3 Chemical Detection & Identification
- 12.6.4 Isotope Analysis/Age Dating
- 12.6.5 Biological Detection and Identification
- 12.6.6 Geophysical Measurements
- 12.6.7 In Situ Instrument Engineering
- 12.6.8 Fundamental Technologies and Components

Draft – 02/05

Specific Potential Connectivity to Sensors and Instruments CRM

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Microwave Instruments and Sensors

- Massively parallel digital correlators - nanoelectronics

Active and Passive Microwave Remote Sensing

- Radiation hardened processors - nanoelectronics

Note: Radiation hardened electronics is a critical cross-cutting technology area for science instruments and sensors

Multi-spectral, VIS-IR-FIR

- Single photon counting sensing in FIR - sensors
- Readout electronics (ex: single electron transistor) - nanoelectronics
- Example: InSb nanowire hyperspectral IR detector, superior to today's technololgy in terms of quantum efficiency, higher operating temperature and sensitivity further into the IR.

Specific Potential Connectivity to Sensors and Instruments CRM

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Multi-spectral, UV-Gamma

- Mega-channel, radiation hard analog electronics - nanoelectronics

Laser/LIDAR

- Higher power lasers which have lifetimes of 5 years - sensors/devices

Direct Sensing of Particles, Fields, and Waves

- Low power, radiation hard, fault tolerant nanoelectronics: emphasis on operation in more radiation harsh, and small satellite constellations
- Miniaturized and sensitive magnetometers - sensors
- High power laser (up to 300 W!) to operate for 5 years - sensors/devices

In-Situ

- Biomarker detection - sensors
- Chemical identification at high spatial resolution - sensors

Electronic Devices

- Micro/Nano Electronics

  CMOS-Based device technologies (TRL 4-8, various ITRS nodes)

- Energy Conversion

  Example: Thermoelectrics (Devices: TRL 1; Materials: TRL 2-3)

- Sources (x-ray, optical)

  Example: Miniaturized X-Ray Source (TRL 5)

- Memory

  Example: CNT based memory (TRL 2-4)

  Nanowire based memory (TRL 2-3)

  Representative Examples in Appendix

Nano-electronics: Opportunities and Challenges

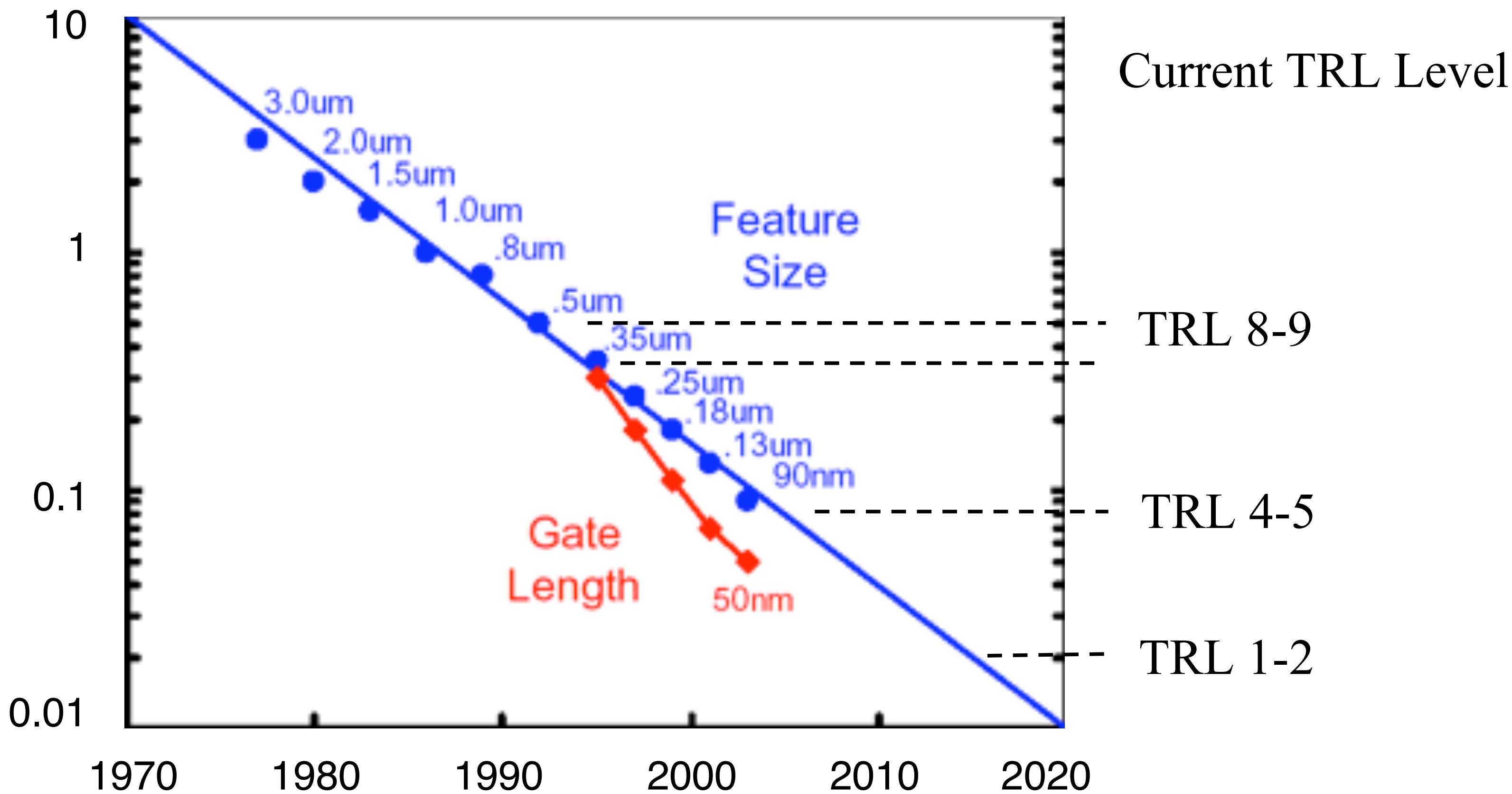
Challenges:

- Stay on the ITRS Roadmap
- Assuring space durability
- Develop of reliable designs and fabrication methods for nano-scale devices suitable for heterogeneous integration
- NASA space-qualified electronics ~3 generations behind ITRS roadmap

Opportunities:

- Semiconductor industry is initiating new partnerships with government and academia (including National Research Initiative)
- Partnership with industry can advance technologies for both commercial, NASA needs
- Participation by NASA can ensure that NASA-specific needs are addressed in technology development

Micro-electronics is becoming Nano-electronics



www.intel.com/research/silicon/90nm_press_briefing-technical.htm

Capability 16.2 CBS Sensing and Devices

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Sensing Devices

- Devices for Chem/Bio sensors (TRL 2-3)

  Example: Conductance-based devices (e.g.nanowires)

- Bioassay/virus/other bioparticles (TRL 1-3)

  Example: Mass/Resonance based (e.g. cantilever)

- Devices/materials for in-situ, optical-based spectroscopy (TRL 2)

  Example: Surface Enhanced Raman (SERS) using nanoparticles)

- LASERs and Photonic/Optoelectronic devices for remote sensing/imaging (TRL 2-3)

  Example: Devices employing quantum dots for multi-wavelength detectors, imagers

Representative Examples in Appendix

Nano-sensors: Opportunities and Challenges

Advanced Planning & Integration Office

Challenges:

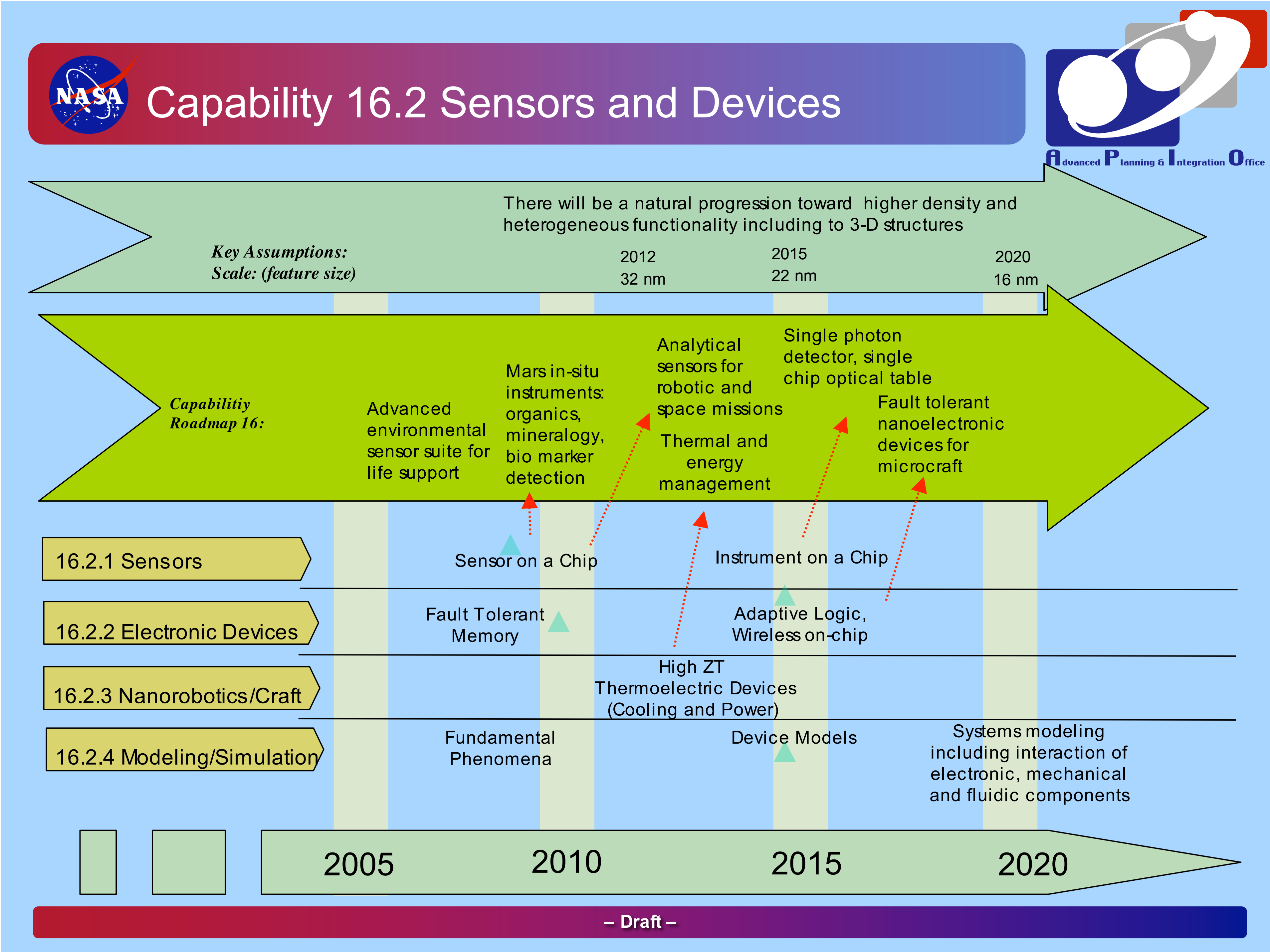
- Sensor industry not as centralized as microelectronics industry
- Many potential species/quantities to sense
- Many emerging approaches to sensing and electronics: “winners” still TBD

Opportunities:

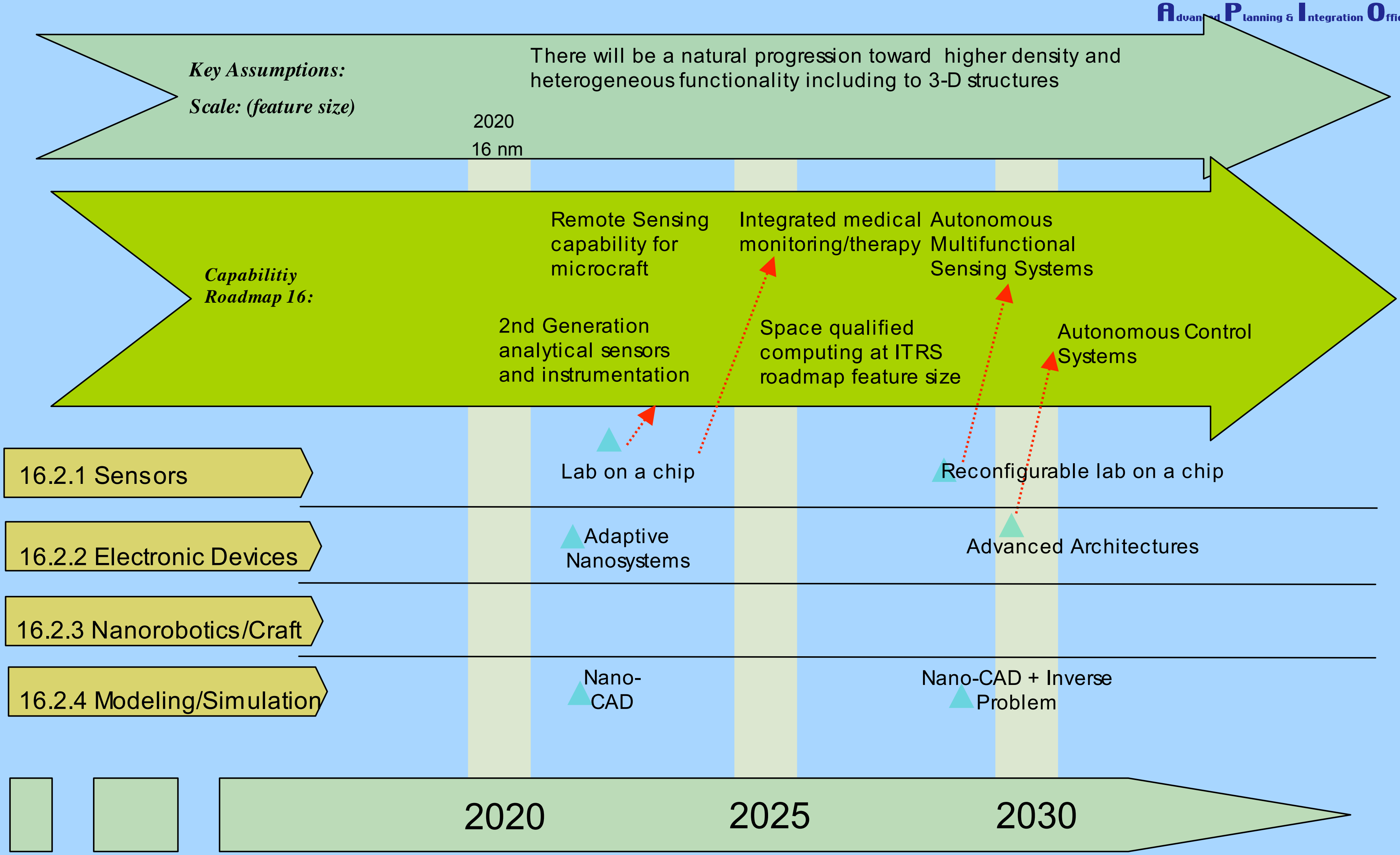
- Strategic investment will be leveraged with dual-use developments
- Nanosensors will enable miniature instruments for rovers, microcraft, spacecraft

