HPC Matters: How Advanced Computing Enables NASA Missions

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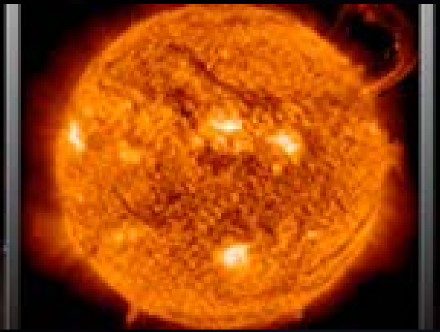
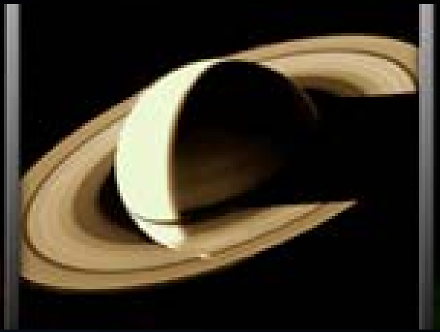
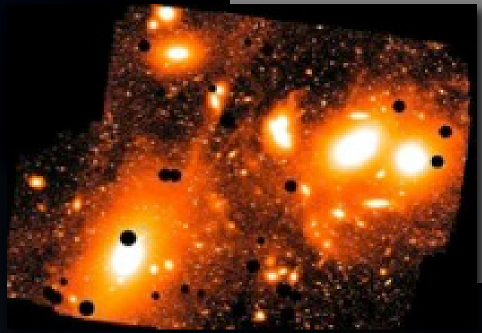
NASA Overview: Mission Directorates

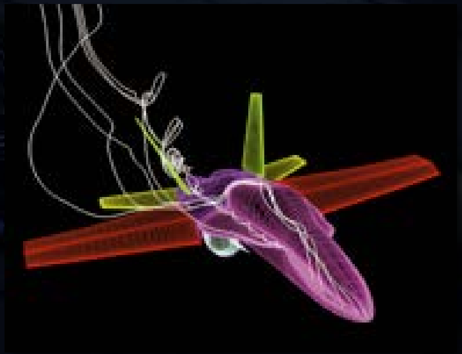
- **Vision**: *To discover and expand knowledge for the benefit of humanity*
- **Mission**: *Lead innovative and sustainable program of exploration with partners to enable human expansion across Solar System and bring new knowledge and opportunities back to Earth; support growth of Nation’s economy in space and aeronautics, and increase understanding of the Universe*
- **Aeronautics Research (ARMD):** Transform aviation via innovative research to reduce environmental impact of flight; improve aircraft and operations efficiency while maintaining safety
- **Human Exploration & Operations (HEOMD):** Lead exploration in and beyond low Earth orbit by developing new spacecraft & other capabilities for affordable, sustainable human life outside Earth
- **Science (SCMD):** Expand frontiers of Earth science, heliophysics, planetary science, and astrophysics via robotic observatories, explorer craft, ground-based instruments, and research
- **Space Technology (STMD):** Pursue, develop, and infuse transformational technologies with high potential for offsetting future mission risk, reducing cost, and advancing existing capabilities



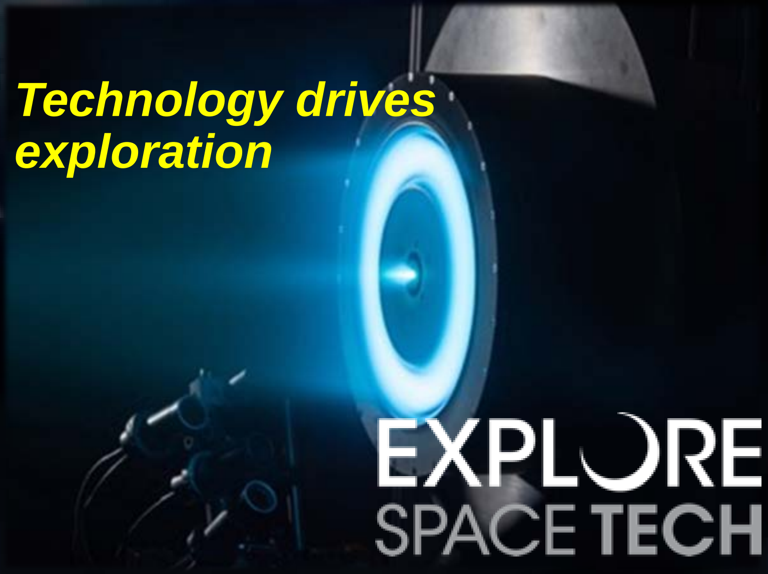


NASA Overview: Centers & Facilities





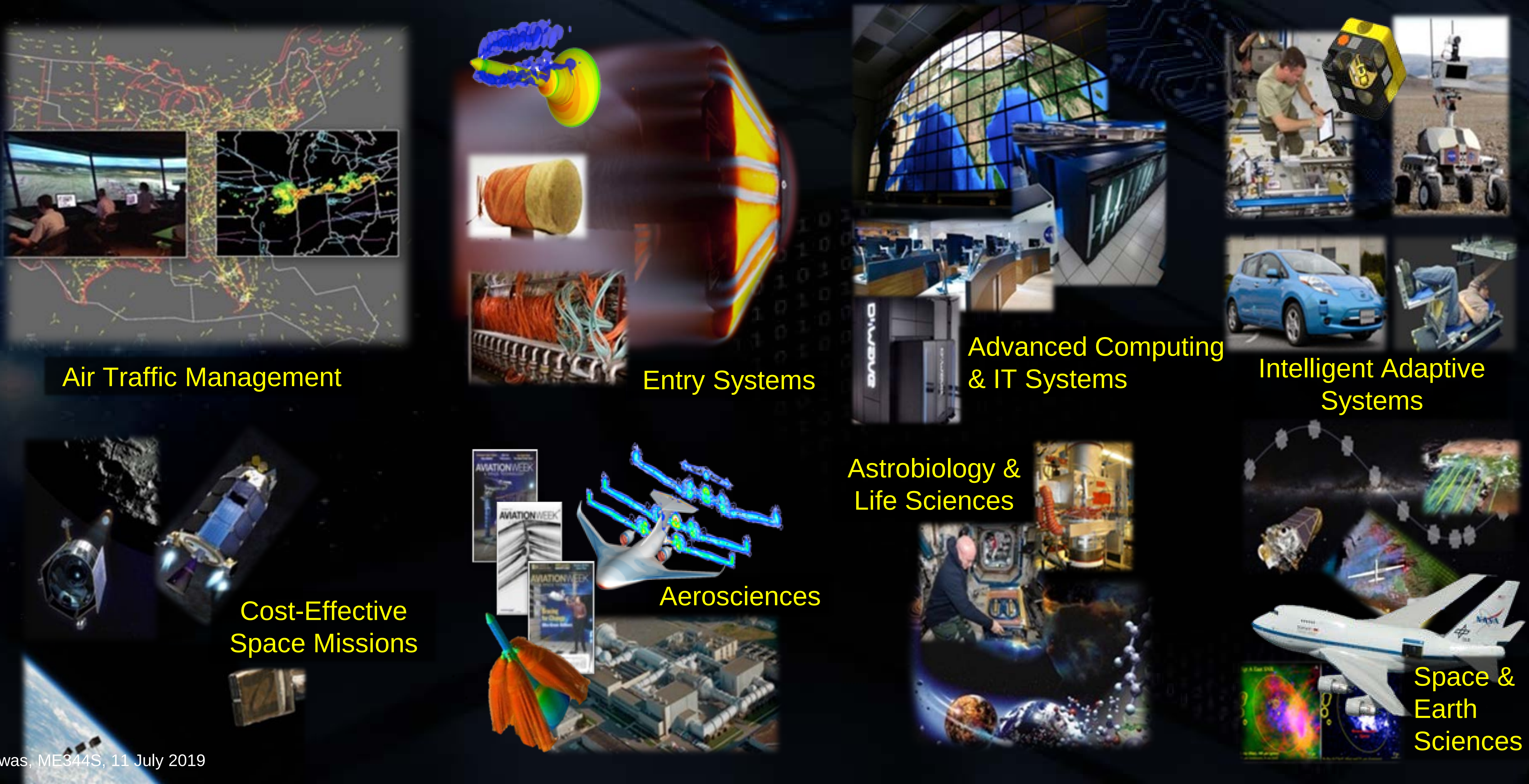
Current NASA Focus Areas



NASA Ames Research Center

- **<u>Occupants</u>:** ~1,200 civil servants; ~1,400 contractors; ~1,600 tenants; ~900 summer students (in 2018)
- **<u>FY2018 Budget</u>:** ~$918M (including reimbursable and Enhanced Use Lease (EUL) revenue)
- **<u>Real Estate</u>:** ~1,900 acres (400 acres security perimeter); 5M building ft^{2}; Airfield: ~9,000 and 8,000 ft. runways

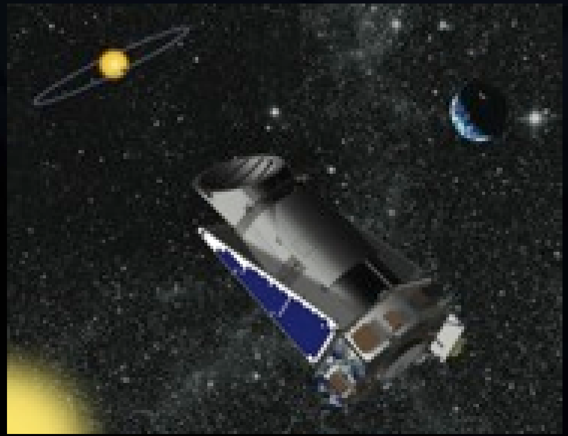
Ames Core Competencies Today



Need for Advanced Computing

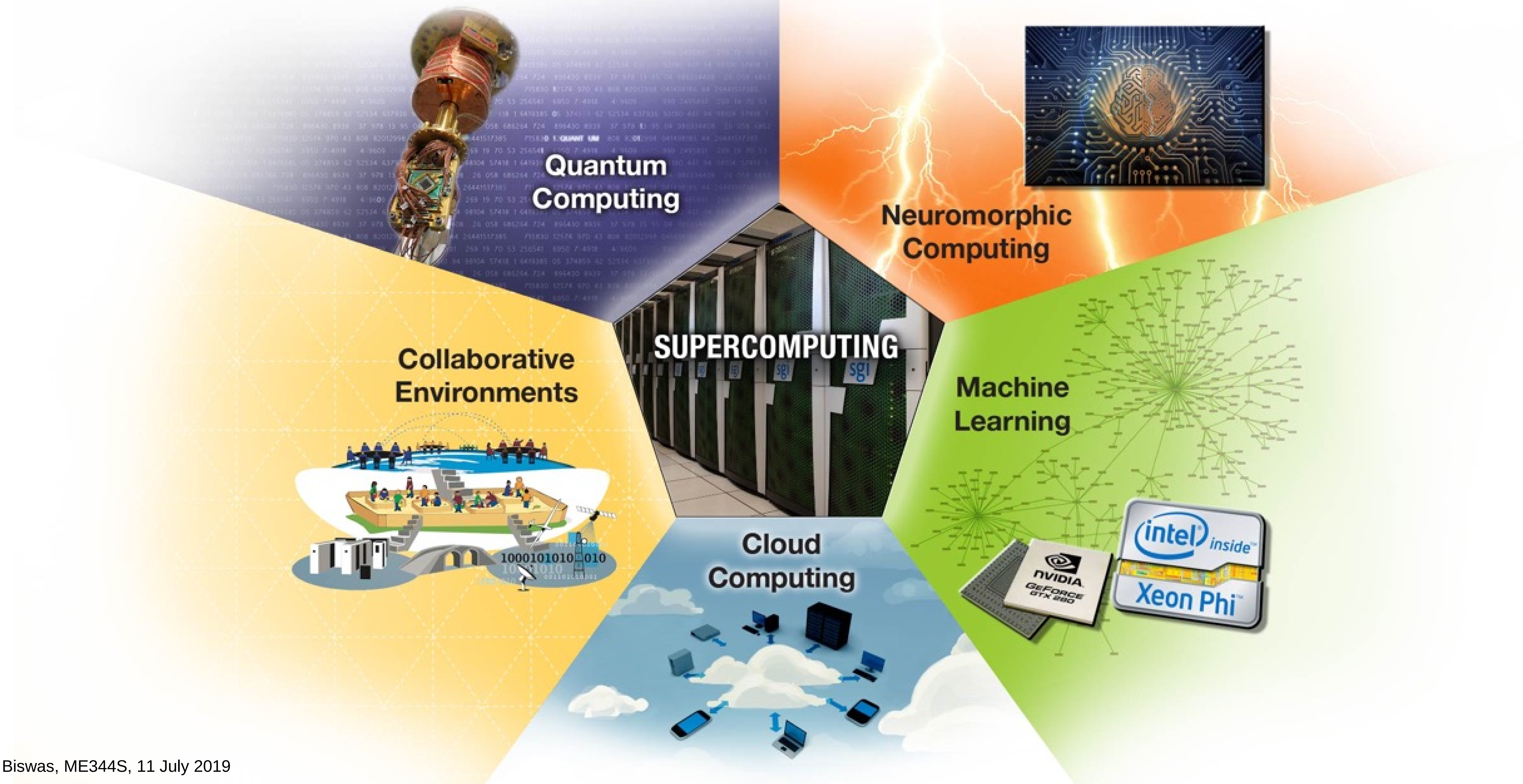
Enables modeling, simulation, analysis, and decision-making

- Digital experiments and physical experiments are tradable
- Physical systems and live tests generally expensive & dangerous (e.g., extreme environments), require long wait times, and offer limited sensor data
- NASA collects and curates vast amounts of observational science data that require extensive analysis and innovative analytics to advance our understanding



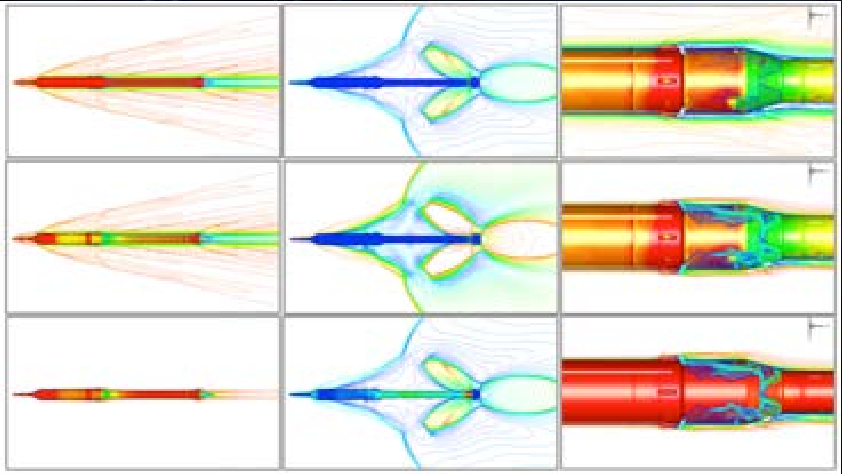
- Decades of exponentially advancing computing technology has enabled dramatic improvements in cost, speed, and accuracy – in addition to providing a predictive capability
- Many problems pose extremely difficult combinatorial optimization challenges that can only be solved accurately using advanced technologies such as quantum computing
- NASA's goals in aeronautics, Earth & space sciences, and human & robotic exploration require orders-of-magnitude increase in computing capability to enhance accuracy, reduce cost, mitigate risk, accelerate R&D, and heighten societal impact

Advanced Computing Environment

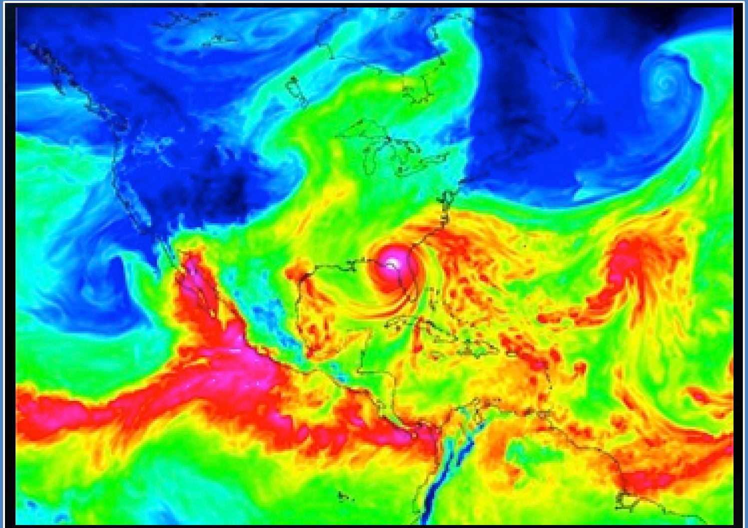


NASA's Diverse HPC Requirements

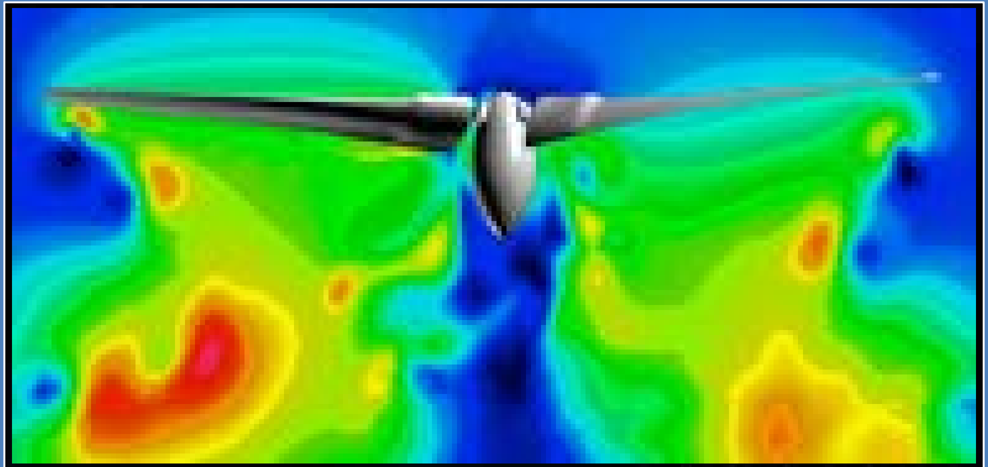
- Engineering requires HPC resources that can process large ensembles of moderate-scale computations to efficiently explore design space ***(high throughput / capacity)***
- Research requires HPC resources that can handle high-fidelity long-running large-scale computations to advance theoretical understanding ***(leadership / capability)***
- Time-sensitive mission-critical applications require HPC resources on demand ***(high availability / maintain readiness)***



Aerodynamic database generation



Real-time hurricane prediction



Rotary wing unsteady aerodynamics

Balanced HPC Environment

Computing Systems

- ***Pleiades:*** 242K-core SGI Altix ICE (now HPE) with 4 generations of Intel Xeon (19 nodes GPU-enhanced: Nvidia V100); 932 TB RAM; 7.85 PF peak (#31 on TOP500, #19 on HPCG)
- ***Electra:*** 124K-core Altix ICE with Intel Broadwell & Skylake; modular containers; 590 TB RAM; 8.32 PF peak (#37 on TOP500, #27 on HPCG)
- ***Merope:*** 22K-core Altix ICE with Intel Westmere; 86 TB RAM; 252 TF peak
- ***Endeavour:*** Two SGI UV2000 nodes with 2 and 4 TB shared memory SSI via NUMALink-6; 32 TF peak
- ***hyperwall:*** 2560-core Intel Ivy Bridge, 128-node Nvidia GeForce GTX78 cluster for large-scale rendering & concurrent visualization (245M pixels)

Data Storage

- 48 PB of RAID over 10 Lustre filesystems
- 1 EB of tape archive (max capacity)

Networks

- InfiniBand interconnect for Pleiades and Electra in partial hypercube topology; connects all other HPC components as well
- 10 Gb/s external peering

Modular Supercomputing Facility (MSF)

Current HEC Facility

- Limited to 6 MW electrical power of which 25% used for cooling
- Open-air cooling tower with four 450 T chillers

Prototype MSF (FY17)

- Modular container currently holds Electra (3456 nodes, 8.32 PF peak)
- External air fan cooling; switch to adiabatic evaporative cooling when needed
- PUE of 1.03 resulting in 91% power savings and 96% water use reduction over traditional computer floor (hosting Pleiades)
- Pad has 2.5 MW of electrical power and can accommodate 2 modules
- In production use since Jan '17

Full MSF (FY18 – FY22)

- Larger second pad with 30 MW electrical power and associated switchgear
- Ability to hold up to 16 modular units (and 1 M cores)
- Flexibility to rapidly modify and react to changes in NASA requirements, computing technology, and facility innovations

Current MSF hosting Electra

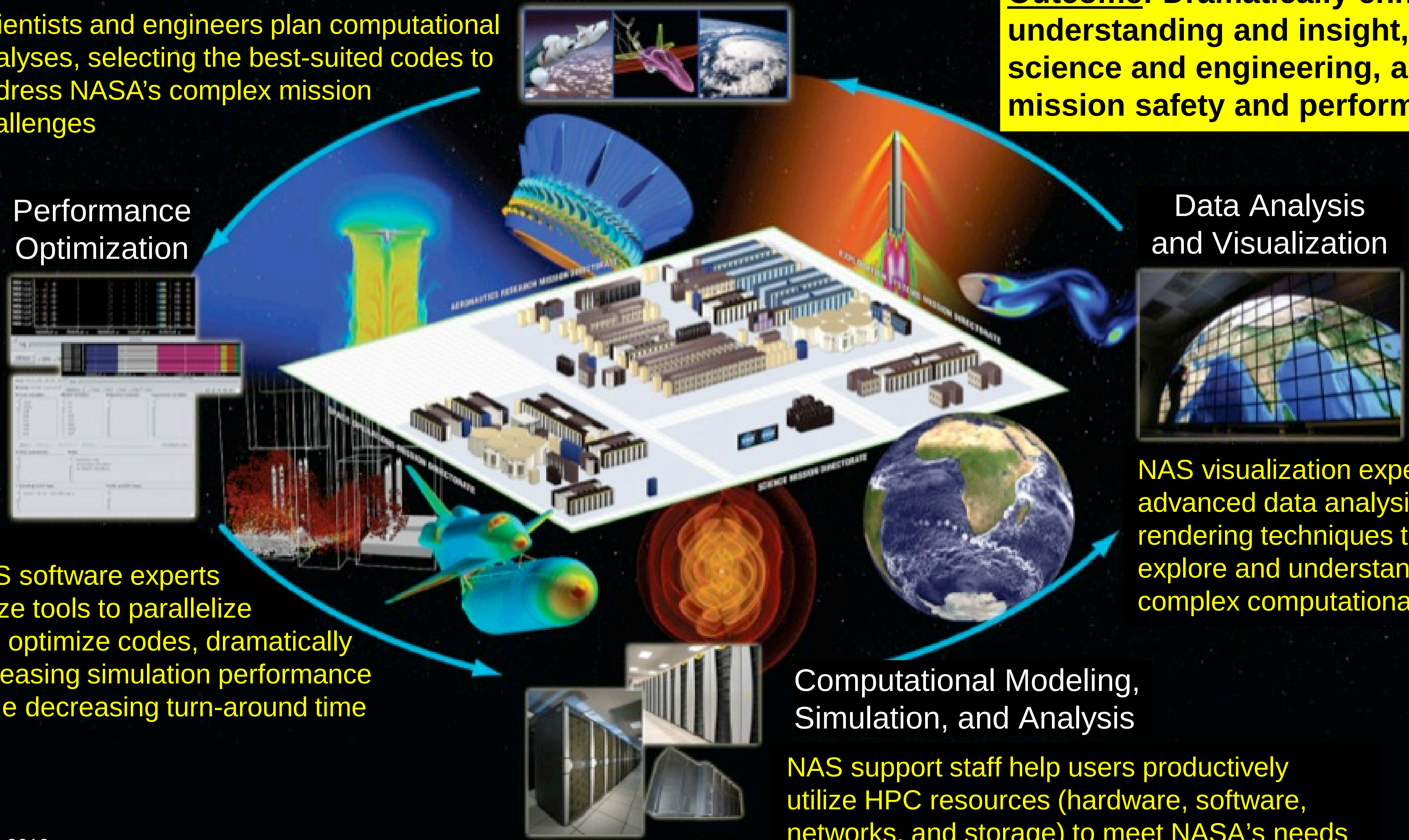
Artist's rendering of future MSF

Integrated Spiral Support Services

Outcome: Dramatically enhanced understanding and insight, accelerated science and engineering, and increased mission safety and performance

NASA Mission Challenges

Scientists and engineers plan computational analyses, selecting the best-suited codes to address NASA's complex mission challenges



Performance Optimization

NAS software experts utilize tools to parallelize and optimize codes, dramatically increasing simulation performance while decreasing turn-around time

Computational Modeling, Simulation, and Analysis

NAS support staff help users productively utilize HPC resources (hardware, software, networks, and storage) to meet NASA's needs

Data Analysis and Visualization

NAS visualization experts apply advanced data analysis and rendering techniques to help users explore and understand large, complex computational results

The NASA Charge to the Moon

In keeping with SPD-1, NASA is charged with landing the first American woman and next American man at the South Pole of the Moon by 2024, followed by a sustained presence on and around the Moon by 2028.

NASA will "use all means necessary" to ensure mission success in moving us forward to the Moon.

Vice President Mike Pence speaks about NASA's mandate to return American astronauts to the Moon and on to Mars at the U.S. Space & Rocket Center in Huntsville, Alabama.

Why Go to the Moon?

Establishes American leadership and strategic presence

Proves technologies and capabilities for sending humans to Mars

Inspires a new generation and encourages careers in STEM

Leads civilization changing science and technology

Expands the U.S. global economic impact

Broadens U.S. industry & international partnerships in deep space

The Artemis Program

Artemis is the twin sister of Apollo and goddess of the Moon in Greek mythology. Now, she personifies our path to the Moon as the name of NASA's program to return astronauts to the lunar surface by 2024.

When they land, Artemis astronauts will step foot where no human has ever been before: the Moon's South Pole.

With the horizon goal of sending humans to Mars, Artemis begins the next era of exploration.