Draft: Roadmaps

- Roadmaps are currently draft only
- Represent first cut at organizing needed technological capability and timelines when it may be available
- Will be modified as more definitive priorities and roadmaps are produced by other capability road mapping teams


Capability 16.2 Sensors and Devices
Advanced Planning & Integration Office
There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures
Key Assumptions:
Scale: (feature size)
2012
32 nm
2015
22 nm
2020
16 nm
Capabilitiy Roadmap 16:
Advanced environmental sensor suite for life support
Mars in-situ instruments: organics, mineralogy, bio marker detection
Analytical sensors for robotic and space missions
Thermal and energy management
Single photon detector, single chip optical table
Fault tolerant nanoelectronic devices for microcraft
16.2.1 Sensors
Sensor on a Chip
Instrument on a Chip
16.2.2 Electronic Devices
Fault Tolerant Memory
Adaptive Logic, Wireless on-chip
16.2.3 Nanorobotics/Craft
High ZT Thermoelectric Devices (Cooling and Power)
16.2.4 Modeling/Simulation
Fundamental Phenomena
Device Models
Systems modeling including interaction of electronic, mechanical and fluidic components
2005
2010
2015
2020
– Draft –

Capability 16.2 Sensors and Devices



Detailed Roadmaps

Capability 16.2 Nanotechnology Roadmap

Advanced Planning & Integration Office

Key Assumptions:
ITRS roadmap
NNI roadmap

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures

2012 32 nm
2015 22 nm
2020 16 nm

Capability Roadmap 16:

Advanced environmental sensor suite for life support

Advanced sensor suite for Earth science

Sensor Constellations, multipoint environmental

Vehicle health monitoring

Sensor Constellations, multipoint environmental

Advanced sensor suite life detection

16.2.1 Sensing

Sensor on a chip — Instrument on a chip — Lab on a chip

Chem Bio:	Multiplex sensing components		Single chip sensing, bioassays	Health monitoring suite
Photon:	Discrete sources/detectors		Single photon detector, single chip optical table	Network of optical sensor chips
State Variables/ Particles:		Imbedded sensors for structural integrity	Imbedded sensors for structural integrity and performance	
Sensor Systems:			Wireless comm for distributed sensors	Distributed sensors with Integrated communication
Extreme environment operation:	High Temperature 150-400K		High Radiation, temp and pressure	Venus conditions

2005 — 2010 — 2015 — 2020

Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
ITRS roadmap
NNI roadmap

2020
16 nm

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures

Capability Roadmap 16:

Multifunctional Microcraft/ Microrovers

Advanced Life Support System

16.2.1 Sensing

Lab on a chip — Reconfigurable lab on a chip

	2020	2030
Chem Bio:	Health monitoring suite	Automatic health monitor/ response, Integrated Trigger
Photon:	Network of optical sensor chips	
State Variables/		
Particles: Sensor Systems:	Distributed sensors Integrated communication	Large-scale wireless sensor systems
Extreme environment operation:	Venus conditions	Near-Sun conditions

2020 2025 2030

Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
ITRS roadmap
NNI roadmap

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures

2012
32 nm

2015
22 nm

2020
16 nm

Capability Roadmap 16:

On-chip interfaces and controls for advanced instruments

Highly reliable non-volatile on-board memory

On-board computing near ITRS performance levels

16.2.2 Electronics	Fault Tolerant Memory		Adaptive Logic	Adaptive Nanosystems
General Computation:	Low power, fault tolerant memory architecture; demos of nanoelectronics in extreme environments		Low power, adaptive logic; NASA electronics near ITRS performance	Self-adaptive/ configurable; NASA electronics at ITRS performance
Sense and control:		On-chip interfaces and controls	Ultra-low noise electronics for sensors	Integrated sense/ computing
Special purpose:			On-chip photovoltaics; Flexible electronics	THz Local Oscillator

2005 2010 2015 2020

Capability 16.2 Nanotechnology Roadmap

Advanced Planning & Integration Office

Key Assumptions:
ITRS roadmap
NNI roadmap

2020
16 nm

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures

Capability Roadmap 16:

Rad-hard, fault tolerant electronics
Pico probes

16.2.2 Electronics

Adaptive Nanosystems

Advanced Architectures

General Computation:

Self-adaptive/ configurable

NASA electronics at ITRS performance

Spintronics

Quantum computing

Integrated sense/control:

Integrated sense/ electronics

Special purpose:

THz Local Oscillator

Ultra-sensitive atomic interferometric gyroscope

2020 2025 2030

Capability 16.2 Nanotechnology Roadmap

Planning & Integration Office

Key Assumptions:
ITRS roadmap
NNI roadmap

2012	2015	2020
32 nm	22 nm	16 nm

Capability Roadmap 16: Thermal and Energy Management

16.2.3 Nanorobotics TBD TBD TBD TBD

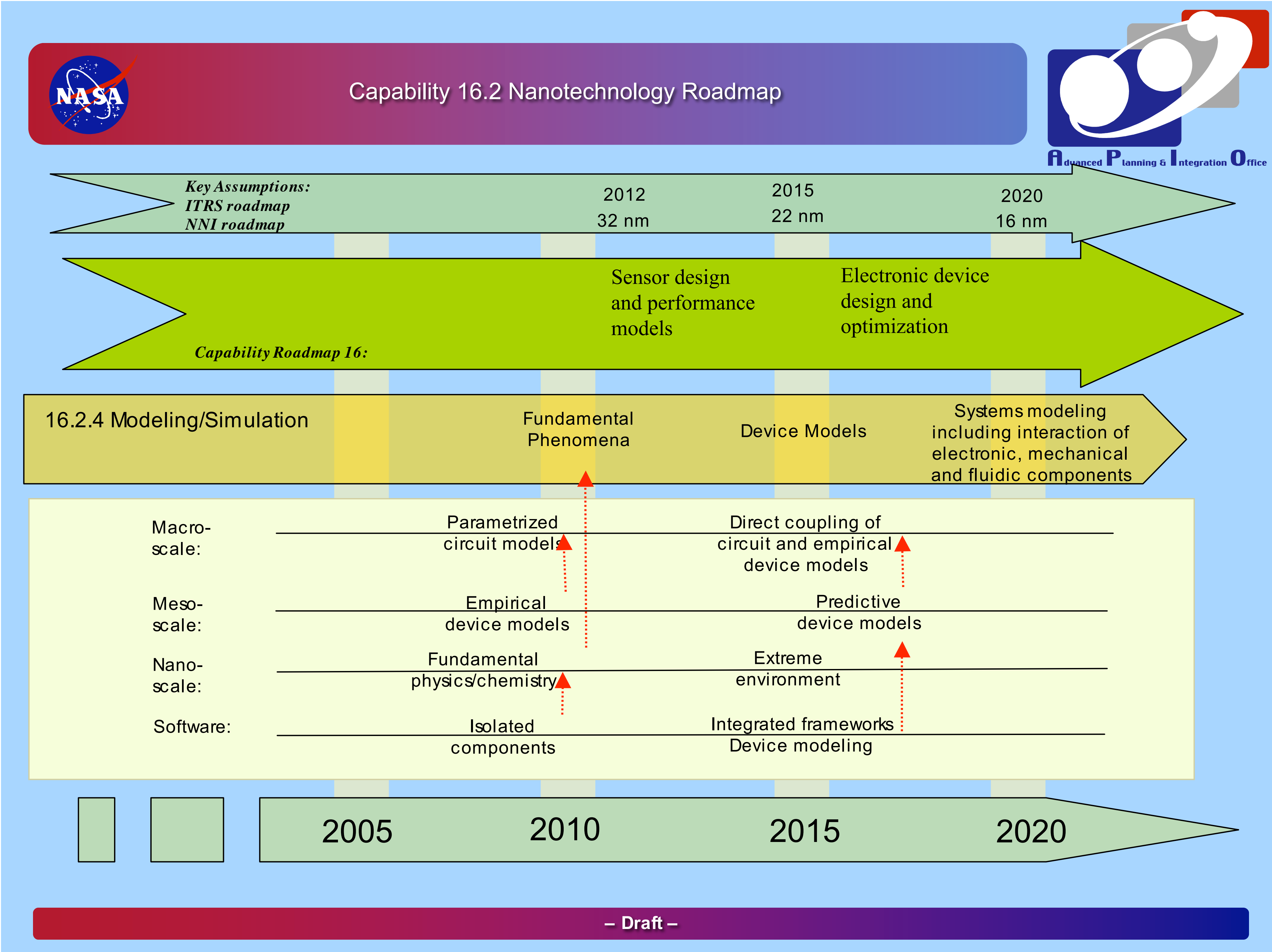
Incomplete

NEMS Devices

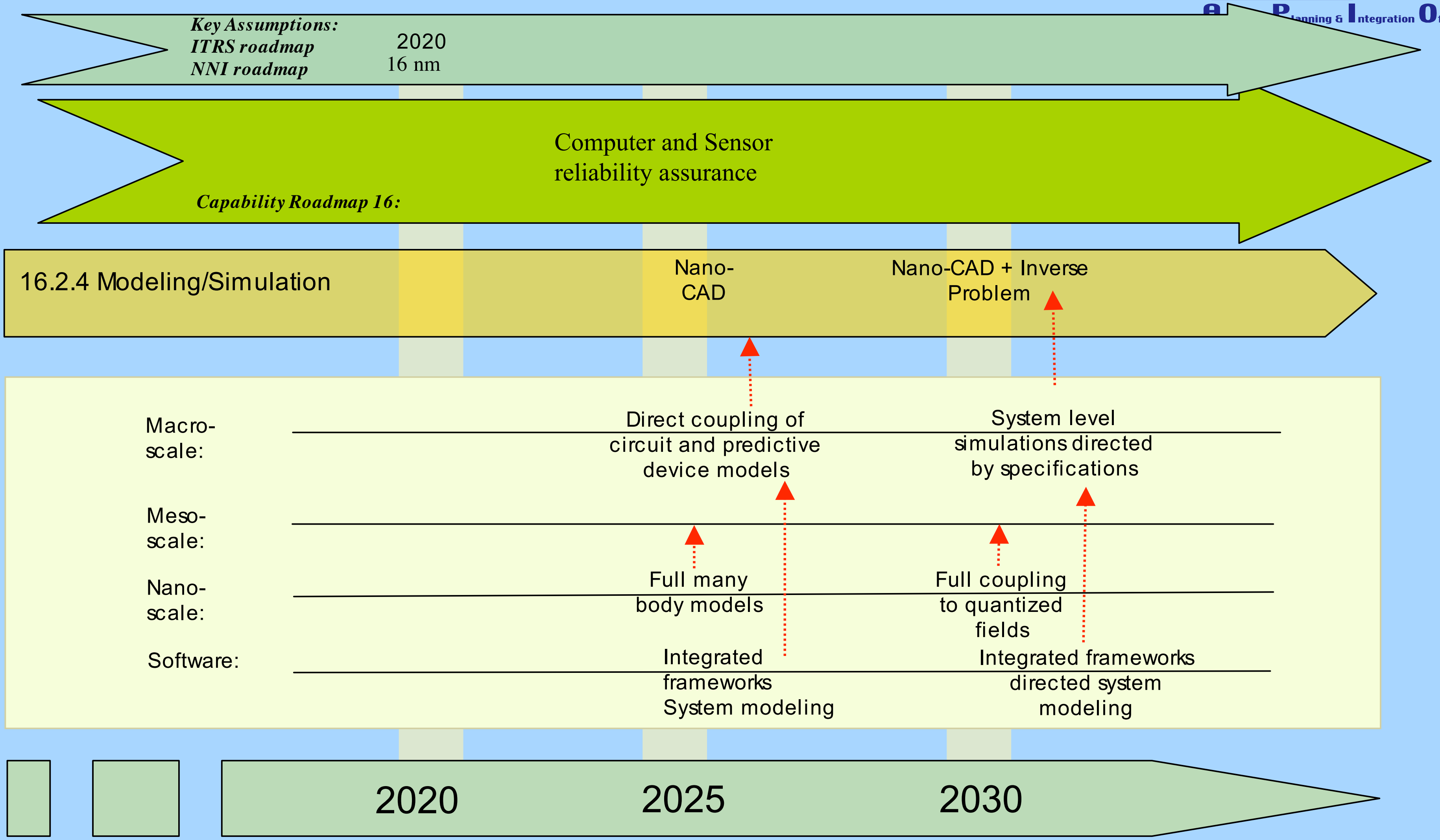
Thermal Management: High ZT Thermoelectric Devices (Cooling and Power)

Computing

2005 2010 2015 2025 2030


Capability 16.2 Nanotechnology Roadmap
Advanced Planning & Integration Office
Key Assumptions:
ITRS roadmap
NNI roadmap
2012
32 nm
2015
22 nm
2020
16 nm
Capability Roadmap 16:
Sensor design and performance models
Electronic device design and optimization
16.2.4 Modeling/Simulation
Fundamental Phenomena
Device Models
Systems modeling including interaction of electronic, mechanical and fluidic components
Macro-scale:
Parametrized circuit models
Direct coupling of circuit and empirical device models
Meso-scale:
Empirical device models
Predictive device models
Nano-scale:
Fundamental physics/chemistry
Extreme environment
Software:
Isolated components
Integrated frameworks Device modeling
2005
2010
2015
2020
– Draft –

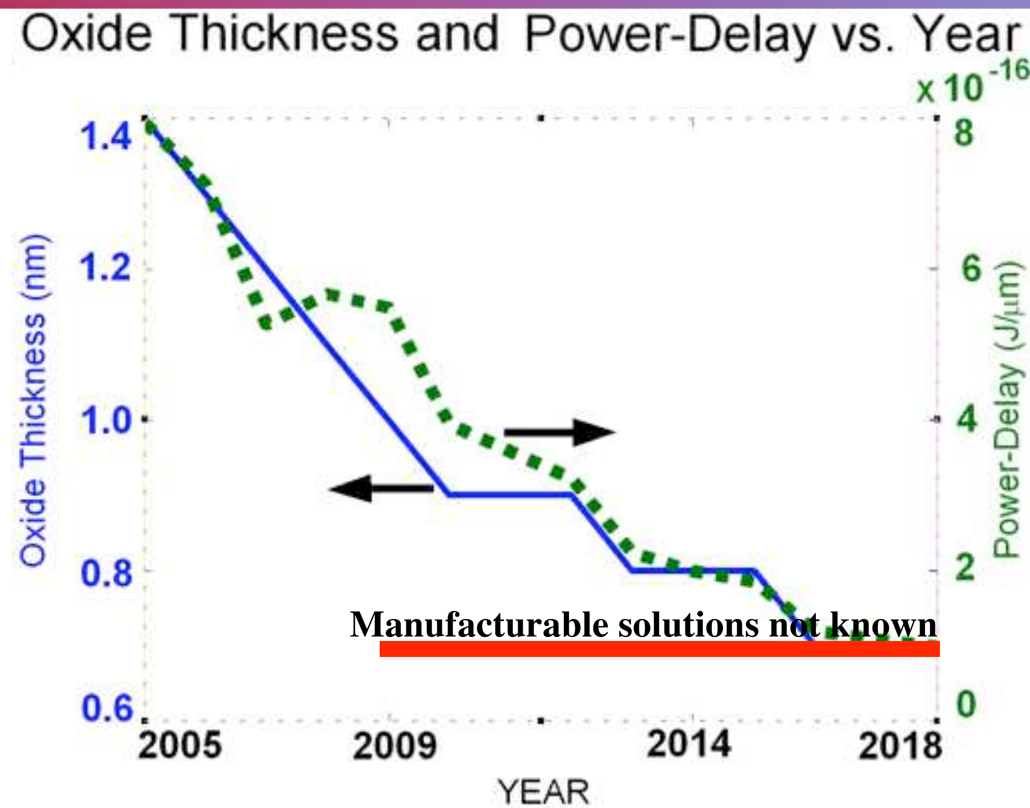
Capability 16.2 Nanotechnology Roadmap



Appendix I – Representative Examples of Nano Devices/Sensors

(used in evaluating connectivity to other CRM areas and TRL levels)