American Leadership in Space Exploration

EARTH ORBIT

- Grow a robust commercial space industry with a constant human presence
- Expand our international partnerships through the ISS
- Conduct exploration science and technology demonstrations aboard ISS
- Continue critical earth science research
- New jobs through in-space manufacturing and assembly
- Low-Earth orbit launches us to farther destinations

LUNAR ORBIT

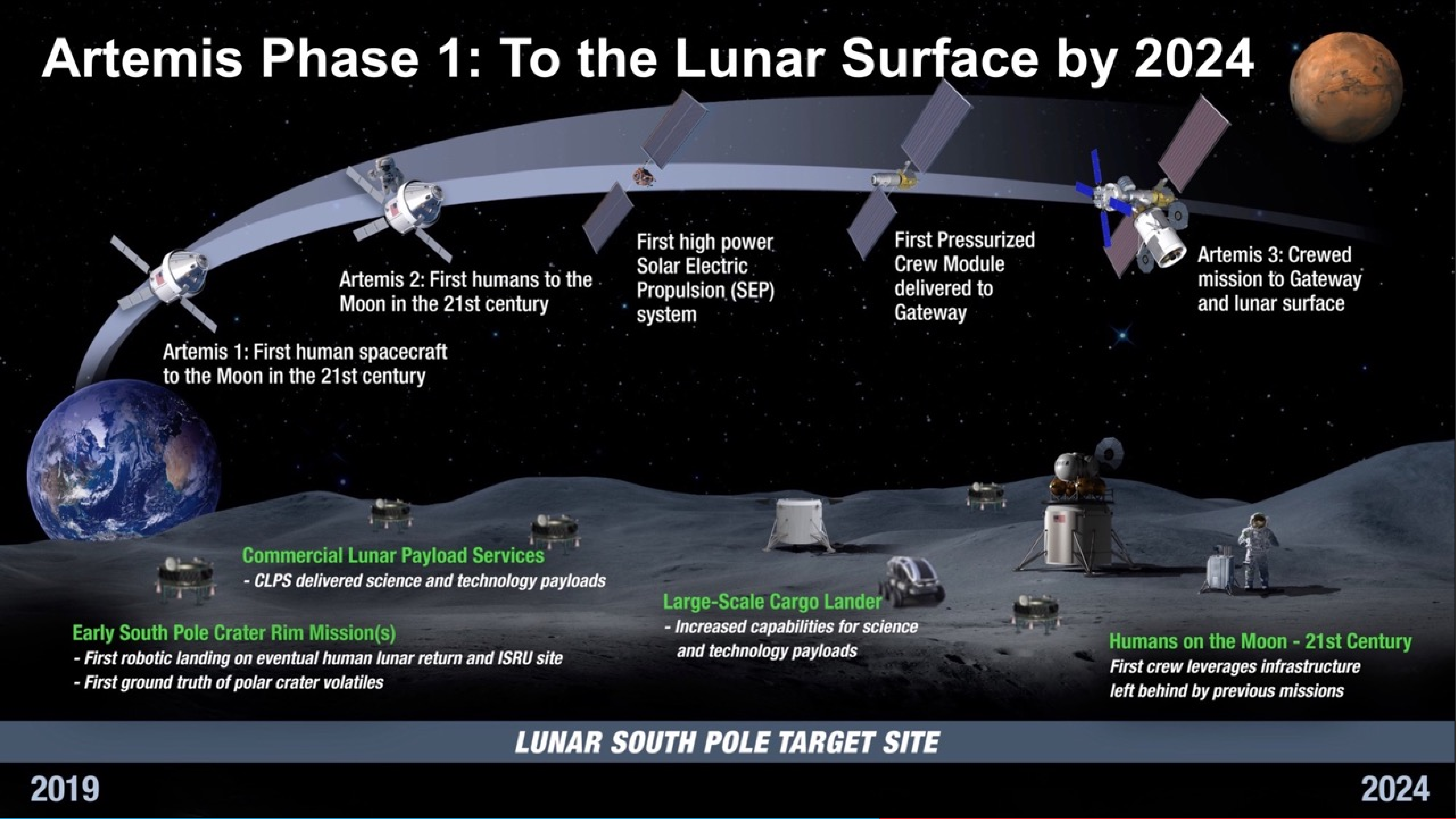
- The next step for commercial space development
- Conduct ground-breaking decadal science
- A new venue to strengthen international partnerships
- Stepping stone and training ground for extending human presence into deep space
- Sustainable and affordable human and robotic programs

LUNAR SURFACE

- Seed investments in commercial lunar landers
- Opportunities to develop technologies for long-term survival
- Explore and exploit space resources
- Create a foothold on a new frontier

MARS & BEYOND

- America's next giant leap – reaching new worlds
- Push the boundaries of human knowledge
- Answer the question of 'are we alone?'
- Unlock the mysteries of the universe



Artemis Phase 1: To the Lunar Surface by 2024
Artemis 1: First human spacecraft to the Moon in the 21st century
Artemis 2: First humans to the Moon in the 21st century
First high power Solar Electric Propulsion (SEP) system
First Pressurized Crew Module delivered to Gateway
Artemis 3: Crewed mission to Gateway and lunar surface
Commercial Lunar Payload Services
- CLPS delivered science and technology payloads
Early South Pole Crater Rim Mission(s)
- First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles
Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE TARGET SITE
2019
2024

Achieving 2024 – A Parallel Path to Success

Artemis will see government and commercial systems moving in parallel to complete the architecture and deliver crew

CREW

NASA Programs SLS and Orion

Artemis 1

First flight test of SLS and Orion as an integrated system

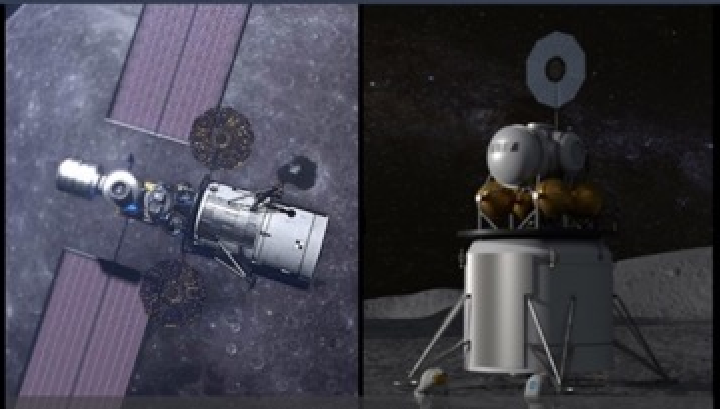
Artemis 2

First flight of crew to the Moon aboard SLS and Orion

Artemis 3

First crew to the lunar surface; Logistics delivered for 2024 surface mission

Between now and 2024, U.S. industry delivers the launches and human landing system necessary for a faster return to the Moon and sustainability through Gateway.



Commercially Provided Elements

CARGO

PPE

Power Propulsion Element arrives at NRHO via commercial rocket

Crew Module

Small pressurized crew module launches to Gateway on a commercial rocket

Human Landing System

Transfer

Transfers lander from Gateway to low lunar orbit

Descent

Descends from Transfer Vehicle to lunar surface

Ascent

Ascends from lunar surface to Gateway

Up to three commercial rocket launches, depending on distribution of the Transfer, Descent, and Ascent functions.

The Power of SLS and Orion

ORION

The only spacecraft capable of carrying and sustaining crew on missions to deep space, providing emergency abort capability, and safe re-entry from lunar return velocities

SLS

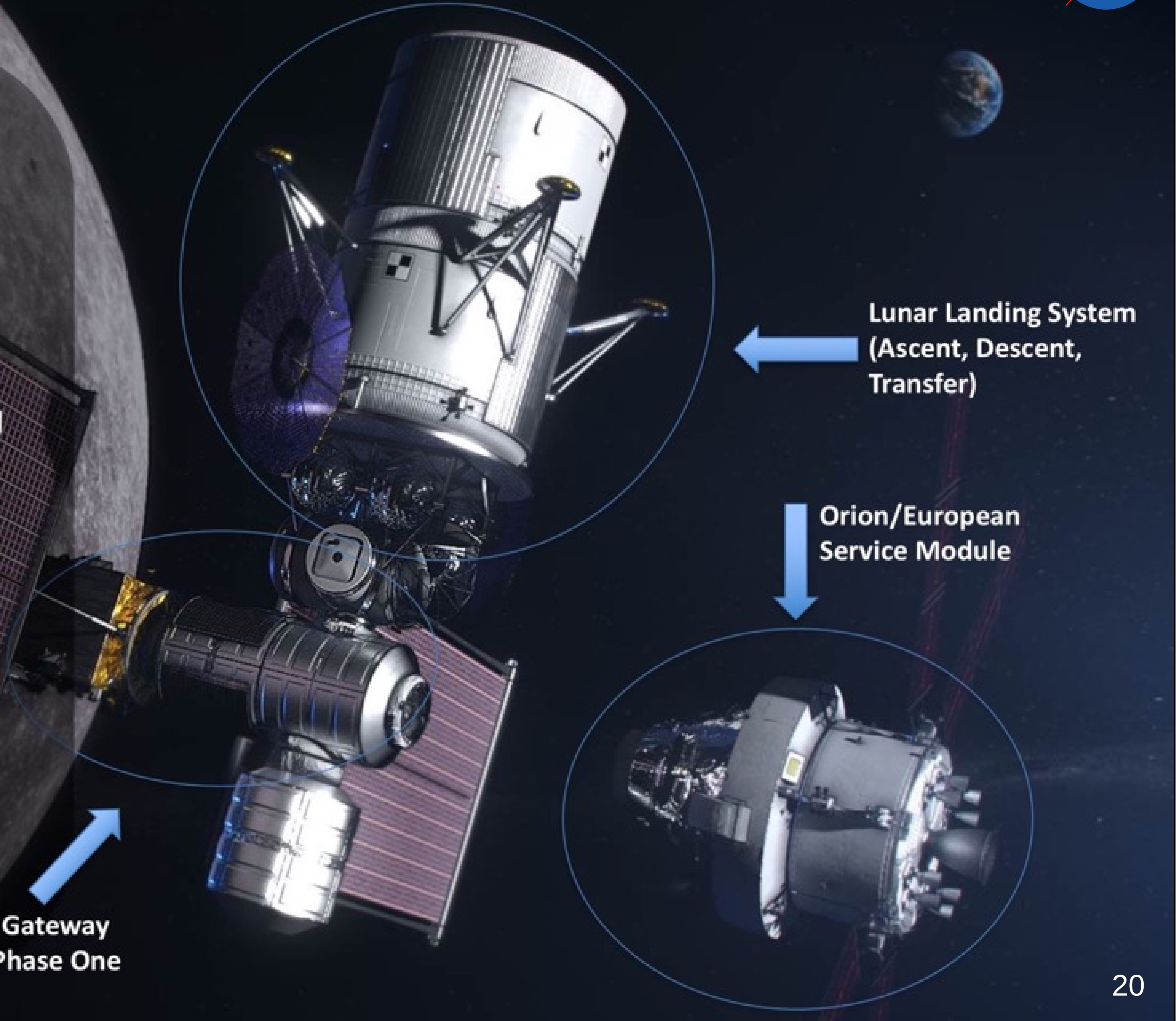
The only rocket with the power and capability required to carry astronauts to deep space onboard the Orion spacecraft

NATIONAL CAPABILITY

The SLS and Orion programs (including Exploration Ground Support at Kennedy Space Center) leverages over 3,800 suppliers and over 60,000 workers across all 50 states

Gateway is Essential for 2024 Landing

- Initial Gateway focuses on the minimum systems required to support a 2024 human lunar landing while also supporting Phase 2
- Provides command center and aggregation point for 2024 human landing
- Establishes strategic presence around the Moon – US in the leadership role
- Creates resilience and robustness in the lunar architecture
- Open architecture and interoperability standards provides building blocks for partnerships and future expansion



Lunar Science by 2024

Polar Landers and Rovers

- First direct measurement of polar volatiles, improving understanding of lateral and vertical distribution, physical state, and chemical composition
- Provide geology of the South-Pole Aitken basin, largest impact in the solar system

Non-Polar Landers and Rovers

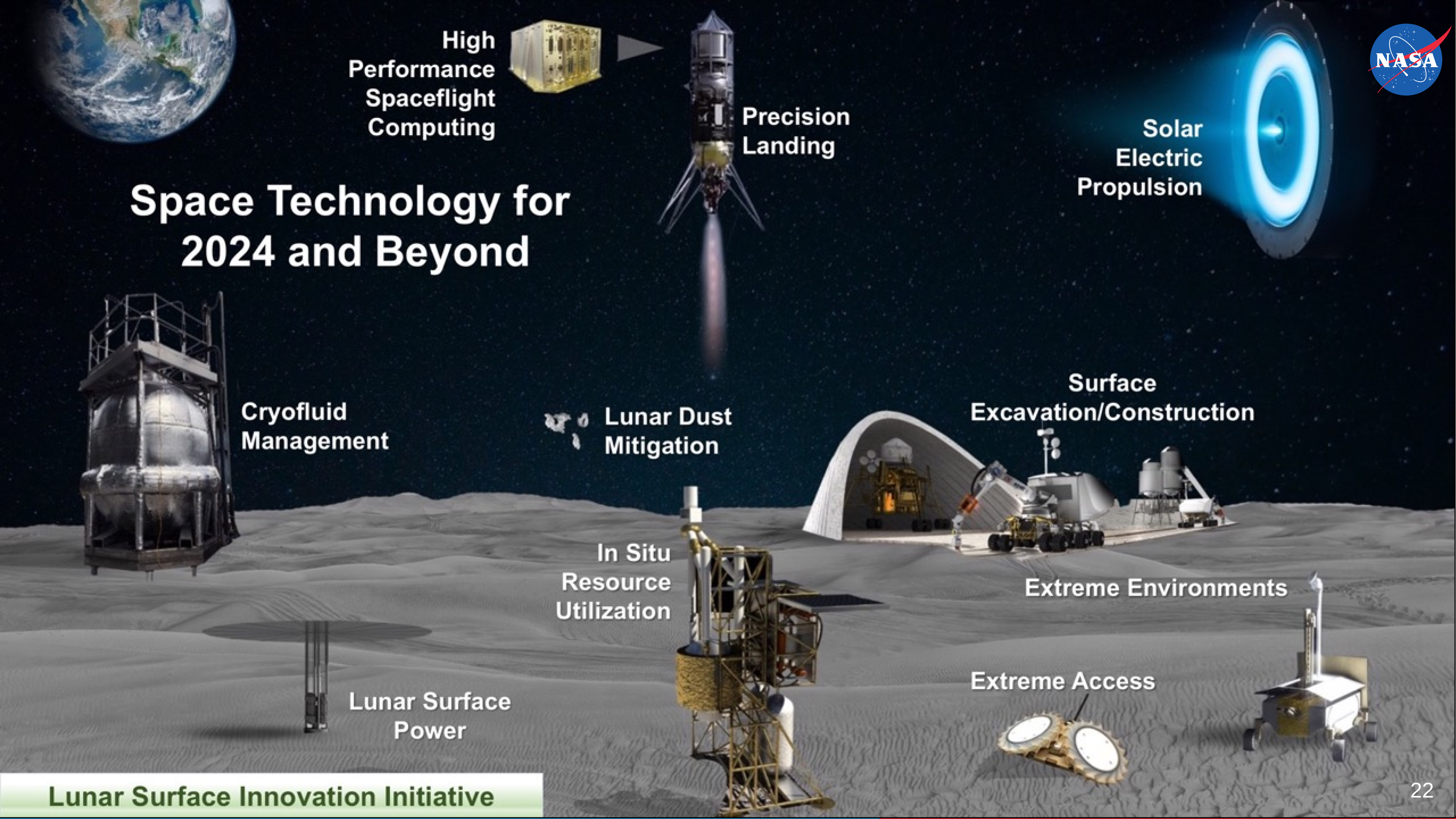
- Explore scientifically valuable terrains not investigated by Apollo, including landing at a lunar swirl and making first surface magnetic measurement
- Using PI-led instruments to generate Discovery-class science, like establishing a geophysical network and visiting a lunar volcanic region to understand volcanic evolution

Orbital Data

- Deploy multiple CubeSats with Artemis 1
- Potential to acquire new scientifically valuable datasets through CubeSats delivered by CLPS providers or comm/relay spacecraft
- Global mineral mapping, including resource identification, global elemental maps, and improved volatile mapping

In-Situ Resource Initial Research

- Answering questions on composition and ability
  to use lunar ice for sustainment and fuel



High Performance Spaceflight Computing
Precision Landing
Solar Electric Propulsion
NASA
Space Technology for 2024 and Beyond
Cryofluid Management
Lunar Dust Mitigation
Surface Excavation/Construction
In Situ Resource Utilization
Extreme Environments
Lunar Surface Power
Extreme Access
Lunar Surface Innovation Initiative

Sustainability at the Moon and on to Mars

- The U.S. leading in exploration and setting the standards for the Moon
- Unbound potential for partnerships and collaboration
- Meaningful, long-duration human missions
- Testing impacts on human performance and exploration operations to be used for Mars
- Repeatable operations traveling from Earth to the Gateway to the surface with reusable systems
- Unprecedented science outside of Earth’s influence
- Maintains strategic presence as a deep space port and refueling depot around the Moon
- Increases international and commercial partnership opportunities, fostering healthy competition

Science After 2024

Human and Robotic Missions Provide Unique Science Opportunities

On Gateway

- Deep space testing of Mars-forward systems
- Hosts groundbreaking science for space weather forecasting, full-disc Earth observation, astrophysics, heliophysics, lunar and planetary science
- Mars transit testbed for reducing risk to humans

Surface Exploration

- Understanding how to use in-situ resources for fuel and life
- Revolutionizing the understanding of the origin and evolution of the Moon and inner solar system by conducting geophysical measurements and returning carefully selected samples to Earth
- Studying lunar impact craters to understand physics of the most prevalent geologic process in the solar system, impact cratering
- Setting up complex surface instrumentation for astrophysics, heliophysics and Earth observation
- Informing and supporting sustained human presence through partial gravity research in physical and life sciences, from combustion to plant growth

Surface Telerobotics to Provide Constant Science

- Sending rovers into areas too difficult for humans to explore; rovers can be teleoperated from Earth to maximize the scientific return

Orion Launch Abort System (LAS)

Multi-purpose crew vehicle to take astronauts to low-Earth orbit and beyond

Aircraft Noise Prediction

Radical Installation Concepts

Validation of Jet Prediction Capabilities

Grand Challenge
Predict full aircraft noise with installation & propulsion

Shielding Concept Capabilities

High-fidelity noise simulation for emerging commercial supersonic technologies

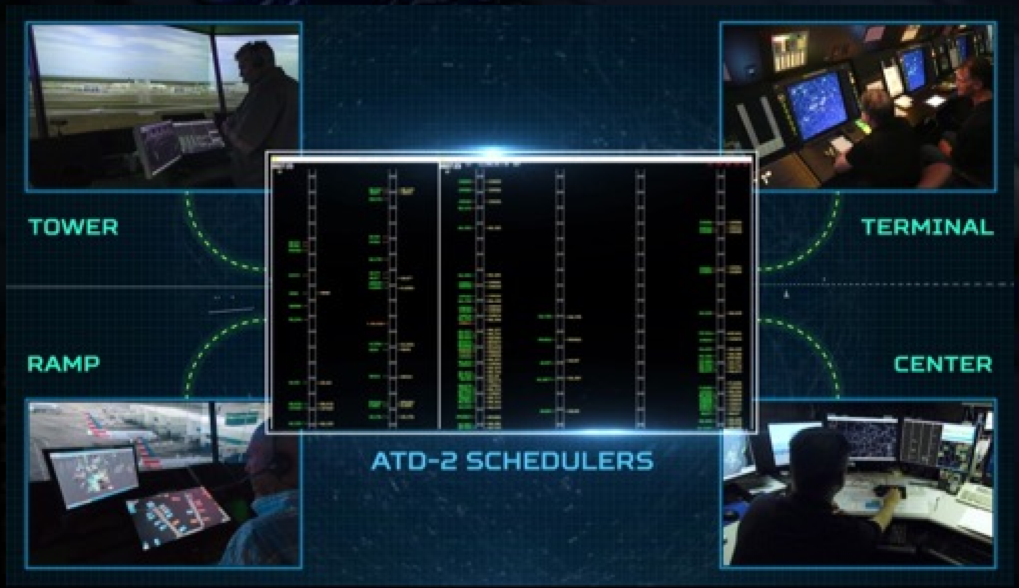
Commercial Supersonic Technologies (CST)
Advanced Air Vehicle Program (AAVP)
Aeronautics Research Mission Directorate (ARMD)

Urban Air Mobility (UAM)

High-Fidelity Modeling and Optimization Method Development
Revolutionary Vertical Lift Technology (RVLT) Project

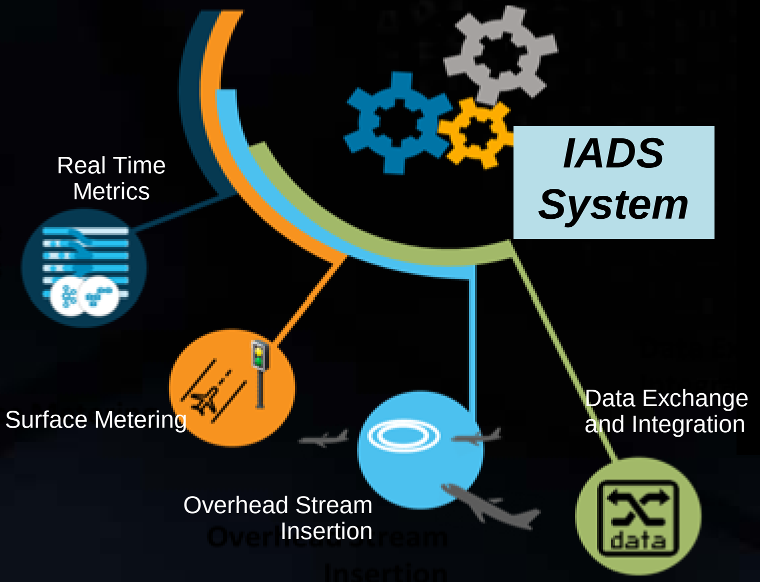
Airspace Technology Demonstrations (ATD)

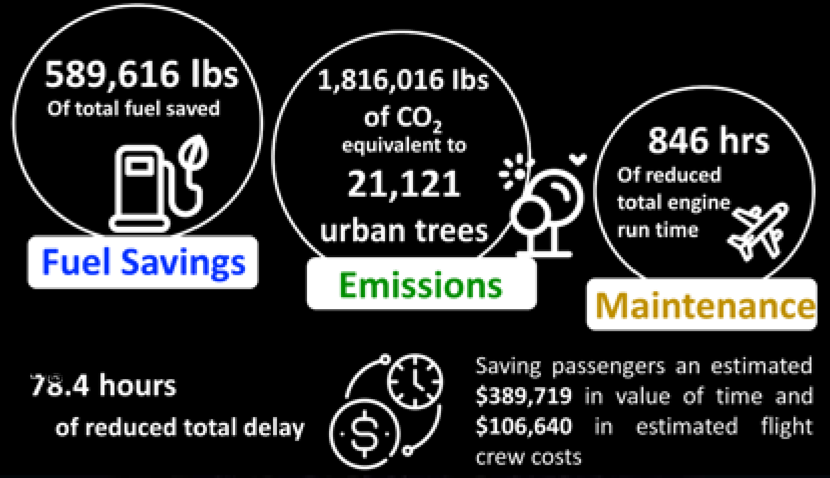
- Collection of critical technology development & demonstration activities to deliver near-term benefits to air transportation system stakeholders
- ATD-1: Terminal Sequencing & Spacing – integrated set of software technologies for planning & executing efficient terminal operations
- ATD-2: Integrated Arrival/Departure/Surface Activity – develop and adjust schedules for gates, spots, runways, and arrival/departure while ensuring efficient individual aircraft trajectory
- ATD-3: Applied Traffic Flow Management – develop concepts and technologies to execute more efficient flight paths for en route aircraft



ATD-2 (IADS)

- Enables operators at multiple control facilities to collaboratively manage traffic in the airport terminal area
- Provides common time-based view and tools to address problems
- Requires real-time data sharing across multiple domains
- Used agile development principles to iteratively refine requirements and software system

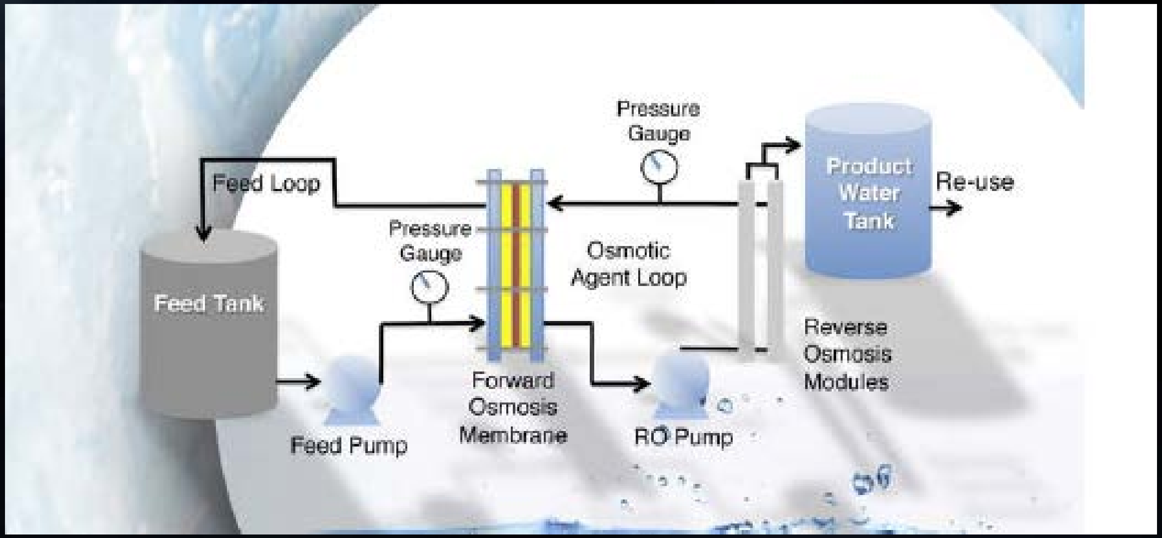


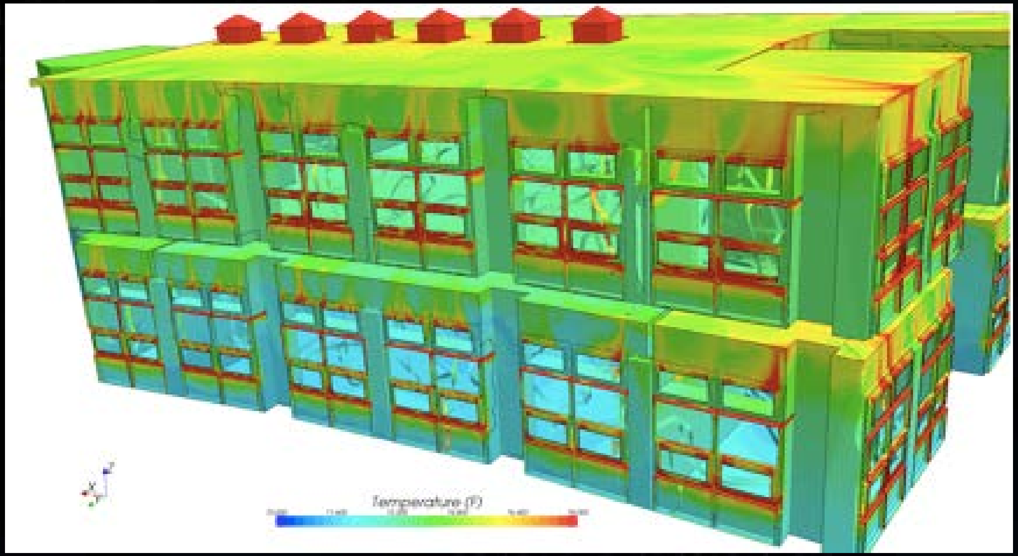


Benefits from 11 months of ATD-2 at Charlotte Airport

NASA Sustainability Base

- Ultra-green building that reduces external resource consumption by an order of magnitude – highest level of achievement for sustainability (LEED Platinum certified)
- Intelligent testbed for automation and autonomy technologies for space and extraterrestrial habitats
- Leverages various NASA space technology (e.g., waste recovery system from ISS, solid oxide fuel cell technology designed for Mars)
- Extensive sensor, diagnostics, and prognostics incorporated for controlling HVAC, electrical power, and water consumption
- Supercomputing modeling & simulation heavily utilized for design