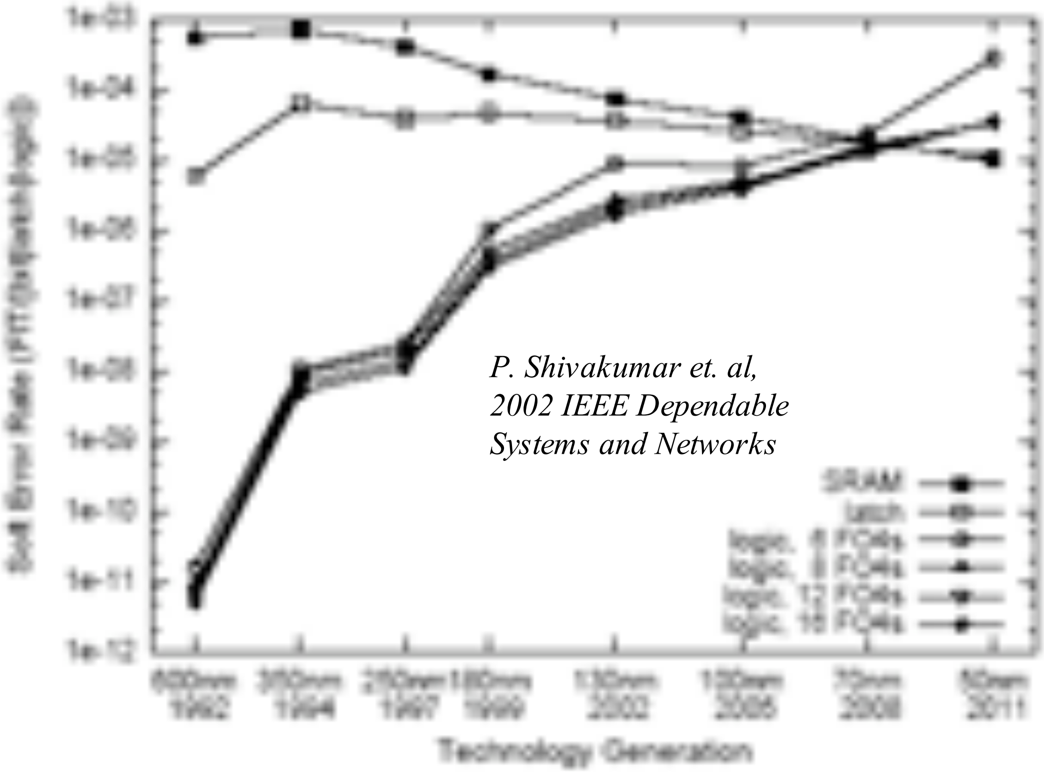
Advanced Planning & Integration Office



- Manufacturable solutions do not exist
  - Oxide thickness scaling, gate capacitance
  - Source-drain resistance
  - Reliable interconnects
- Power delay product is large making chips hot

Downscaling of electronics has major bottlenecks

Soft Error Rate (SER)



- SER of a single SRAM decreases with technology generation
- SER of logic increases → Decrease in critical charge involved in latchup

Fabrication and design to avoid latchup become increasingly important

Thermoelectric Energy Conversion

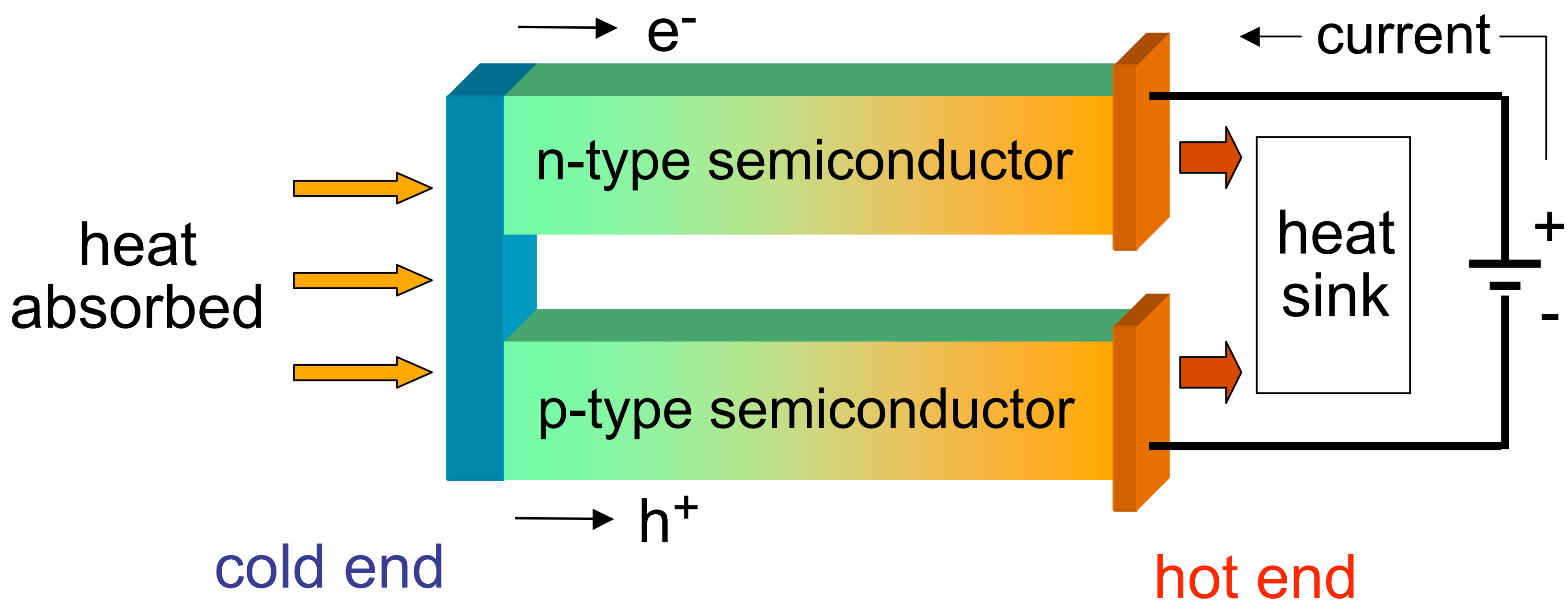


Figure of Merit:

$$ZT = \frac{S^2\sigma}{\kappa} T$$

Large Seebeck Coefficient (S)
Small Thermal Conductivity (κ)
Large electrical conductivity (σ)

In bulk materials, maximum ZT ~ 1

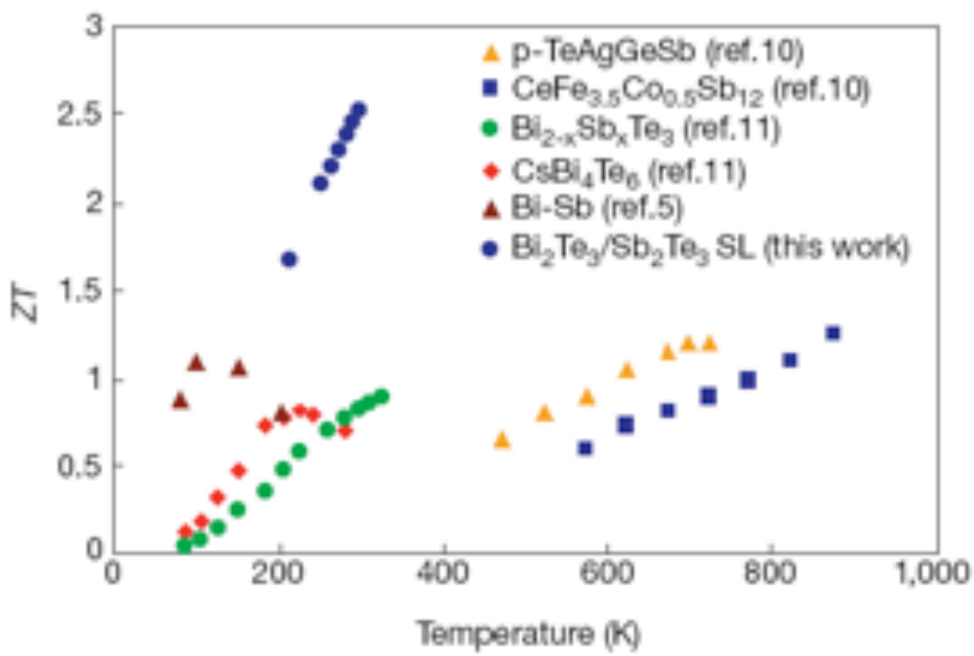
Little progress in 20 years.

Need ZT ~ 4 to displace with other technologies

Nanostructuring materials to improve ZT

Two Dimensional Superlattices

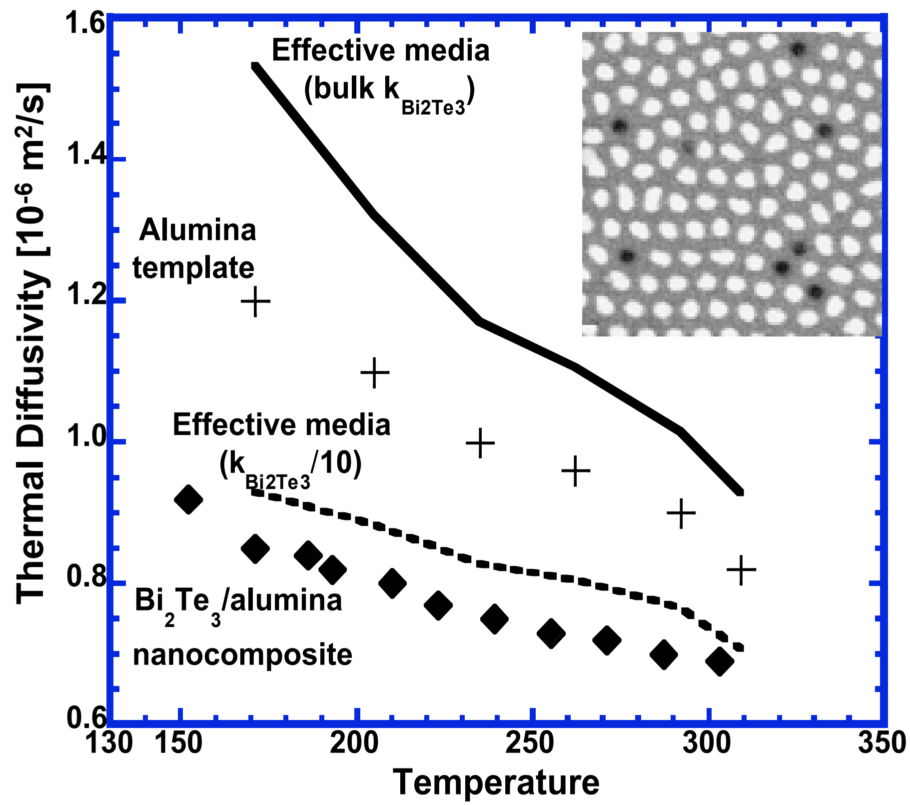
Bi_2Te_3/Sb_2Te_3



Venkatasubramanian, et al. (GTRI), Nature **413** p. 597 (2001)

Arrays of One-Dimensional Wires

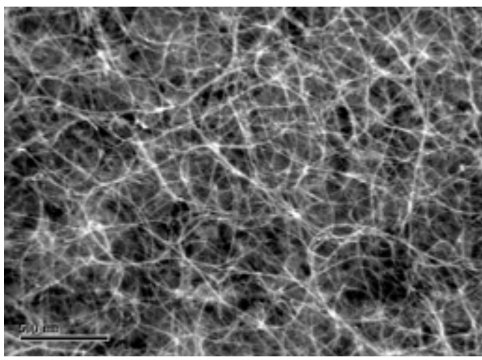
(50 nm Bi_2Te_3 wires in nanoporous alumina)



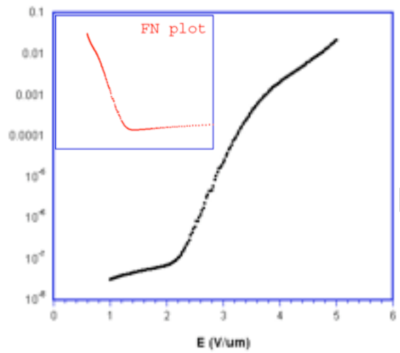
Source: Tim Sands, Purdue

Carbon Nanotube Field Emission

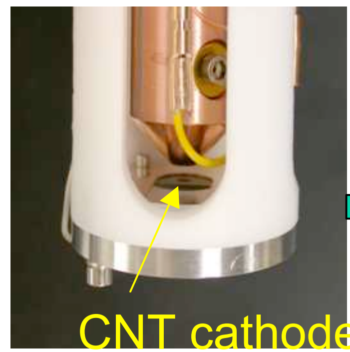
Carbon-Nanotubes: Sharp local tips provide efficient field emission
Miniature X-Ray tube: slated for 2009 NASA mission