Internal temperatures including stream ribbons

NASA Earth Exchange (NEX)

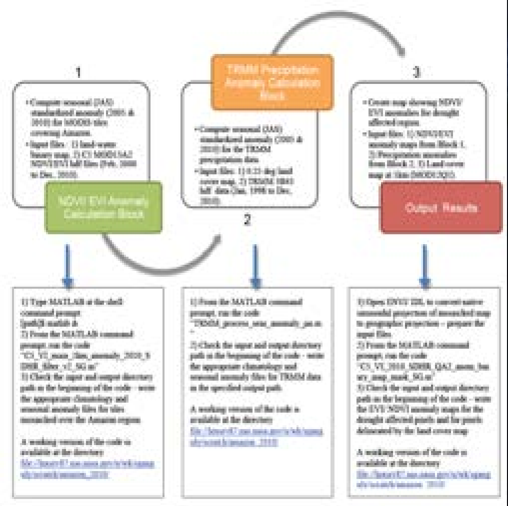
A virtual collaborative environment that brings scientists and researchers together in a knowledge-based social network along with observational data, necessary tools, and computing power to provide transparency and accelerate innovation: **Science-as-a-Service**

VIRTUAL COLLABORATION

Over 650 members

CENTRALIZED DATA REPOSITORY

Over 3.5 PB of observational data



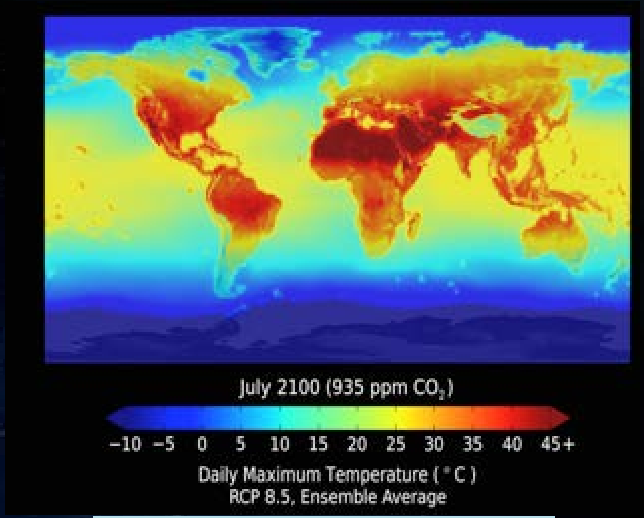
SCALABLE COMPUTING

Heterogeneous and remote, secure access

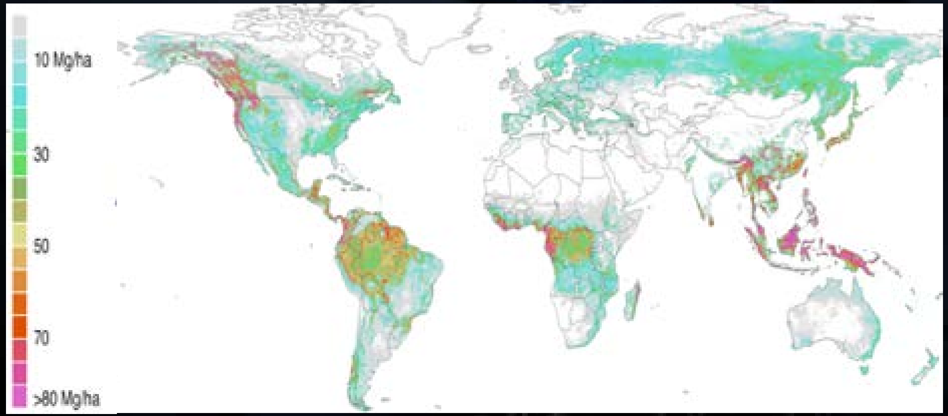
KNOWLEDGE

Workflows, virtual machine images, model codes, and reusable software

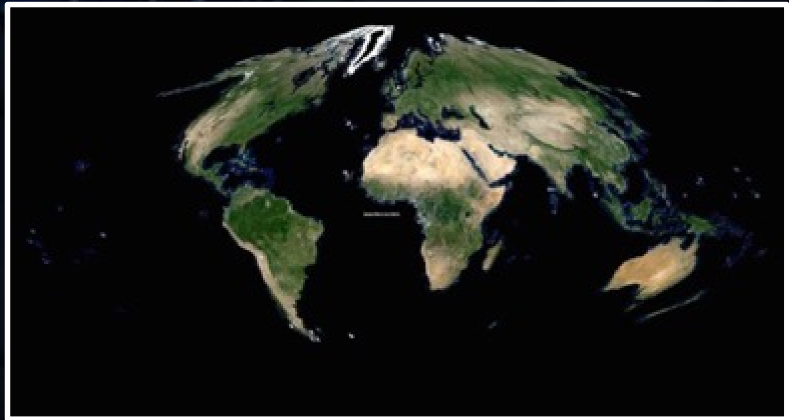
Science via NEX



High-resolution projections for climate impact studies

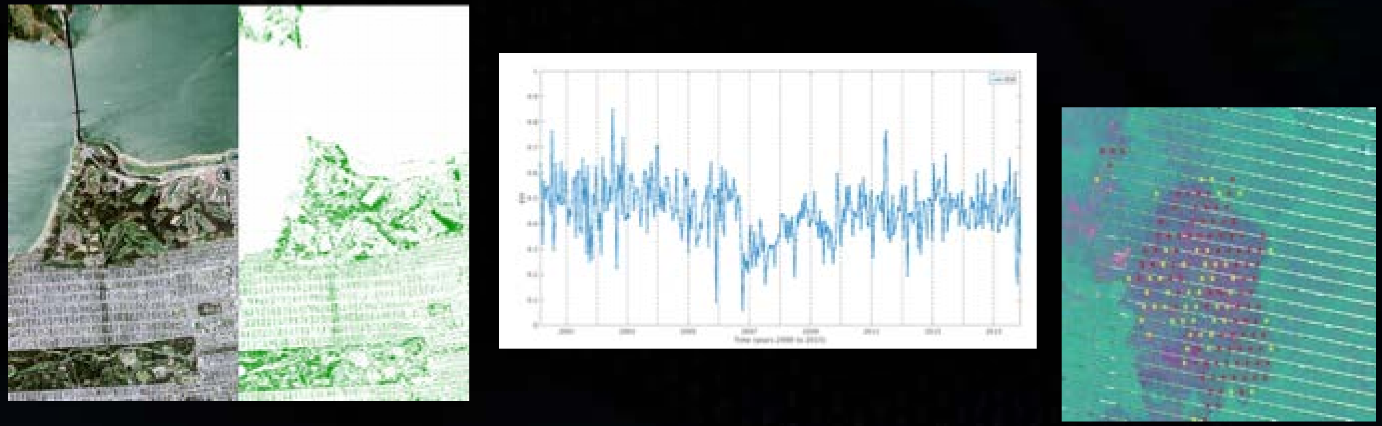


Global vegetation biomass at 100m resolution by blending data from 4 different satellites



High-resolution monthly global data for monitoring crops, forests, and water resources

Sample publication using NEX environment:
Nature 532.7599 (2016): 357



Machine learning and data mining – moving toward data-driven approaches

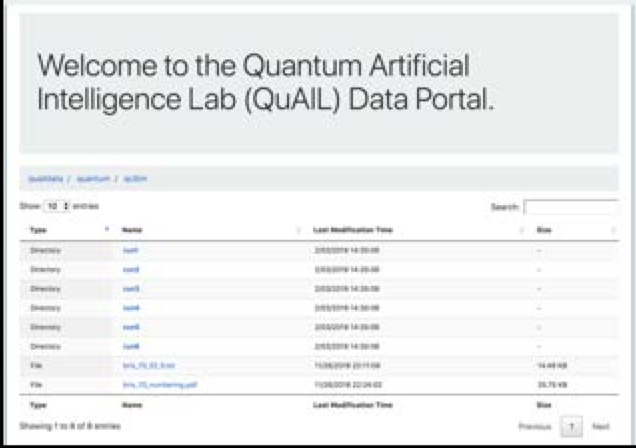
Data Portals

Support sharing & searching of data stored within NASA secure enclave with external community

- **Heliophysics Portal** provides highlights of the latest solar events using multi-instrument database
- Integrated view of reported flares (from NASA, NOAA, and Lockheed-Martin) and event catalogs from spacecraft and ground-based observations since 2002
- Interactive web interface to search and query unique flare events based on their physical characteristics and other pre-defined criteria
- http://helioportal.nas.nasa.gov

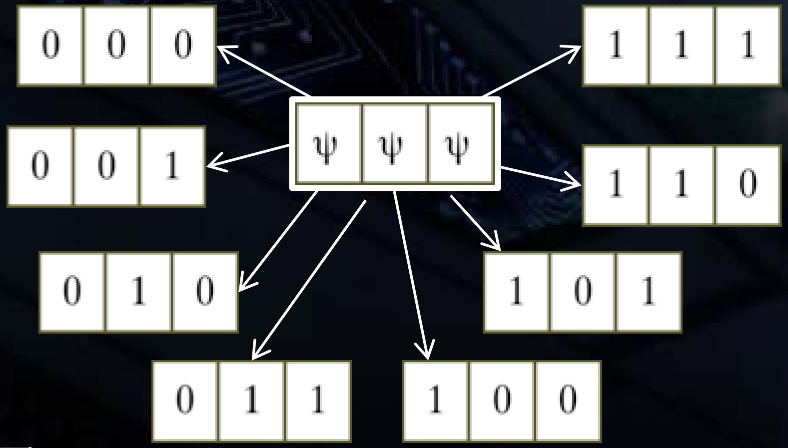
- **ECCO Portal** provides global ocean and sea-ice state estimates from high-resolution syntheses of observational data with circulation models (4 PB)
- ECCO: Estimating the Circulation and Climate of the Ocean
- https://data.nas.nasa.gov/ecco/

- **QuAIL Portal** provides simulation results (amplitudes of output wave-functions) from random quantum circuits on the Google Bristlecone QPU (43 GB)
- QuAIL: Quantum Artificial Intelligence Laboratory
- https://data.nas.nasa.gov/quail/

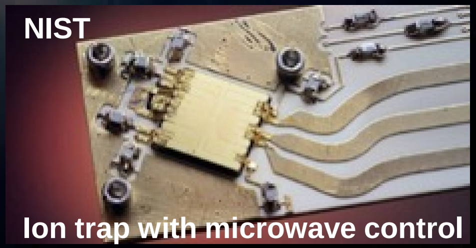


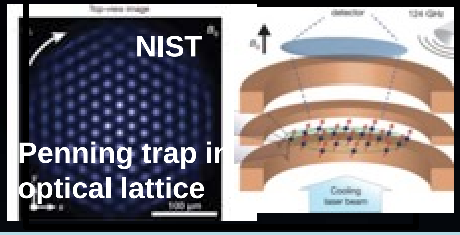
Quantum Computing 101

- Quantum mechanics deals with physical phenomena at very small scales (~100nm) and at very low temperatures (few K) where actions are quantized
- The outcome of a quantum experiment is probabilistically associated both with what was done before the measurement and how the measurement was conducted
- Qubits (quantum bits) can exist in a superposition of states, allowing *n* qubits to represent 2^n states simultaneously
- At the end of a computation, on measurement, the system collapses to a classical state and returns only one bit string as a possible solution

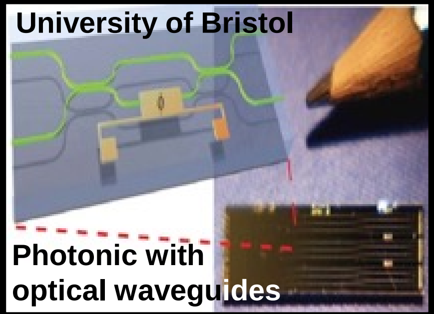


Numerous Implementations

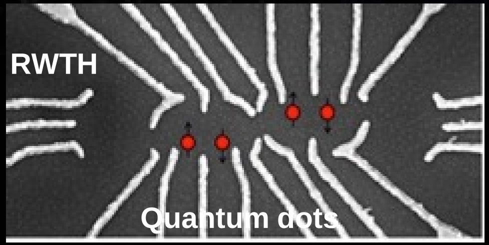


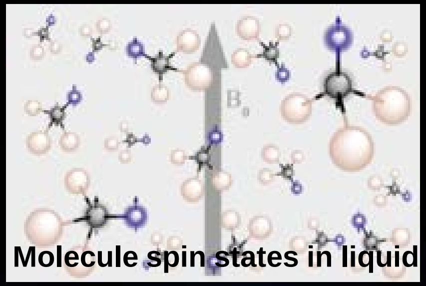


Trapped Ions and Neutral Atoms

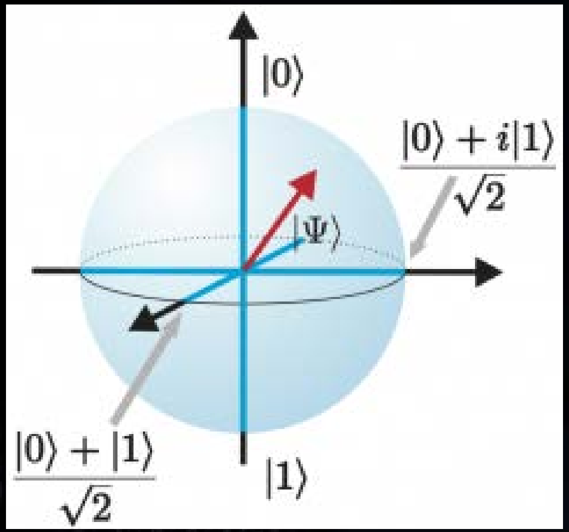


Photonic Quantum Chips



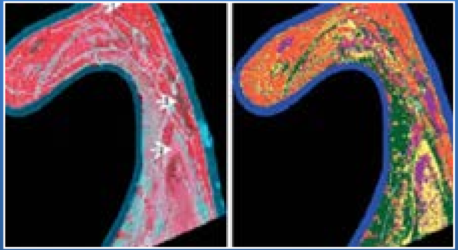


Nanoelectronics, NMR, Diamond Chips, etc.