CNT emitter fabrication
NASA Ames



Field emission characterization
NASA Ames

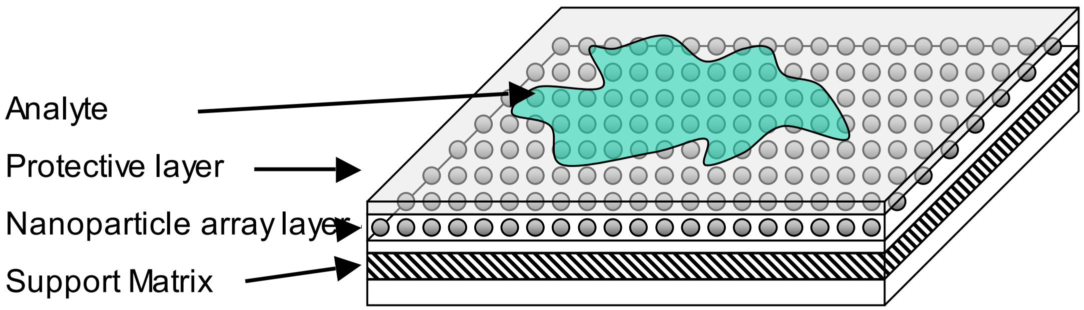


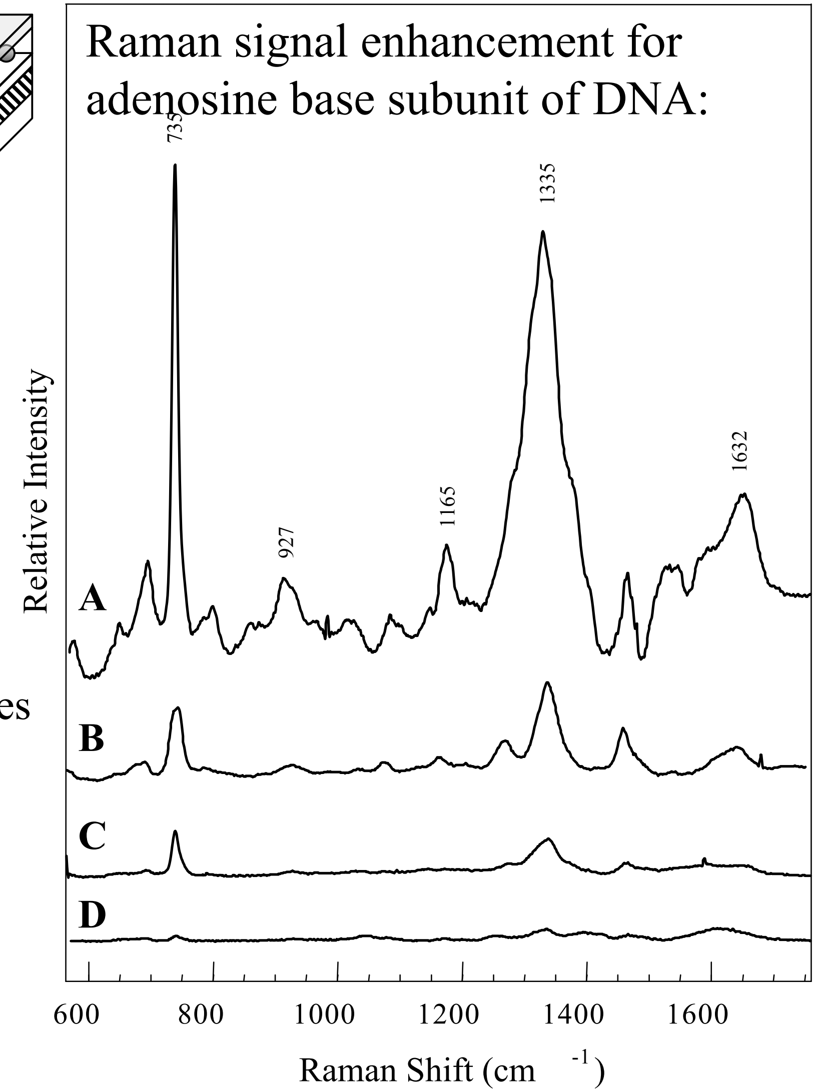
Integration in miniature X-ray tube
(Oxford XTG Inc.)

- SWNT - MWNT - nanofibers
- Silicon and metal substrates
- Film, arrays

➢ Optimum type of CNT?
➢ Optimum CNT/substrate attachment?
➢ Optimum site density?

Surface Enhanced Raman Scattering (SERS) enhancement Using Nanostructured Surface





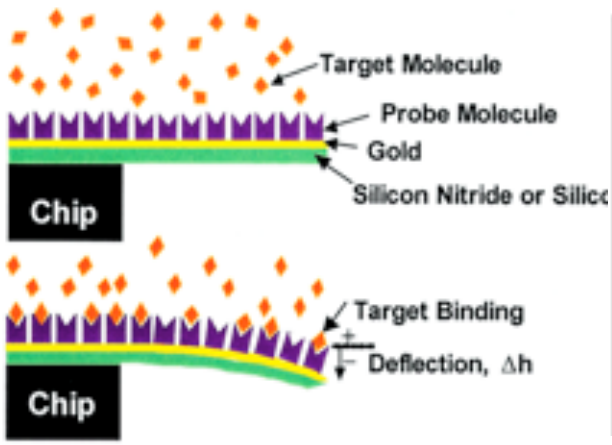
Nanoparticle based structure is produced by self assembly of particles that create
a substrate for use in Surface Enhanced Raman Spectroscopy (SERS).

(A) on plasmon resonant substrate with metal nanoparticles (460 nm plasmon maximum), (B) on electrochemically roughened Ag electrode, (C) on laser ablated Ag films (old), and (D) on laser ablated film (new).

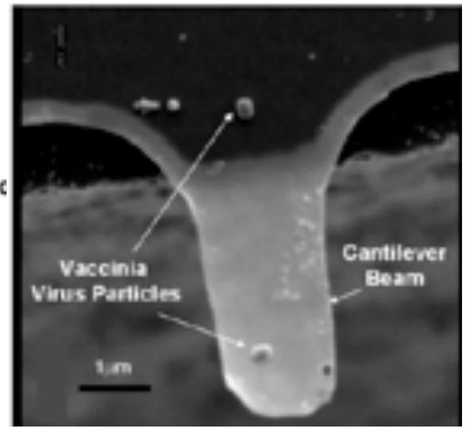
Source: Viktor Stolc, NASA Ames Research Center

Biosensor

- Optical, Electrical, Mechanical methods for detection



Cantilever based sensor
Wu, PNAS (2001)



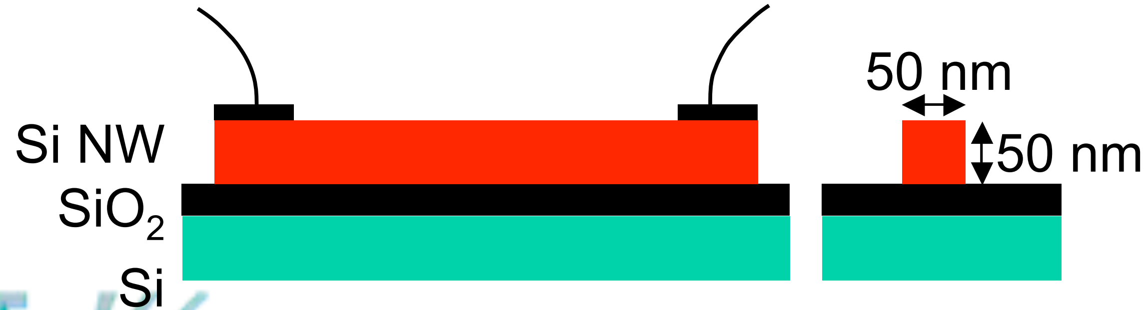
Mass sensing of single virus,
Gupta et. al, APL (2004)

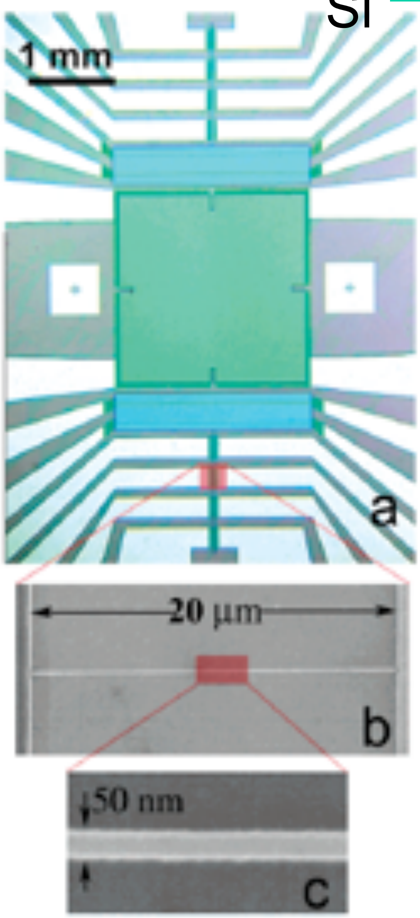
Silicon Nanowire (20 nm) based
DNA sensor, Hahm, Nanolett (2004)

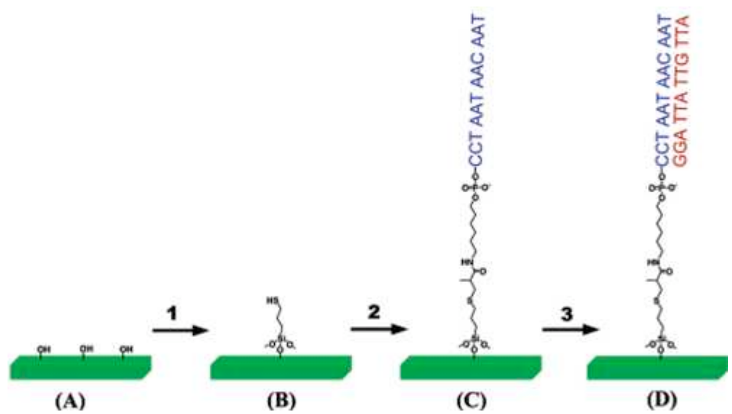
100 fM DNA solution

- Label free detection of biomolecules in real time
- Cantilever Bending: Probe is attached to top surface. Hybridization causes bending
- Nanowire: Charge of biomolecule affects electrical current in nanowire / nanotube
- Detection of mutation causing cystic fibrosis is demonstrated
- Ultra low detection limits, single particle detection in some cases

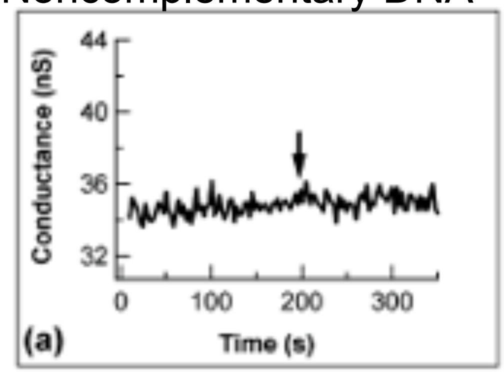
Electron-beam fabricated SOI DNA sensor



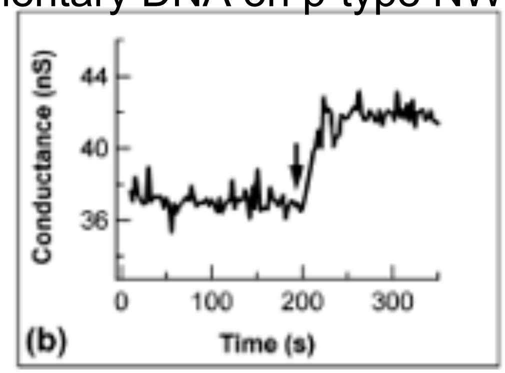




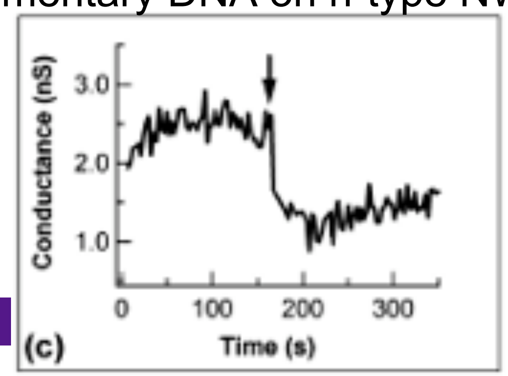
Noncomplementary DNA



Complementary DNA on p-type NW



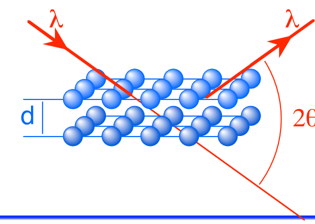
Complementary DNA on n-type NW

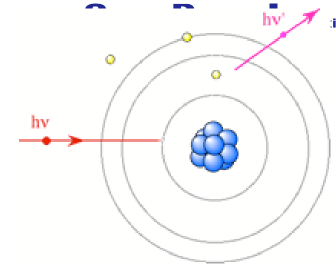


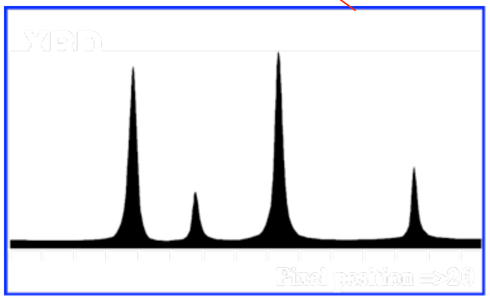
"Sequence-Specific Label-Free DNA Sensors Based on Silicon Nanowires," Z. Li, Y. Chen, X. Li, T. I. Kamins, K. Nauka, and R. S. Williams, Nano Letters **4**, 245-247 (2004).

Chemistry & Mineralogy

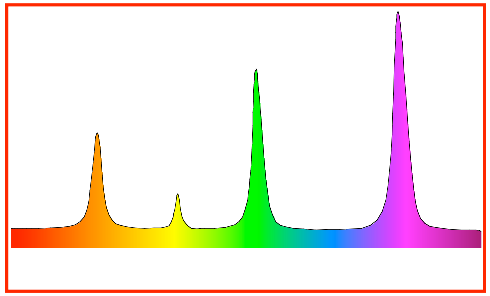
- DETECTOR
- SIMULTANEOUS ANALYSES
- NO MOVING PARTS



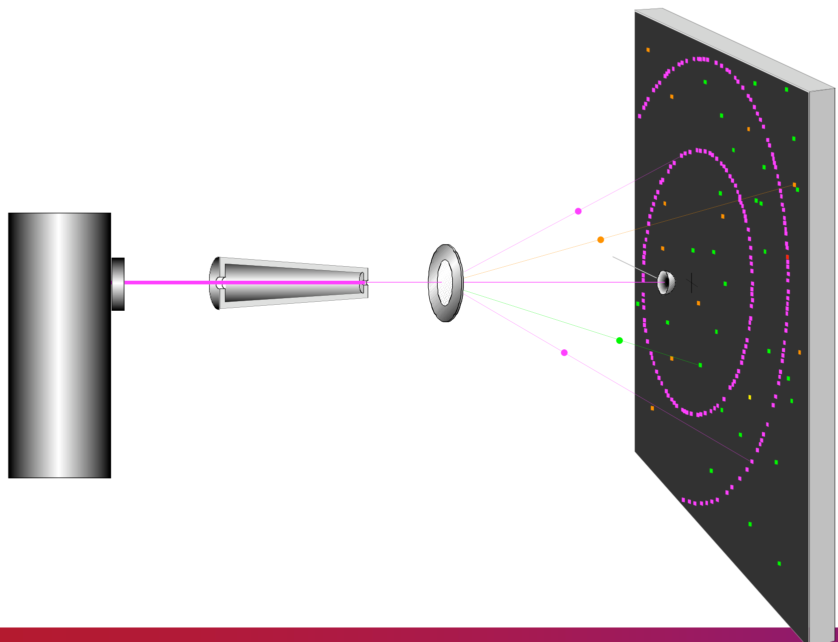




X-ray diffraction



X-ray fluorescence



- Carbon nanotube field emitters
- Low threshold for emission
- Volume < 10 liter (1 liter)
- Mass < 5 kilogram (1 kg)
- Power < 15 Watts (5 W)

Appendix III – Representative Example of potential (and actual) applications in Missions:

In-Situ Science Instruments for Mars

Mars Science in-situ Instruments

Capability

Astrobiology Field Lab

Life Bio-markers Detection and Identification

Mars Science Laboratory

Organic Detection & Mineralogy

Phoenix

Chemical Analysis & Microscopy

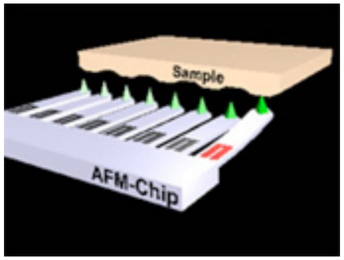
Time

– Draft –

Mars 2007 = Phoenix

Chemical analysis& Microscopy

- Thermal and Evolved Gas Analyzer (TEGA)
- Microscopy, Electrochemistry, and Conductivity Analyzer (MECA)



The atomic force microscope will provide morphology images down to 10 nanometers--the smallest scale ever examined on Mars.