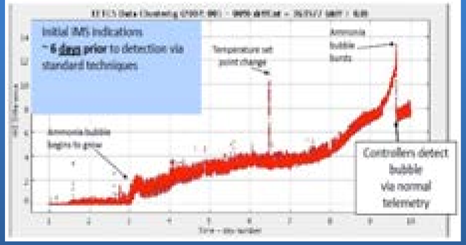


Quantum Computing for NASA Applications

Objective: Find “better” solution
- Faster
- More precise
- Not found by classical algorithm

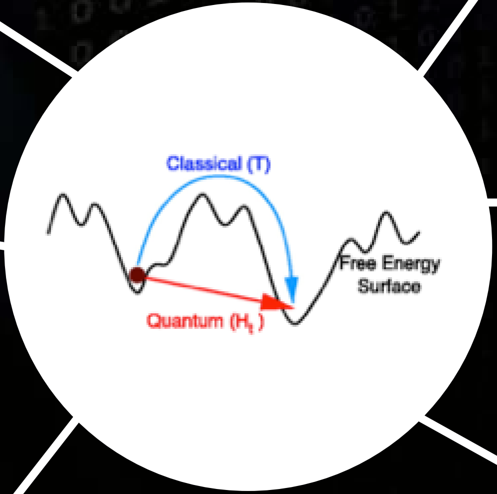


Data Analysis and Data Fusion



Anomaly Detection and Decision Making

Air Traffic Management



V&V and Optimal Sensor Placement

Mission Planning, Scheduling, and Coordination

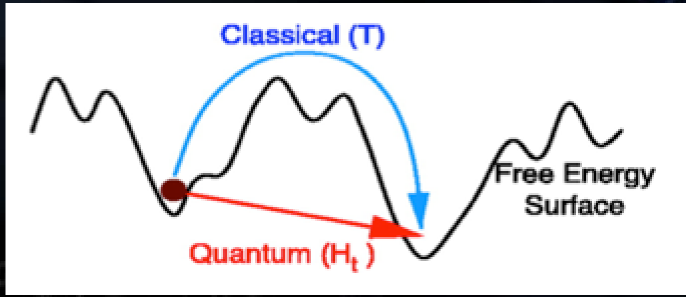
Topologically-aware Parallel Computing

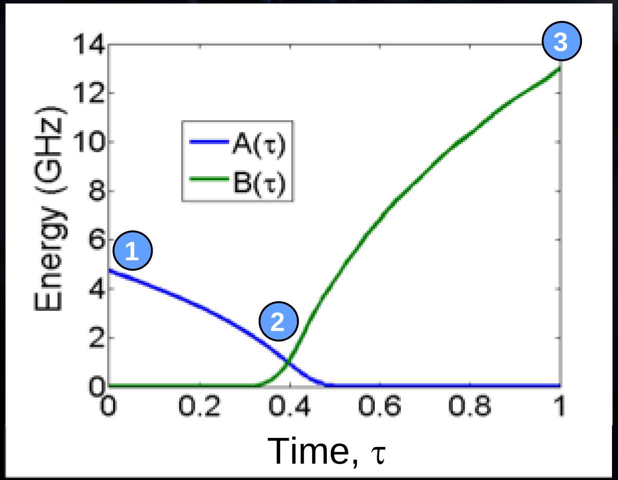
Common Feature: Intractable (NP-hard / NP-complete) problems!

Quantum Annealing

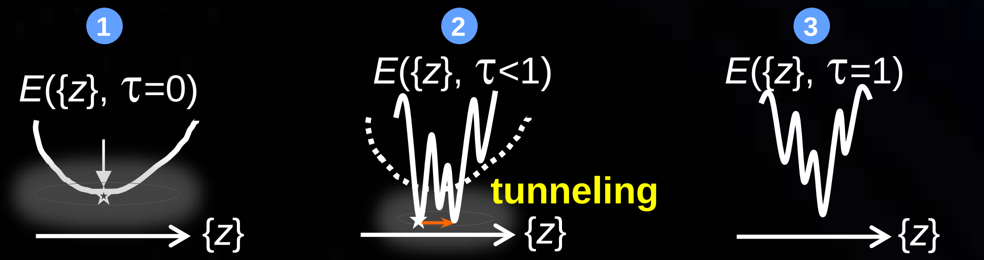
A physical technique to solve combinatorial optimization problems

$$E(z_1, z_2, \dots z_n) = \underbrace{\left(1 - \frac{t}{T}\right)}_{A(t)} H_0(\{z\}) + \underbrace{\frac{t}{T}}_{B(t)} H_P(\{z\})$$





- *N*-bit string of unknown variables {*z*}
- H_0: Hamiltonian with known ground state
- H_P: Hamiltonian whose ground state represents solution to the problem
- Large *A(t)* responsible for quantum fluctuations slowly (adiabatically) lowered to zero while maintaining minimum energy of the system at all times
- In conjunction, cost function of interest *B(t)* gradually turned on
- Transitions between states occur via tunneling through barriers due to quantum fluctuations
- Solution is configuration {*z*} that produces minimum *E* with non-zero probability
- Method similar to simulated annealing where transitions between states occur via jumping over barriers due to thermal fluctuations



Initialize in an easy-to-prepare full quantum superposition

Quantum states explored by quantum tunneling

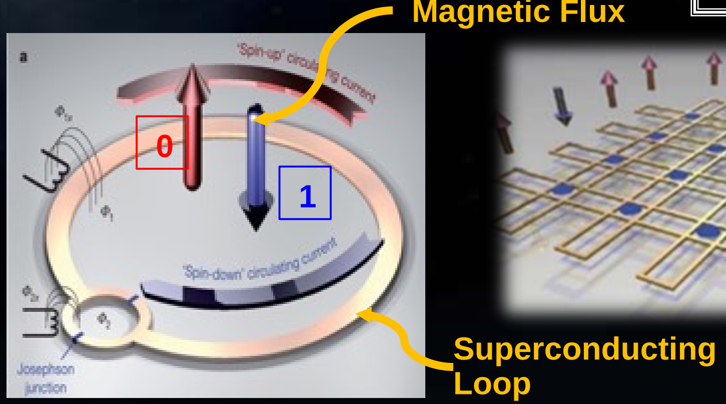
Final state a bit-string encoding solution with probability

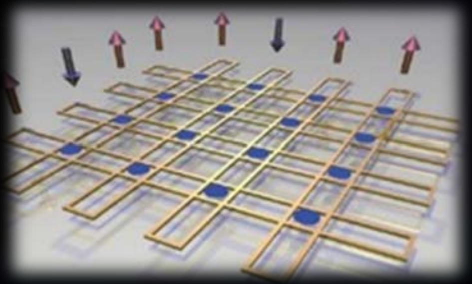
D-Wave System Hardware

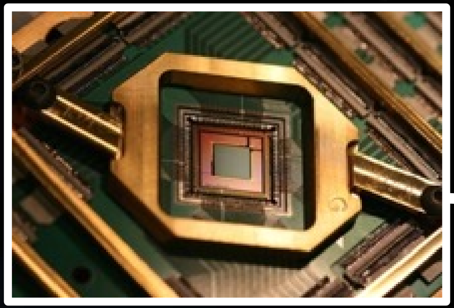
- Collaboration with Google and USRA led to installation of system at NASA Ames in early 2013
- Started with 512-qubit Vesuvius processor – currently 2031-bit Whistler
- 10 kg of metal in vacuum at ~15 mK
- Magnetic shielding to 1 nanotesla; Protected from transient vibrations
- Single annealing typically 20 μs
- Typical run of 10K anneals
- Uses 15 kW of electrical power
- Solves only one binary optimization problem

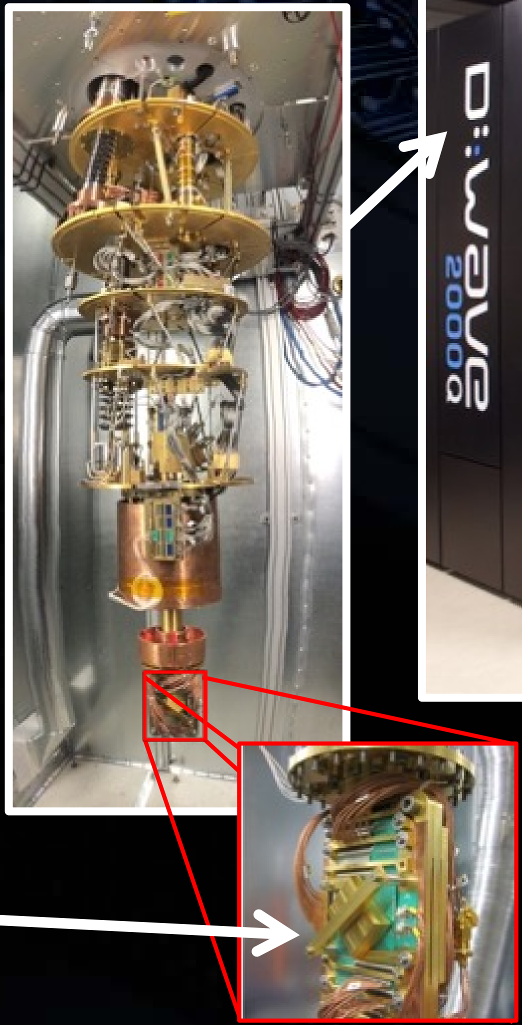
Given $\{ h_j, J_{ij} \}$, find $\{ s_k = \pm 1 \}$ that minimizes

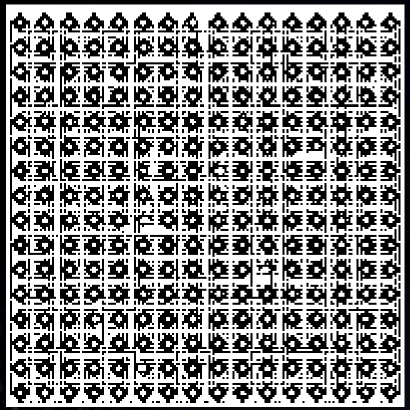
$$\xi(s_1, \dots, s_N) = \sum_{j=1}^{N} h_j s_j + \sum_{i,j \in E}^{N} J_{ij} s_i s_j$$











Focus on solving discrete optimization problems using quantum annealing

Programming the D-Wave System

1 Map the target combinatorial optimization problem into QUBO

No general algorithms but smart mathematical tricks (penalty functions, locality reduction, etc.)

$$\alpha_{ijk} z_i z_j z_k$$

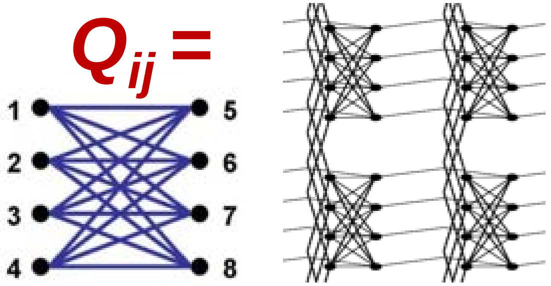
$$\alpha_{ijk}\, y_{ij} z_k + \beta_{ijk}(3y_{ij} - 2z_i y_{ij} - 2z_j y_{ij} + z_i z_j)$$

$$\sum_{ij} Q_{ij} z_i z_j \rightarrow \sum_i h_i s_i + \sum_{i,j} J_{ij} s_i s_j$$

Mapping not needed for random spin-glass models

2 Embed the QUBO coupling matrix in the hardware graph of interacting qubits

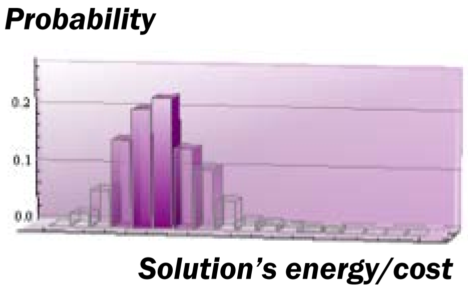
D-Wave qubit hardware connectivity is a Chimera graph, so embedding methods mostly based on heuristics