Mars 2009 = Mars Science Laboratory

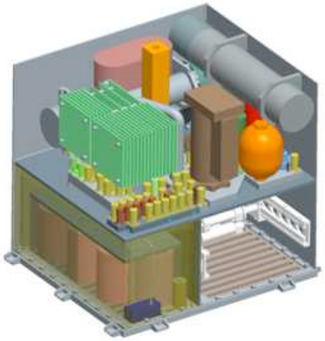
Organic Detection & Mineralogy

Sample Analysis at Mars (SAM)

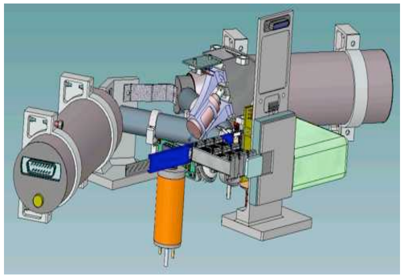
- Gas Chromatograph
- Mass Spectrometer
- Tunable Laser Spectrometer
  - Detection sensitivity of **ppm-ppb**

CheMin

- X-Ray Diffraction/X-Ray Fluorescence Instrument
  - (grain size 150 micron)



3D model of SAM Instrument

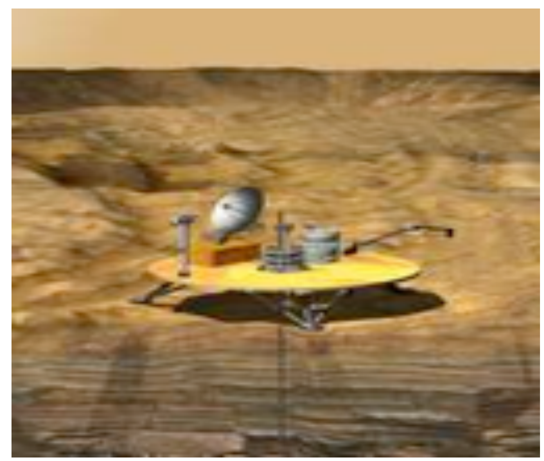


3D model of the CheMin instrument

Detection and identification of life bio-markers

- Meso-Micro Scale Imaging
- Microscopy
- Mineralogical/Elemental Analysis
- Isotope Analysis/Age Dating
- Bio-Sensors
- Geophysical & Geochemical Measurements

Astrobiology Field Lab



Deep Drill Lander

- Compact multi-hyper spectral imagers
  - E-beam fabrication of analog-relief diffractive optics
- Miniaturized Scanning electron microscopy,
  - Sub nm resolution imaging
- Light and tip enhanced AFM,
  - Sub nm resolution imaging
- Fluorescent nano-particulate tagging
- Nano structures based sources (UV, X-Ray, IR)
- Micro-nano electrodes,
- Micro-nano manipulators,
- Array of Ion channel sensors
- Array of nano sensors
- Micro-nano fluidics

- Measure pH, temperature, conductivity, and concentrations of major ions and redox sensitive aqueous compounds, including O_2, H_2, HCO_3^-, NO_3^-, Fe^{2+}, SO_4^{2-}, H_2S, NH_4^+ *(e.g., microelectrodes, micromanipulators).*
- Determine presence (if possible, concentrations) of DOC and aqueous organic monomers, including carboxylic acids, amino acids, sugars, hydrocarbons and/or corresponding functional groups *(e.g., liquid and gas chromatography, IR).*
- Determine presence (if possible, sequence or composition) of aqueous and particulate organic polymers, including proteins, lipids, nucleic acids, saccharides.
- Attempt to visualize and enumerate variably stained microbial cells in suspension or on particulate matter *(e.g., light or scanning electron microscopy, microspectroscopy, fluorescent nanoparticulate tagging)*.
- Consider culturing on 1-3 samples using ~10-100 pre-designed growth media at several different temperatures *(microfluidics, microculturing, "lab-on-a-chip")*.

Appendix IV – Excerpts from NNI Grand Challenges Workshop on

NATIONAL NANOTECHNOLOGY INITIATIVE

Advanced Planning & Integration Office

Biotechnology

Nanotechnology

NNI
"Research Directions II"
Workshop

September 8-10, 2004
Washington, D.C.

Grand Challenge: Microcraft & Robotics

Information Technology

Summary Quad Charts for: Nano-Sensor and Instrumentation Nanorobotics

– Draft –

Nano-sensors and Instrumentation

Goals

Enable missions with nano-sensors:

- Remote sensing
  - Viewing there
- Vehicle health and performance
  - Getting there
- Geochemical and astrobiological research
  - Being there
- Manned space flight
  - Living there

Hard Problems

- Band-gap engineered materials
- Control Atomic layers of substrates
- Template pattern controls
- Dark current reductions
- Readout electronics
- Assembly of large arrays
- Modeling, simulation and testing
- Upward integration into macro-systems

Value to Space Systems

- 10X to 100X smaller, lower power & cost
- Tailorable for very high quantum efficiency
- Tailorable for space durability in harsh environments
- Improved capabilities at comparable or reduced cost
- Mission enabling technology

State of the Art (all ground based)

- Designer bio/chemical sensors
  - Characteristic Properties of Molecules
  - Functionalized structures (CNTs, etc.)
- Assembly of nano-structures
  - Template development
  - Electro-static control
  - Nano-fluidics/separation tools

Nanorobotics

Goals

- Millimeter and sub-millimeter size robots
- 3D nanoassembly and nanomanufacturing
- Self-reconfigurable miniature robots
- Controlling biosystems
- Hybrid (biotic/abiotic) robots
- Cooperative networks of micro-robots
- Atomic and molecular scale manufacturing
- Design and simulation tools for nano-robots

Hard Problems

- **Mobility**: Surface climbing, walking, hopping, flying, swimming; Smart nanomaterials for adhesion, multi-functionality, …
- **Power**: Harvesting; Novel miniature power systems (e.g. chemical energy); Wireless
- **Actuation**: CNT, polymer, electrostatic, thermal, SMA, and piezo actuators
- **Complexity**: New programming methods for controlling massive numbers of robots

Value to Space Systems

- In-space (CEV, space station, Hubble telescope, & satellites) and planetary inspection, maintenance, and repair
- Searching for life on planets (retrieving and analyzing samples)
- Astronaut health monitoring
- Assembly and construction
- Manufacturing on-demand
- Microcraft

State of the Art

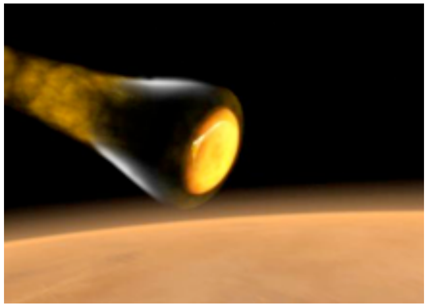
- **Miniature Micro/Nano-Robots:** Centimeter scale autonomous robots; Chemically powered bio-motor actuation; Endoscopic micro-capsules; MEMS solar cells powered micro-robots; Reconfigurable mini-robots
- **Micro/Nano-Manipulation:** Scanning Probe Microscope based nanomanipulation; 3D micro-assembly; Optical tweezers and dielectrophoretic bio-manipulation; Virtual Reality human-machine user interfaces

Intelligent / Integrated Systems

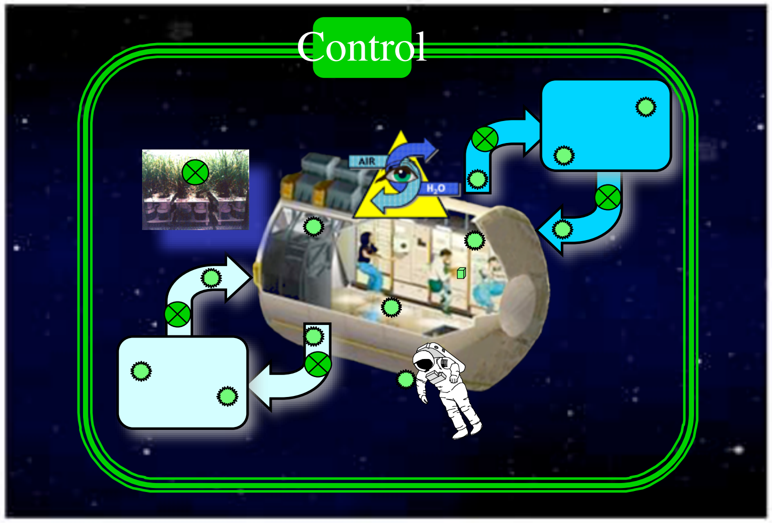
Capability 16.3 Intelligent Systems

Presenter/Team Lead:
Chih Ming Ho, UCLA
chihming@ucla.edu
Co-Lead:
Benny Toomarian - JPL
Team Members:
Minoo Dastoor – NASA HQ
Jose Fortes - Univ. of Florida,
Dan Herr - SRC,
Dimitris Lagoudas - Texas A&M Univ.
Stan Williams - HP Labs

- Principles, frameworks, and nano-components for the design, fabrication, integration of mission-appropriate intelligent systems capable of continua of awareness.



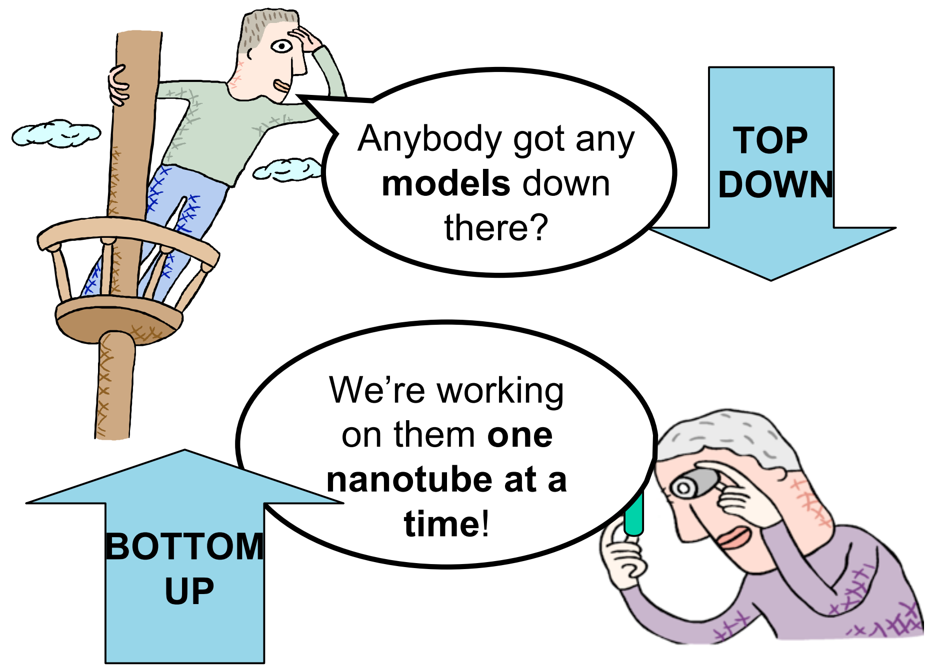
Guided entry for energy dissipation or precision / pinpoint landing



Monitoring & Controlling the environment

Key technical challenges:

- Multiscale hierarchical models **for analysis and prediction /design /synthesis of intelligent systems.**
- Multiscale manufacturing processes (**that can encompass the nano, micro and the macro scales).**
- Interconnectivity **for signal and material transports**
- Preservation and utilization of nano-properties **at the device and system levels.**
- Information representation **and processing models and architectures from the nano scale to the macro scale that are well suited to emergent**

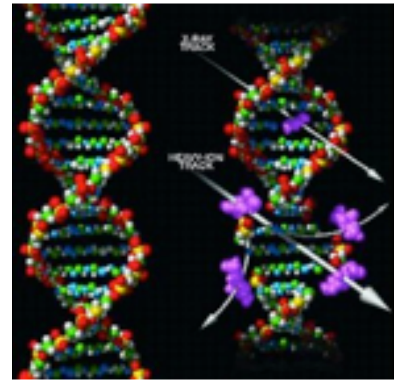


Benefits of the 16.3 Intelligent Systems

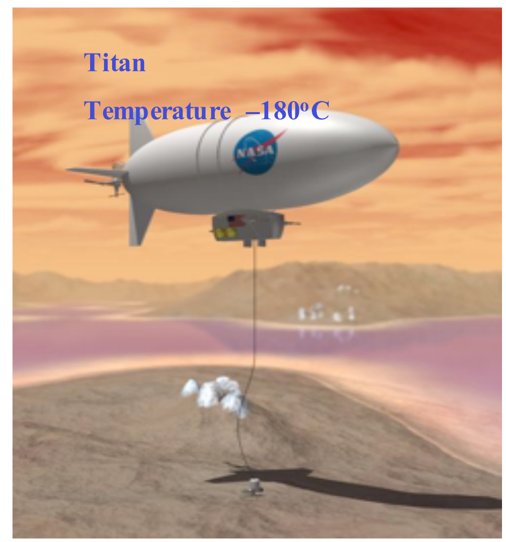
Advanced Planning & Integration Office

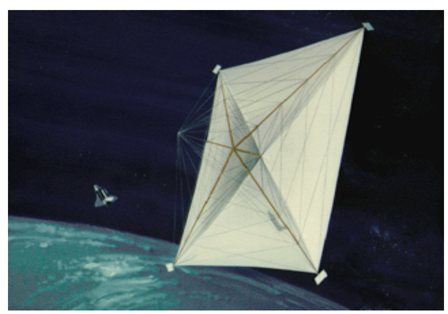
Intelligent systems will benefit:

- Crew health monitoring and drug delivery
  - Cell imaging and penetration
- Crew environment monitoring and control
  - Air and Water purification
- Miniaturized planetary probes, e,g,;
  - Titan probe
  - Mars astrobiology field laboratory
    - Integrated array of nano-sensors with nano fluidics
- Thermal protection system
  - Smart skin
- Large aperture systems
  - Smart skin,