Embedding not needed for native Chimera problems

3 Run the problem several times and collect statistics

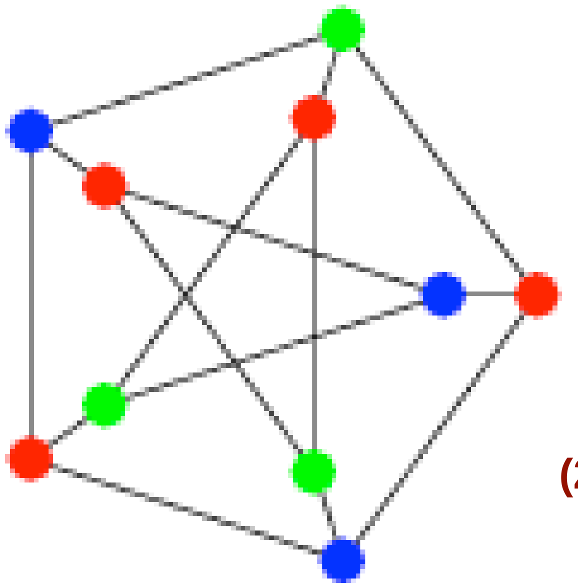
Use symmetries, permutations, and error correction to eliminate the systemic hardware errors and check the solutions



Performance can be improved dramatically with smart pre-/post-processing

Mapping to QUBO: Graph Coloring Example

Assign one of *k* colors to each vertex so that no two vertices sharing an edge have the same color



Binary variable:

$$x_{v,c} = \begin{cases} 1 & \text{vertex } v \text{ with color } c \\ 0 & \text{vertex } v \text{ not with color } c \end{cases}$$

Violation of requirements encoded as cost:

- (1) unique assignment: Each vertex v must be assigned exactly one color:

Costing cases

(1) No color or Multi-colored

$$H_v^{(unique)} = (\sum_{c \in C} x_{v,c} - 1)^2 \Leftarrow \sum_{c \in C} x_{v,c} = 1$$

- (2) Connected vertices cannot use the same color

(2) Same color for connected vertices

$$H_{v,v',c}^{(exclude)} = x_{v,c} x_{v',c} \text{ if } vv' \in E$$

Final QUBO form:

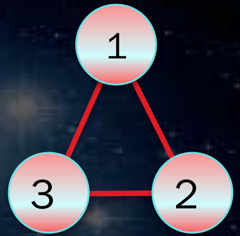
$$H = \sum_v H_v^{(unique)} + \sum_{v,v' \in E} \sum_c H_{v,v',c}^{(exclude)}$$

H = 0 corresponds to a valid coloring

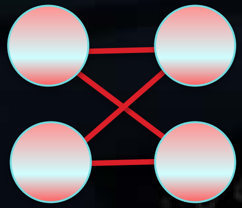
Embedding the QUBO

Embed a triangle onto a bipartite graph

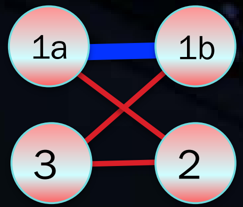
original QUBO



hardware connectivity



QUBO embedded



$$H_0 = J_{12}x_1x_2 + J_{23}x_2x_3 + J_{13}x_1x_3$$

$$H_1 = J_{12}x_{1a}x_2 + J_{23}x_2x_3 + J_{13}x_{1b}x_3 + J_{\texttt{Ferro}}x_{1a}x_{1b}$$

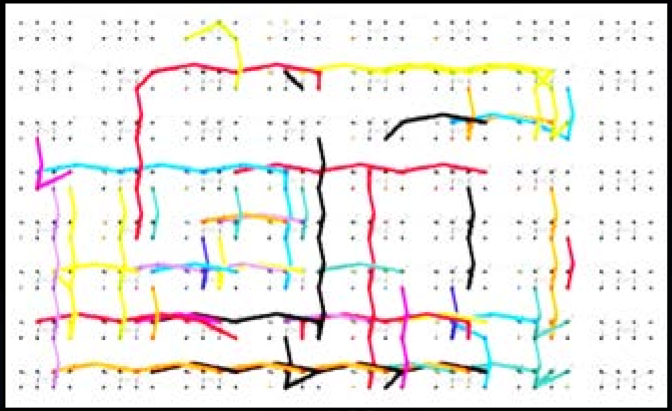
Strong, but not too strong, ferromagnetic coupling between physical qubits x_{1a} and x_{1b} encourages them to take the same value, thus acting as a single logical qubit x_1

H_0 and H_1 have the same ground state but the energy landscape of the search space differs

Current research investigation: How best to set the magnitude of these "strong" couplings to maximize probability of success

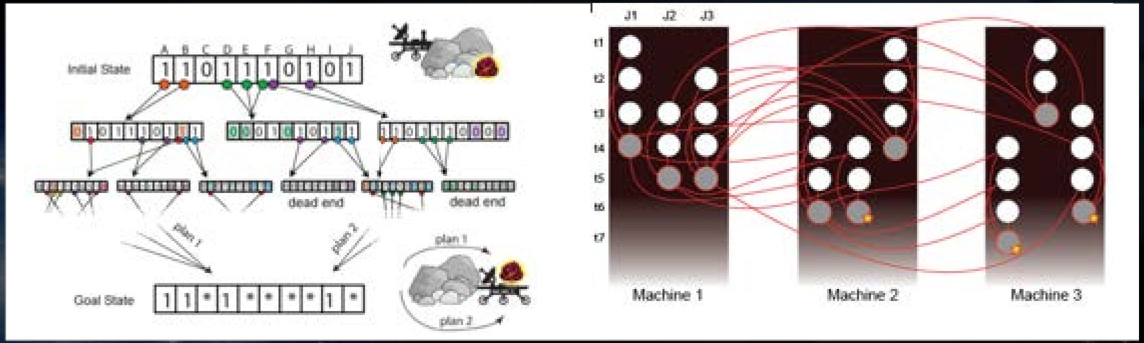
Embedding a realistic problem instance:

Physical qubits on each colored path represent one logical qubit

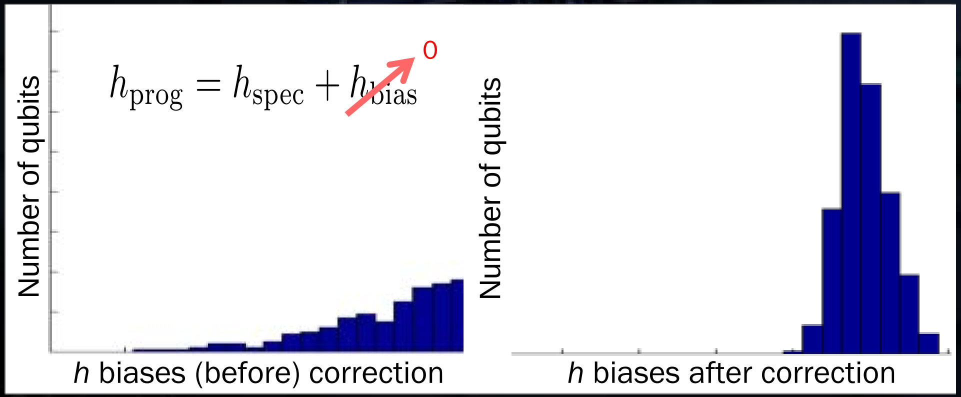


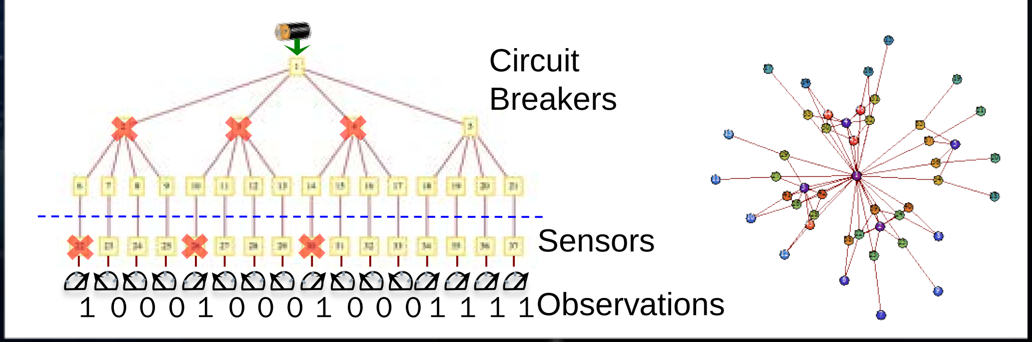
Current NASA Research in Quantum

Complex Planning and Scheduling



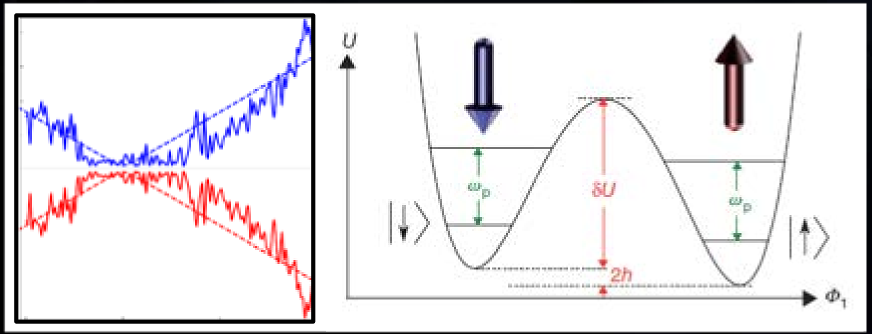
Calibration of Quantum Annealers

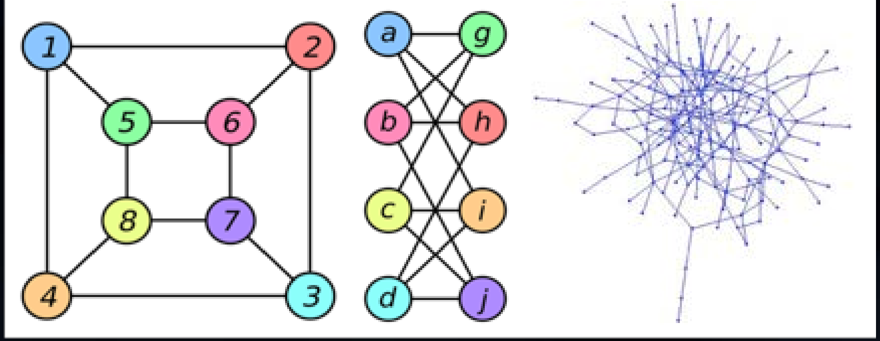




Graph-based Fault Detection

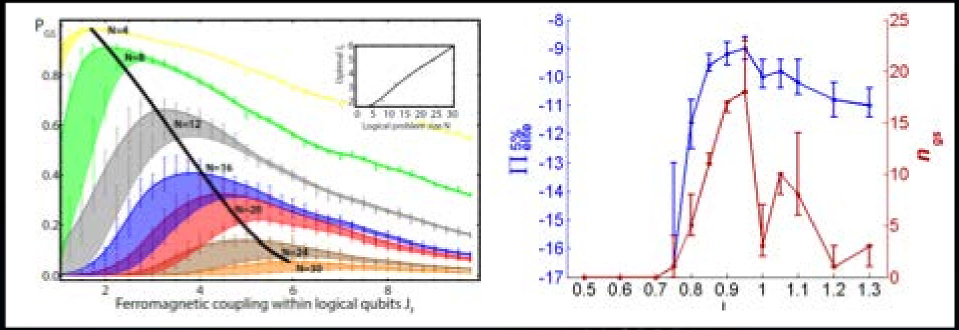
Effect of Noise on Quantum Annealing





Graph Isomorphism

Optimal Embedding and Parameter Setting



Assured Availability of UTM Network

UTM: UAS Traffic Management

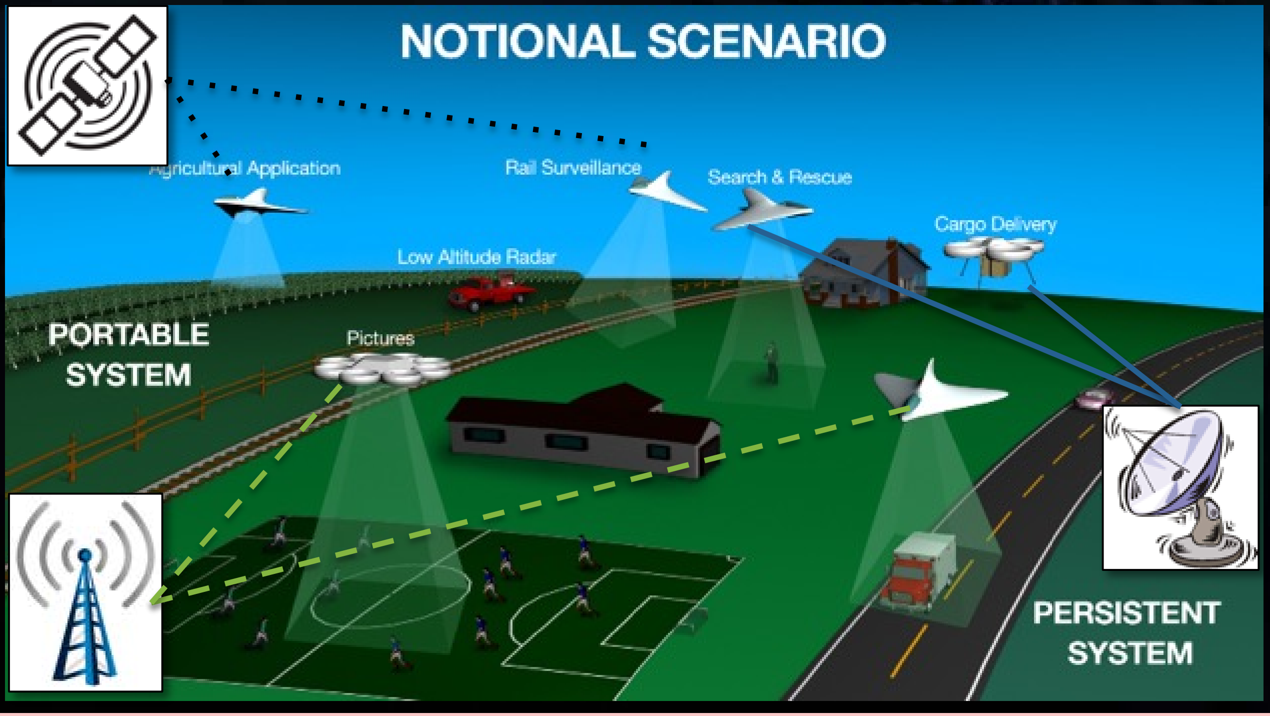
UAS: Unmanned Aerial System (includes UAV, ground control & communication)