High-energy cosmic radiation can cause damage to DNA and make cells behave erratically





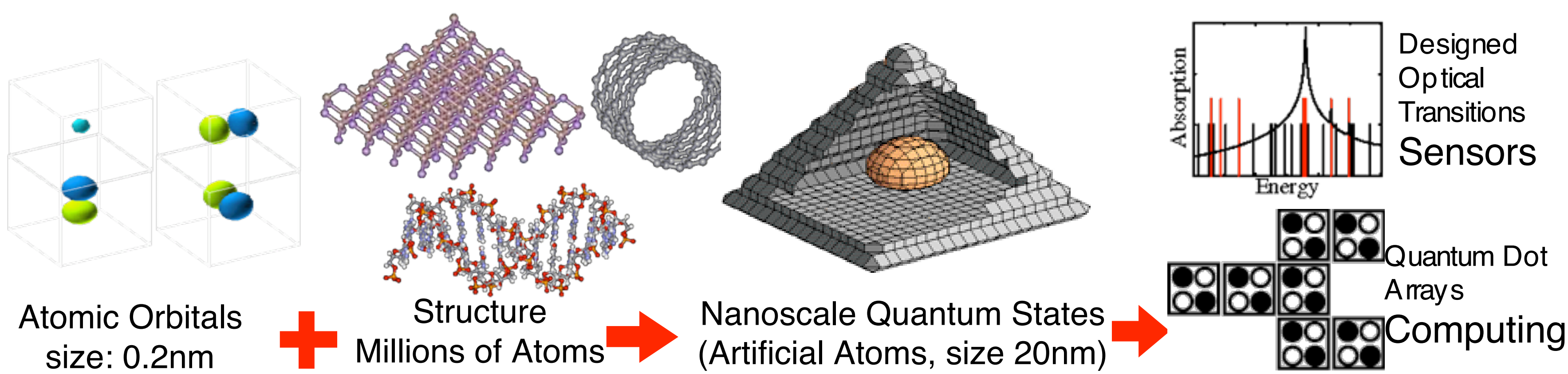
Interplanetary solar sail

Current State-of-the-Art for Capability 16.3 Intelligent Systems

Advanced Planning & Integration Office

Multi-scale Hierarchical Modeling. TRL=1-2

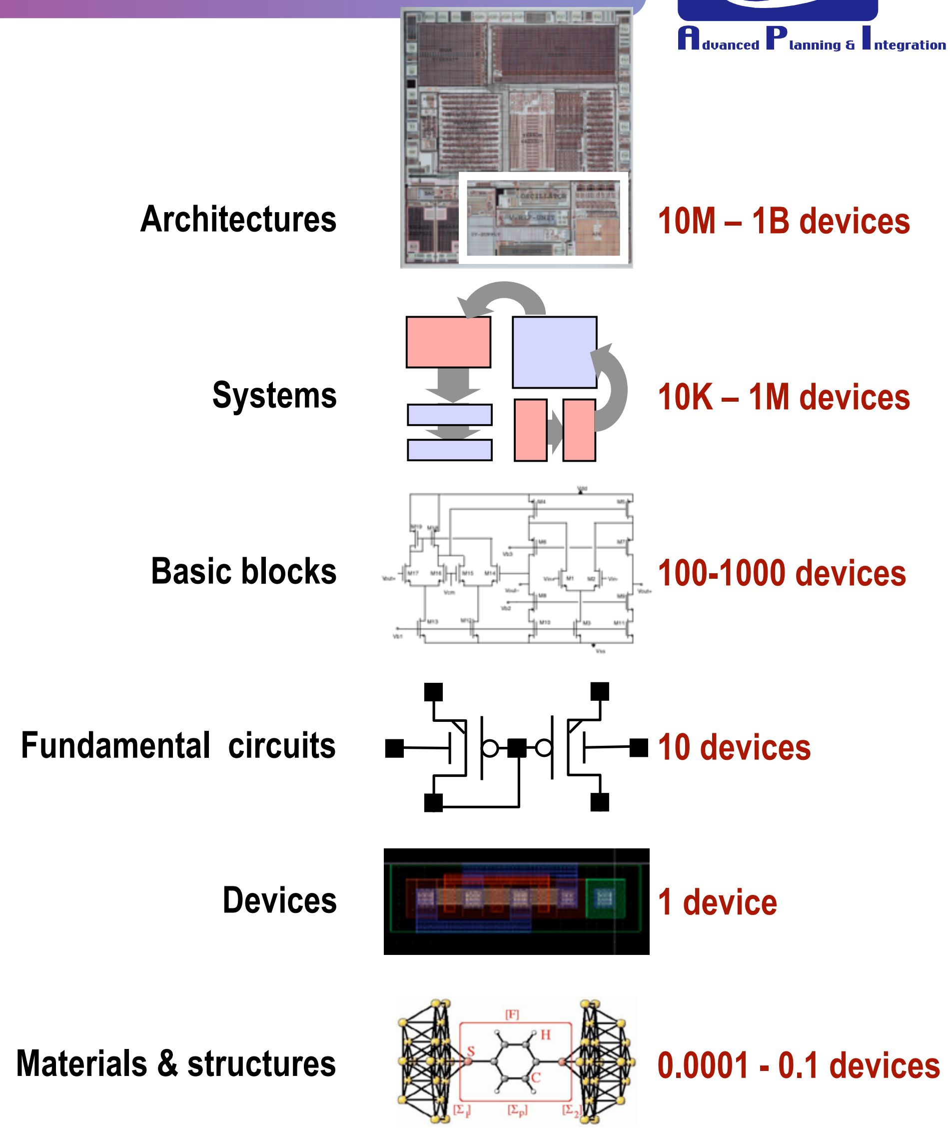
- **Robust multi-scale modeling exists from micro to macro for well-understood systems (excluding, for example, transport-based systems).**
- **Quantum-to-Nano-to-Micro modeling is at a primitive state.**



Current State-of-the-Art for Capability 16.3 Intelligent Systems

Multi-scale Manufacturing Processes.
TRL = 1-3

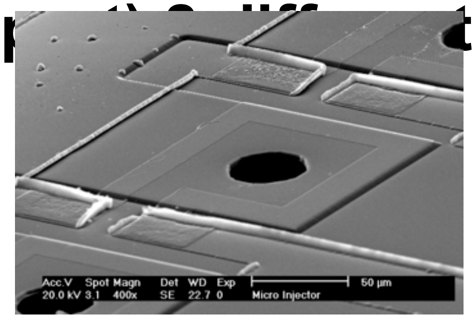
- **Top-down processes (lithography-based) are highly mature; state of the art at 90 nm half-pitch; limits (ITRS) at 32 nm**
- **Commercial sensors: biological bio-nano sensors (e.g., dna-based and protein-based) are very mature; limited capability to build integrated sensor systems (exceptional cases exist).**
- **Design of nanomaterials and upscale to nanocomposites still at infancy (some approaching commercialization).**
- **Nanoimprinting and related technologies are emerging primarily for research purposes (some commercially available).**
- **Directed self-assembly still immature.**

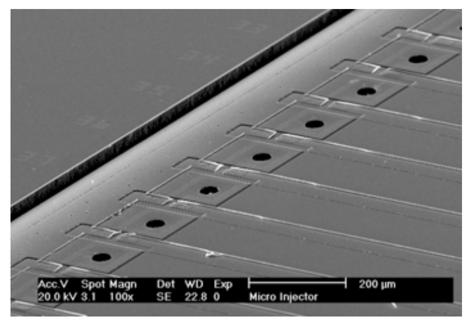


Current State-of-the-Art for Capability 16.3 Intelligent Systems

Interconnectivity. TRL = 2 - 4

- **Electronic-based signaling through multi-level metal wires (as in most ICs) is very mature … but reaching limits (ITRS) 90 nm at top level, ~ 8 levels**
- **Ink-jet printing (as an example of material transp[illegible]t fluids and pico-liter drops**





Array of ink-jet nozzles for less than pico-liter fluid delivery
(Tseng et al, JMEMS 2002)

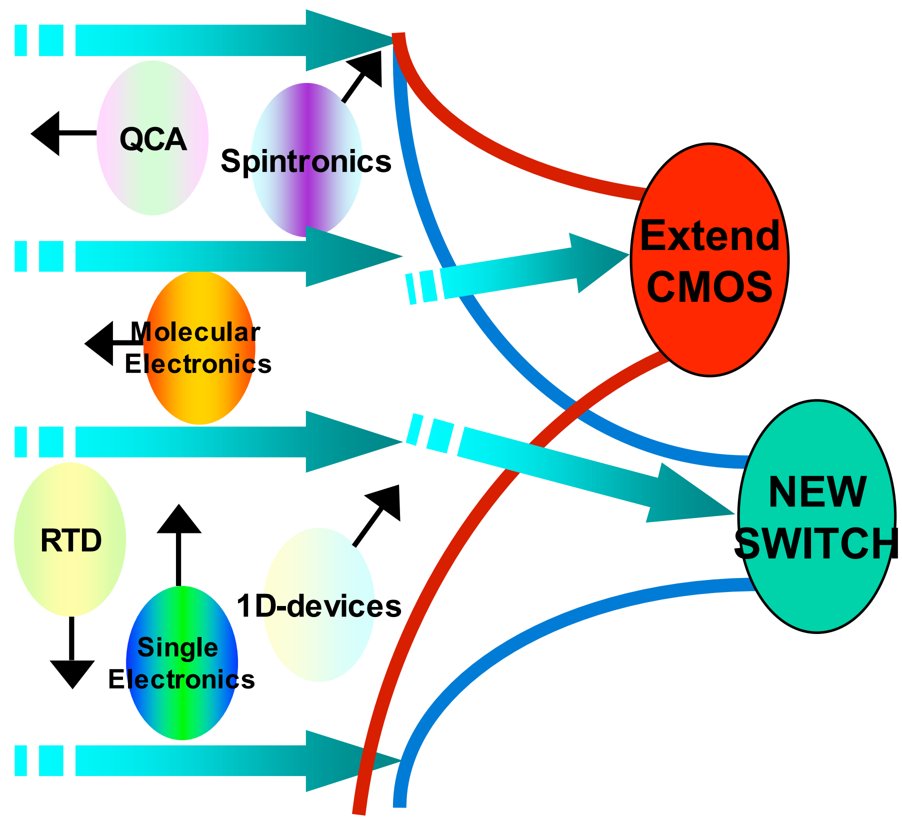
- Utilization of nano-properties. TRL = 1 to 4
  - **Quantum-well structures, giant magneto resistance (GMR) disk reading heads). SOA controlling phenomena in one dimension**
  - **Commercially available pharmaceuticals exploit designed molecule properties.**
  - **Quantum-dot based structures for research purposes (for tags)**

Current State-of-the-Art for Capability 16.3 Intelligent Systems

Advanced Planning & Integration Office

Information Representation TRL = 1 to 5

- **Von-Neumann models/computing is pervasive, dominated by major microprocessor architectures**
- **Programmable structures (a la FPGA) emerging as alternatives to lithographically-defined designs**
- **Neural networks/models and genetic algorithmics offer alternatives to programmed von Neumann systems by learning**
- **Bioinspired/Biomimetic/neuromorphic at research stage**
- **Emergent untried computing models (QCA, quantum**



Requirements /Assumptions for Capability 16.3 Intelligent Systems

- NASA will have a focused effort in nanotechnology
- Substantial progress in nanotechnology will continue based on support from other government and industry participants, which NASA can exploit (e.g. NNI roadmap)
- NASA will actively collaborate with academia and Industry in developments
- Modeling will utilize trend that computing power goes up 100 times every 10 years
- Level of development to TRL 4 in roadmap;
- Other “capabilities” are our principal customers

Capability 16.3 Intelligent Systems Roadmap

Advanced Planning & Integration Office

	2005	2010	2015
16.3 Intelligent Systems (capabilities)	Nanostructures based sources and detectors	Nanomaterial based air & water purification system	Arrayed Lab-on-a-chip
16.3.1 Multi-scale Modeling	Forward Nanoscale Modeling of Nanoscale Component nano-composites		Forward and Inverse Modeling of Nanoscale Component nano-photonic crystals
16.3.2 Multi-scale Manufacturing	Integrated regular top-down and undirected bottom-up DNA micro-sensor		Integrated irregular top-down and undirected bottom-up Sub-lithographical irregular arrays
16.3.3 Interconnectivity		Nanowire Interconnects Crossbar based memory	Material Transport Multiplexing arrayed lab-on-a-chip
16.3.4 Utilization of Nano Properties	Deep submicron-accurate uniform nanostructures Nanostructures based devices		Nanometer-accurate uniform nanostructures nano-composites & supramolecules
16.3.5 Information Representation		Nanoscale logic gates	Reliable reconfigurable nano-computing

Capability 16.3 Intelligent Systems Roadmap

Advanced Planning & Integration Office

16.3 Intelligent Systems (capabilities): "Artificial Muscle" | Lab in a Tea Cup | Self-Healing Materials | "Artificial Skin" | "Artificial Retina"

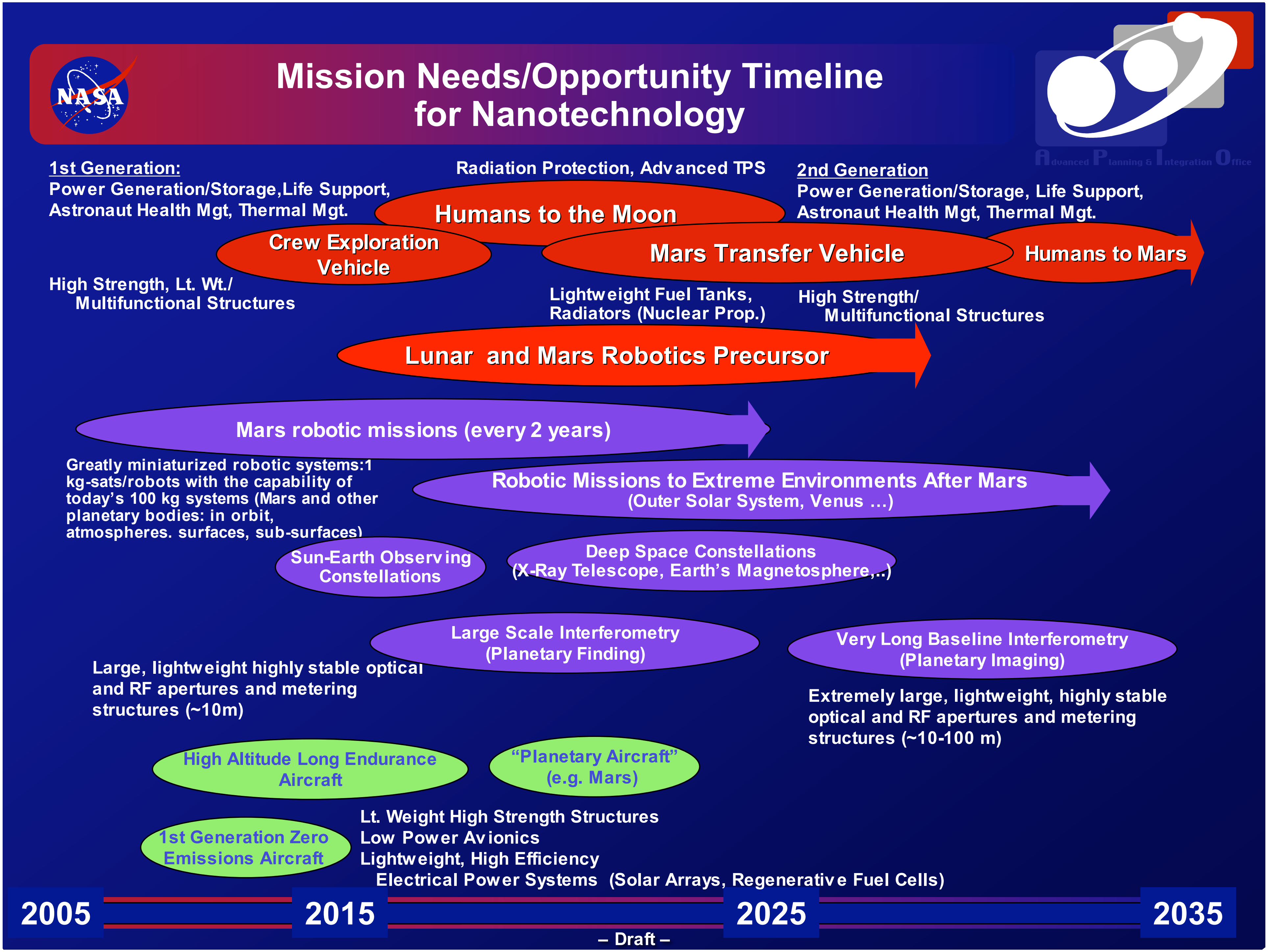
	2020	2025	2030
16.3.1 Multi-scale ` Modeling	Nano-micro interface models DNA-protein interactions; supra-molecular structures (20 nm3)	Nanoscale module models circuits/systems, nano-Spice	Nano CAD
16.3.2 Multi-scale Manufacturing	Directed bottom-up Artificial muscle	Fully integrated general bottom-up Self-healing materials	Large array systems Artificial skin
16.3.3 Interconnectivity	Nanowire routing (irregular layouts) Post-charge signal transfer	Programmable interconnect for material transport 3D lab-on-a-chip	Biotic/abiotic interconnections Electrochemical signaling Artificial retina Bio-silicon signaling
16.3.4 Utilization of Nano Properties	Atomically uniform nanostructures Quantum sensors	Integrated system level reliable nanostructure arrays Metrology and structure self aligning to optical tolerances of 200 picometers	
16.3.5 Information Representation	Distributed reconfigurable systems	Real Time Diagnosis and Prognosis.	

– Draft –

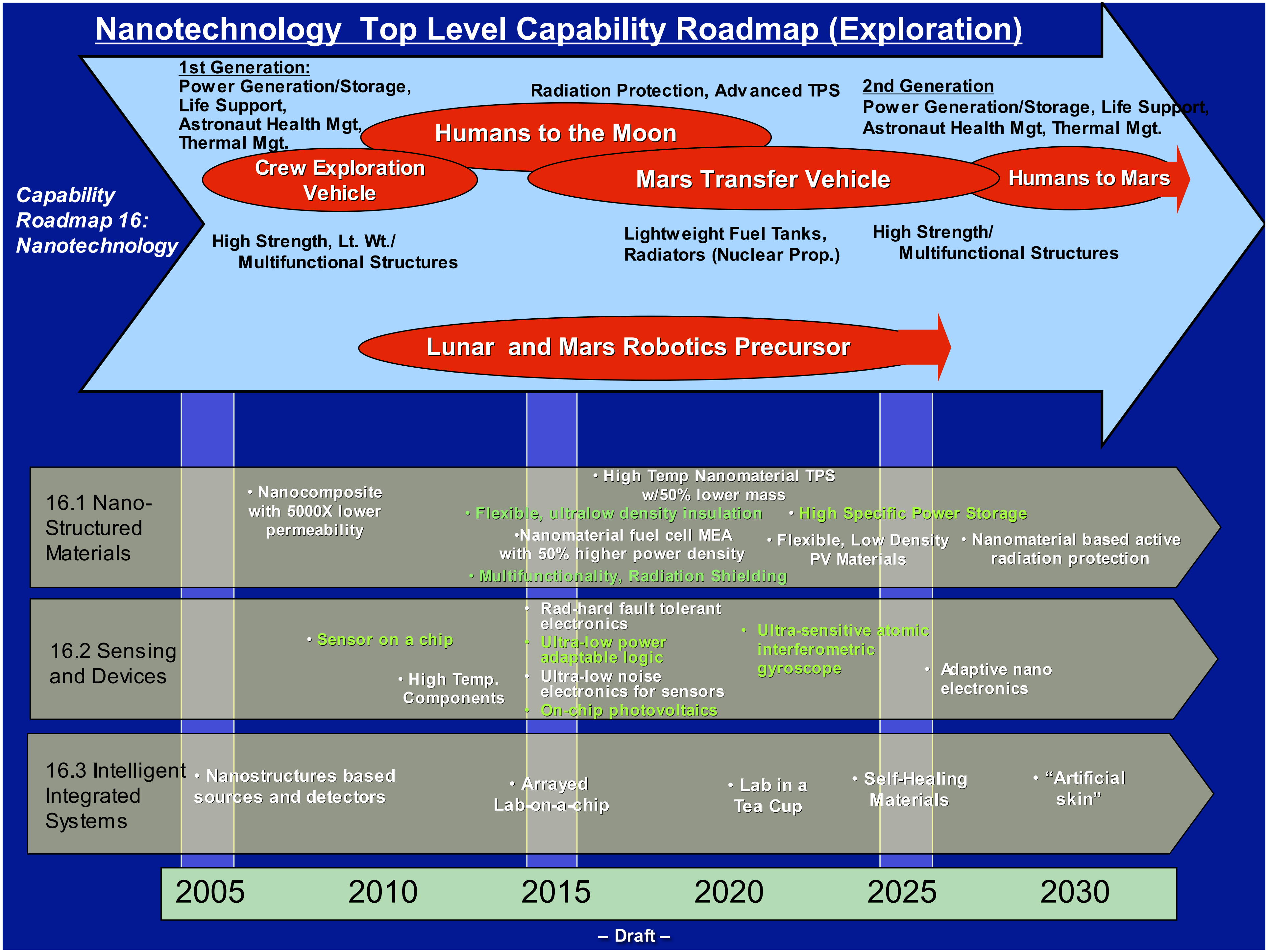
Crosswalk

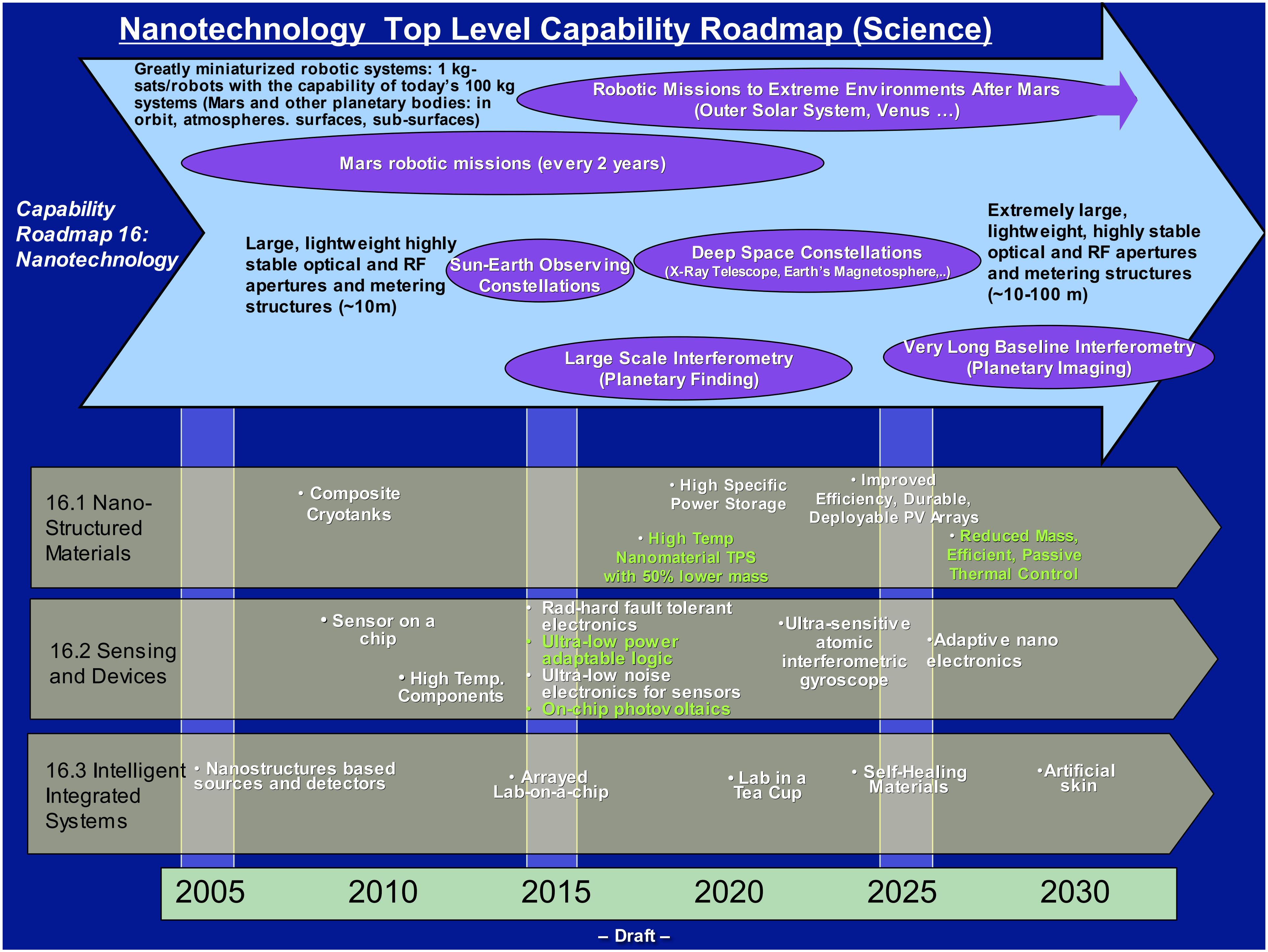
Sample Requirements	1: Multi-scale Models	2: Multi-scale Manufacturing	3: Inter-connectivity	4: Utilization of Nano-Properties	5: Information Reps. of Emerg. Props.
Robotic Access to Planetary Surface Autonomous Systems and Robotics	Self-reconfigurable miniature robots	3D Nano-assembly and Nano-Manufacturing	Programmable interconnect	Controlled Mechanical, Chemical, Thermal properties	Distributed Reconfigurable Systems for a single or network of nano-robots
Scientific Instruments and Sensors	Reliable nanoscale module	Large array systems (artificial skin)	Biotic – abiotic interconnection (artificial retina)	Integrated system level reliable nano-structure arrays	Biologically inspired high-distributed intelligent systems
Human Health and Support Systems	Reliable nano-micro interface models (DNA-Protein	Fully integrated general bottom up (self-healing materials)	Bio-electronic signaling for integrated non-invasive	Diagnosis and utilization of appropriate	Real Time Diagnosis and Prognosis

Summary and Next Steps



Mission Needs/Opportunity Timeline for Nanotechnology
Advanced Planning & Integration Office
1st Generation:
Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.
Radiation Protection, Advanced TPS
2nd Generation
Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.
Humans to the Moon
Crew Exploration Vehicle
Mars Transfer Vehicle
Humans to Mars
High Strength, Lt. Wt./ Multifunctional Structures
Lightweight Fuel Tanks, Radiators (Nuclear Prop.)
High Strength/ Multifunctional Structures
Lunar and Mars Robotics Precursor
Mars robotic missions (every 2 years)
Greatly miniaturized robotic systems:1 kg-sats/robots with the capability of today's 100 kg systems (Mars and other planetary bodies: in orbit, atmospheres. surfaces, sub-surfaces)
Robotic Missions to Extreme Environments After Mars
(Outer Solar System, Venus …)
Sun-Earth Observing Constellations
Deep Space Constellations
(X-Ray Telescope, Earth's Magnetosphere,..)
Large Scale Interferometry
(Planetary Finding)
Very Long Baseline Interferometry
(Planetary Imaging)
Large, lightweight highly stable optical and RF apertures and metering structures (~10m)
Extremely large, lightweight, highly stable optical and RF apertures and metering structures (~10-100 m)
High Altitude Long Endurance Aircraft
"Planetary Aircraft" (e.g. Mars)
1st Generation Zero Emissions Aircraft
Lt. Weight High Strength Structures
Low Power Avionics
Lightweight, High Efficiency Electrical Power Systems (Solar Arrays, Regenerative Fuel Cells)
2005
2015
2025
2035
– Draft –


Nanotechnology Top Level Capability Roadmap (Exploration)
Capability Roadmap 16: Nanotechnology
1st Generation:
Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.
Radiation Protection, Advanced TPS
2nd Generation
Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.
Humans to the Moon
Crew Exploration Vehicle
Mars Transfer Vehicle
Humans to Mars
High Strength, Lt. Wt./ Multifunctional Structures
Lightweight Fuel Tanks, Radiators (Nuclear Prop.)
High Strength/ Multifunctional Structures
Lunar and Mars Robotics Precursor
16.1 Nano-Structured Materials
• Nanocomposite with 5000X lower permeability
• High Temp Nanomaterial TPS w/50% lower mass
• Flexible, ultralow density insulation
• High Specific Power Storage
•Nanomaterial fuel cell MEA with 50% higher power density
• Flexible, Low Density PV Materials
• Nanomaterial based active radiation protection
• Multifunctionality, Radiation Shielding
16.2 Sensing and Devices
• Sensor on a chip
• High Temp. Components
• Rad-hard fault tolerant electronics
• Ultra-low power adaptable logic
• Ultra-low noise electronics for sensors
• On-chip photovoltaics
• Ultra-sensitive atomic interferometric gyroscope
• Adaptive nano electronics
16.3 Intelligent Integrated Systems
• Nanostructures based sources and detectors
• Arrayed Lab-on-a-chip
• Lab in a Tea Cup
• Self-Healing Materials
• “Artificial skin”
2005
2010
2015
2020
2025
2030
– Draft –