Future

- Higher vehicle density
- Heterogeneous air vehicles
- Mixed equipage
- Increased autonomy
- Greater vulnerability to communication disruptions

Explore quantum approaches for:

- Robust network design
- Track and locate moving jammers
- Secure communication of codes supporting anti-jamming protocols

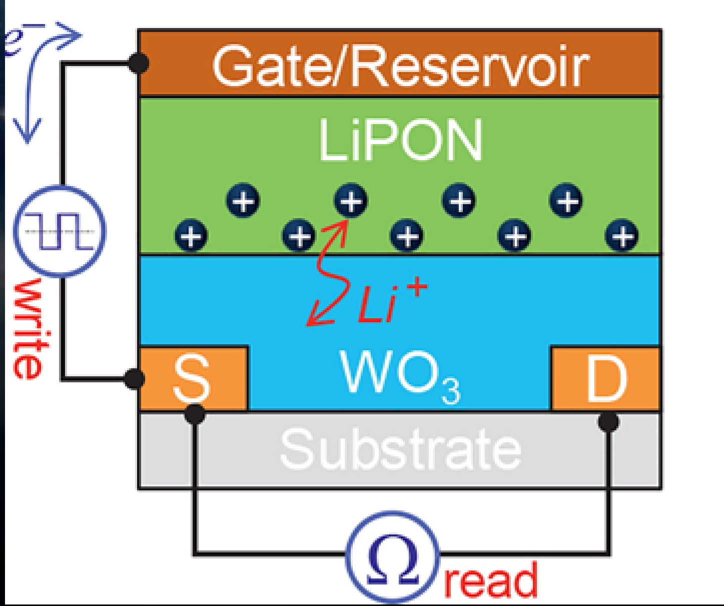


- Harness power of quantum technologies to address cybersecurity challenge of assured availability
- Leverage work on QKD for spread spectrum codes

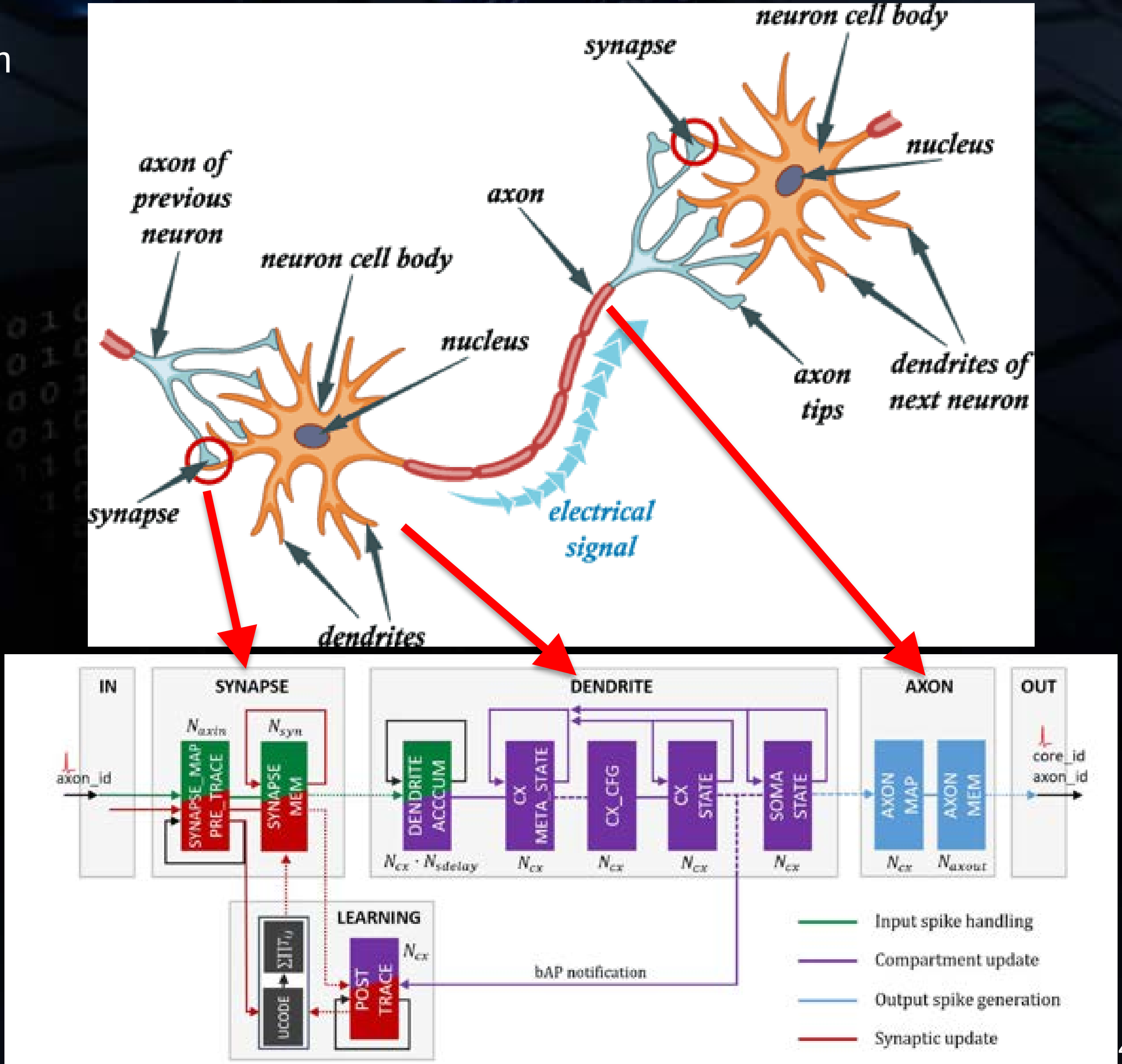
P. Kopardekar, et al., ***Unmanned Aircraft System Traffic Management (UTM) concept of operations***, AIAA 2016-3292

Neuromorphic Computing 101

- Mead in 1990: Map insights from biological nervous system to silicon (from the device level to the architectural level
- Energy efficient high-throughput computing through specialization to neural nets, analog processing, and massive parallelism



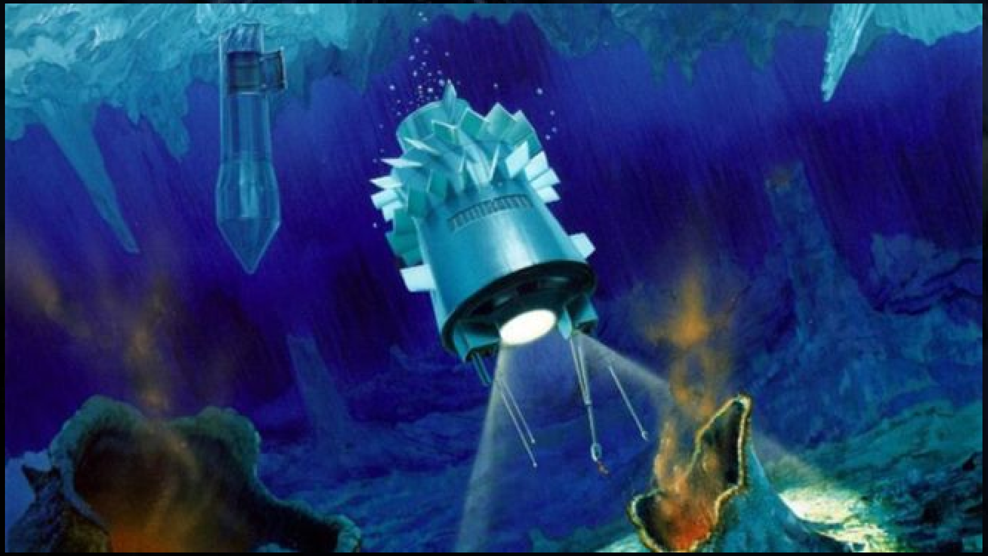
IBM ECRAM: New artificial synapse with 100s of distinguishable states (electrochemical RAM)



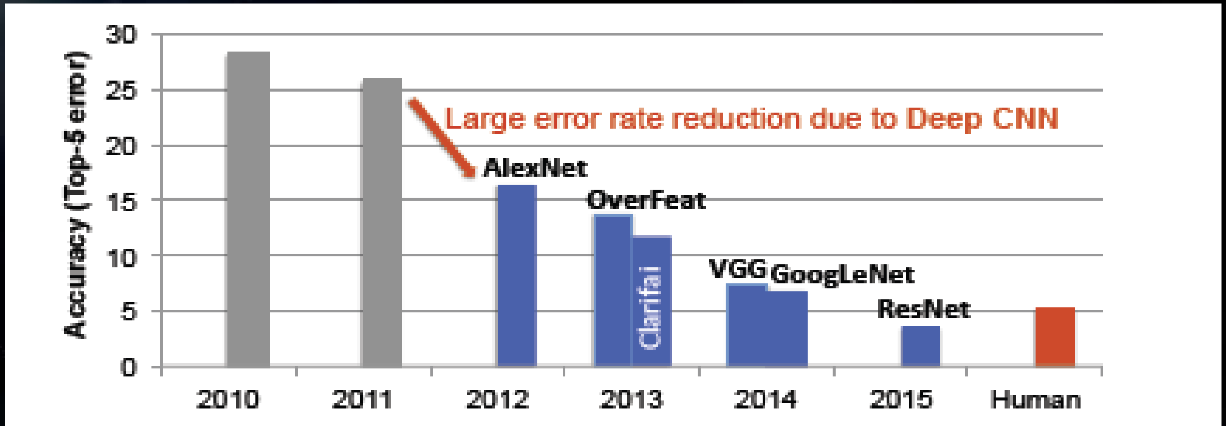
Intel Loihi: Asynchronous Spiking Neural Network Microarchitecture

Neuromorphic Computing for NASA Applications

- Aerospace missions in harsh environments require power efficient and robust embedded computing – vehicle limited by onboard computers
- Deep-space missions need in-situ learning to enable adaptation and decision-making due to low bandwidth and large latencies back to Earth
- Neuromorphic processors can power robots to operate as humans while maintaining safety through fast perception, sensor fusion & fine control
- Deep learning & related AI yield large gains in accuracy and performance for perception, discrimination, classification over conventional algorithms
- After learning, inferencing requires very large artificial neural nets to execute fast real-time loops – also enabled by neuromorphic processors

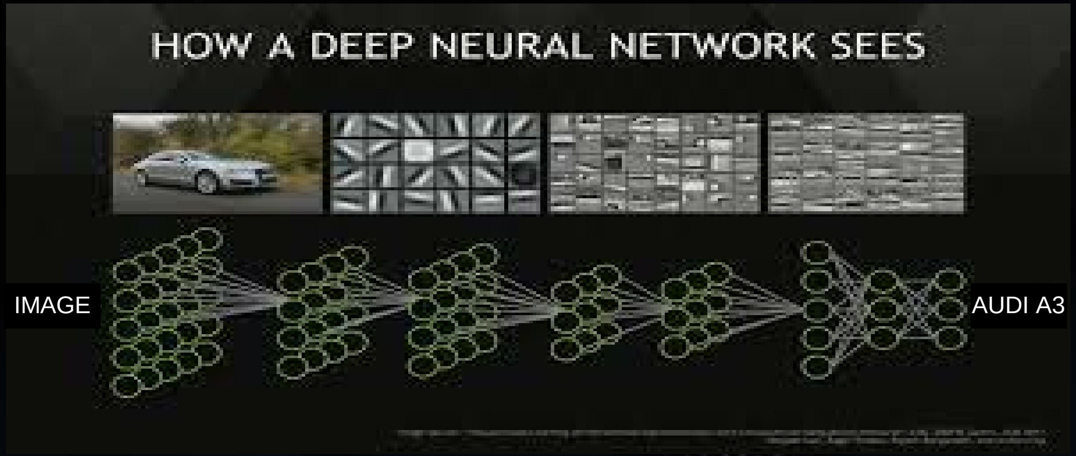


Europa submersible explorer



2012: Prof. Hinton DL breakthrough (AlexNet)

2015: ResNet surpasses humans on image classification



NASA Advanced Computing Environment

Enable the science & engineering required to meet NASA’s missions and goals