Nanotechnology Top Level Capability Roadmap (Science)
Capability Roadmap 16: Nanotechnology
Greatly miniaturized robotic systems: 1 kg-sats/robots with the capability of today's 100 kg systems (Mars and other planetary bodies: in orbit, atmospheres. surfaces, sub-surfaces)
Robotic Missions to Extreme Environments After Mars (Outer Solar System, Venus …)
Mars robotic missions (every 2 years)
Large, lightweight highly stable optical and RF apertures and metering structures (~10m)
Sun-Earth Observing Constellations
Deep Space Constellations (X-Ray Telescope, Earth's Magnetosphere,..)
Extremely large, lightweight, highly stable optical and RF apertures and metering structures (~10-100 m)
Large Scale Interferometry (Planetary Finding)
Very Long Baseline Interferometry (Planetary Imaging)
16.1 Nano-Structured Materials
• Composite Cryotanks
• High Specific Power Storage
• High Temp Nanomaterial TPS with 50% lower mass
• Improved Efficiency, Durable, Deployable PV Arrays
• Reduced Mass, Efficient, Passive Thermal Control
16.2 Sensing and Devices
• Sensor on a chip
• High Temp. Components
• Rad-hard fault tolerant electronics
• Ultra-low power adaptable logic
• Ultra-low noise electronics for sensors
• On-chip photovoltaics
•Ultra-sensitive atomic interferometric gyroscope
•Adaptive nano electronics
16.3 Intelligent Integrated Systems
• Nanostructures based sources and detectors
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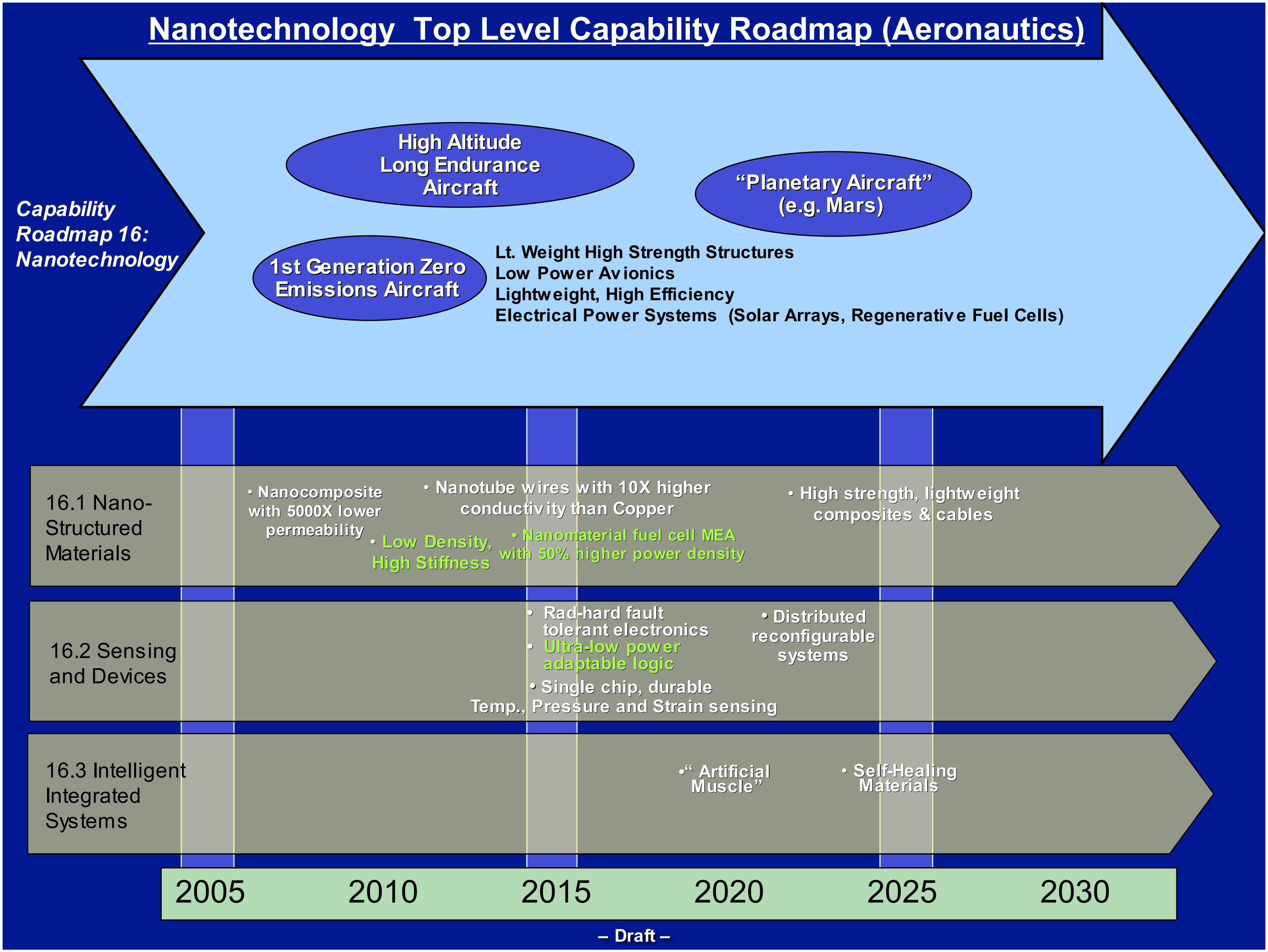

Nanotechnology Top Level Capability Roadmap (Aeronautics)
Capability Roadmap 16: Nanotechnology
High Altitude Long Endurance Aircraft
"Planetary Aircraft" (e.g. Mars)
1st Generation Zero Emissions Aircraft
Lt. Weight High Strength Structures
Low Power Avionics
Lightweight, High Efficiency
Electrical Power Systems (Solar Arrays, Regenerative Fuel Cells)
16.1 Nano-Structured Materials
• Nanocomposite with 5000X lower permeability
• Nanotube wires with 10X higher conductivity than Copper
• High strength, lightweight composites & cables
• Low Density, High Stiffness
• Nanomaterial fuel cell MEA with 50% higher power density
16.2 Sensing and Devices
• Rad-hard fault tolerant electronics
• Ultra-low power adaptable logic
• Distributed reconfigurable systems
• Single chip, durable Temp., Pressure and Strain sensing
16.3 Intelligent Integrated Systems
• "Artificial Muscle"
• Self-Healing Materials
2005
2010
2015
2020
2025
2030
– Draft –

Next Steps

- Make changes to roadmaps based on verbal feedback from NRC review
- Receive the draft Strategic Roadmaps
- Review and Assess all applicable Strategic Roadmaps and their requirements for Nanotechnology capability
- Make changes to Nanotechnology roadmaps to ensure consistency with Strategic Roadmaps requirements and other Capability Roadmaps
- Develop rough order of magnitude cost estimates for the Nanotechnology Capability Roadmap
- Prepare for 2nd NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

Closure and Crosswalk
(with other Roadmaps)

"Closure"

Co-Chairs:

M. Dastoor (NASA HQ) M. Hirschbein (NASA HQ) D. Lagoudas (Texas A&M)

Nanotechnology Closure

- Challenges
- Crosswalk
- Status
- Forward Work

Challenges

<u>Technical</u>

- Production of nanomaterials
- Characterization at both atomic and bulk scale
- Modeling & Simulation
- Applications Development
- System Integration

<u>Managing Expectations (Most Difficult)</u>

- Strongly advocate potential benefit
- Be responsive to needs of future technology users
- Avoid hype at all cost

<u>Institutional</u>

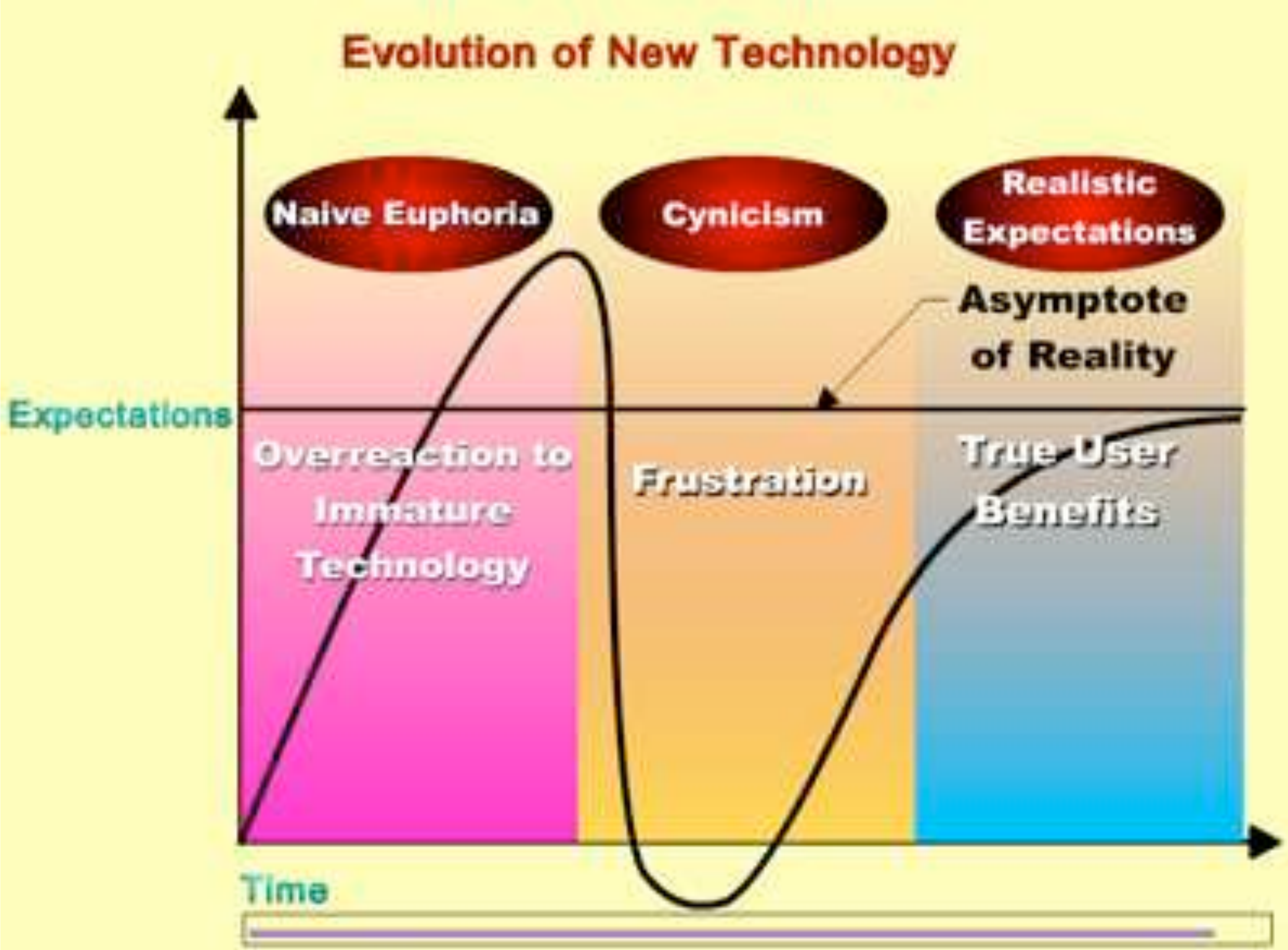
- Coordination/Cooperation among NASA/Industry/Academia/OGA
- Long-term Stability

<u>“Roadmapping”</u>

- Organization
- Condensation
- Connection

Technical Challenges

- **Production of nanomaterials**
  - Quantity, quality, control of properties & production in specified forms
- **Characterization at both atomic and bulk scale**
  - Fundamental mechanical, electrical and optical properties
- **Modeling & Simulation**
  - Prediction of physical/chemical properties and behavior from nanoscale to macroscale as well as models for material production
- **Applications Development**
  - Tools and techniques for applications of nanotechnology
  - Verification of predicted behavior/performance in actual environments
  - Systems Analysis to guide technology development
- **System Integration**
  - Macro-scale assembly and fabrication
  - Validation testing


Evolution of New Technology
Naive Euphoria
Cynicism
Realistic Expectations
Asymptote of Reality
Expectations
Overreaction to Immature Technology
Frustration
True User Benefits
Time

Major “Roadmapping” Challenge

- **Organization, Condensation and Connection**
  - Nanotechnology is extremely broad and deep
  - Multiple ways to present scope and content of nanotechnology
  - Being concise without loosing content -- nanotechnology affects many aspects of all other capability areas
  - Clearly show projection in to other capability areas

Major Institutional Challenges

- **Coordination/Cooperation among NASA/industry/academia/OGA**
  - Many common interests but different missions and priorities
  - All too often the attitude is, ‘why do we need to invest in nanotechnology too?’
  - Need to incentivize major industry: partnerships, long-range planning, investment, ….
- **Long-term stability**
  - Budget, education
  - Infusion of nanotechnology products into plans and missions (“crossing the valley of death between proof-of-concept and prototype”)

Impact: Highest / Next Highest

Nanotechnology Crosswalk (Space)

High Energy Power and Propulsion	Very high efficiency PV, electrodes for advanced batteries, materials for high power fly wheels, supercapacitors, advanced thermoelectric materials, fuel cell membranes, light weight radiators and H2 tanks…
In-Space Transportation	Advanced high strength, lightweight structural materials
Advanced Telescopes and Observatories	Lightweight, high stiffness, low CTE materials for optics and large structures, thermal coatings….
Robotic Access to Planetary Surfaces Human Planetary Landing Systems	Lightweight thermal protection
Human Health and Support Systems	Health monitoring, diagnosis; membranes for life support processes (e.g. air purification, catalysis), radiation protection…
Human Exploration Systems and Mobility	Sensors, electronics, materials (light weight, high strength; high thermal conductivity; radiation protection; self-healing,…)
Autonomous Systems & Robotics	Low power computing and electronics; systems for sub-kg rovers
Scientific Instruments and Sensors	Ultra-sensitive, environmentally robust detectors; compact active sources (laser, X-ray, sub-mm); high temperature IR detectors…
In-Situ Resource Utilization	Process monitoring sensing, catalysis and filtration
Communications and Navigation	Advanced low power electronic and photonic devices and systems
Transformational Spaceport/Range	Sensing for environmental monitoring
Advanced Modeling Simulation & Analysis	Multi-scale modeling for materials, devices and systems
Systems Engineering Cost/Risk Analysis	TBD

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Impact: Highest / Next Highest

Nanotechnology Crosswalk (Aero)

High Energy Power and Propulsion	Very high efficiency PV, electrodes for advanced batteries, actuators, motors, fuel cell membranes and lightweight tanks
Airframe (Transportation)	Advanced high strength/stiffness, lightweight structural materials
Autonomous Systems	Low power computing and electronics
Advanced Modeling Simulation & Analysis	Multi-scale modeling for materials, devices and systems
Systems Engineering Cost/Risk Analysis	TBD

A high degree of commonality between aeronautics and space applications

Status

- **Current roadmapping waypoint, about mid-way to two-thirds**
  - Work-in-progress
  - Significant work left to do
- **In a "forward-looking" mode**
  - Strategic roadmaps under development
  - Other capability roadmaps under parallel development with nanotechnology
  - Current nanotechnology roadmap based on "experience and knowledge"
- **After NRC reviews (end of March) other 14 capability roadmaps will be available**
  - Hold 3rd team workshop
  - Review and revise nanotechnology
  - Address institutional issues
- **Further convergence after strategic roadmaps developed**

Forward Work

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Mature, Proven but Bounded Technology

New, Unproven but "Unboubded" Technology

"Old-Guard" Technology

Technology Limits

"New Era" Technology

Mission Needs

Oops! Maybe We Should Work Together.