

An Overview of Agency Highlights, Research Accomplishments at NASAS Ames with Emphasis on High End Computing Research and Quantum Computing

Dr. Eugene Tu
Director, NASA Ames Research Center



EARTH RIGHT NOW

Your planet is changing. We're on it.



International Space Station



NASA'S JOURNEY TO

MARS



TECHNOLOGY DRIVES EXPLORATION



we're out there

Your Planet is Changing

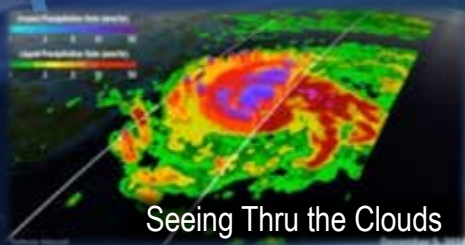


RapidSCAT (ISS)
2014
CATS (ISS)
2015

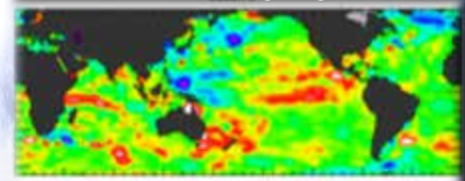
SMAP
2015

DSCOVR (NOAA)
2015

Jason-3
2016



Jason-3 sees Ongoing El Niño



OCO-2
2014

Suomi NPP
2011



GPM
2014



Landsat 8 (USGS)
2013

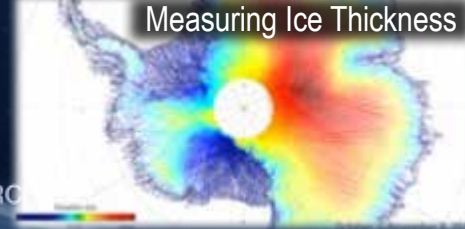


OSTM/Jason-2
2008



CALIPSO
2006

CloudSat



Aura



OROS

GRACE (2)
2002

EO-1
2000

QuikSCAT
1999



Terra
1999



Landsat 7 (USGS)
1999



Oct 2012 00:00

Off the Earth, for the Earth



Dragon Cargo
(SpaceX)



Cygnus
(Orbital)



Crew Dragon (SpaceX)



CST-100 STARLINER (Boeing)



Atlas V (Boeing)



Antares
(Orbital)



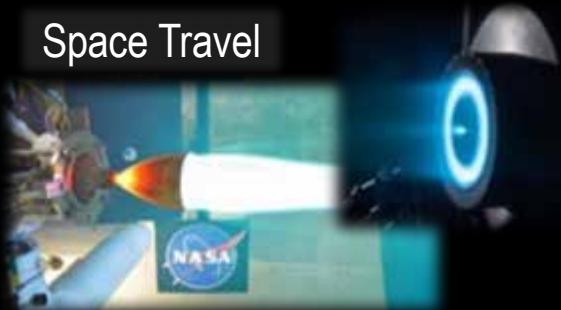
Falcon 9
(SpaceX)



Technology Drives Exploration



Space Travel



Living in Space



Science Instruments



Manufacturing,
Materials,
3-D Printing



High-Tech Computing



Robotics



NASA Is With You When You Fly



Safe, Efficient Growth
in Global Operations



Innovation in Commercial
Supersonic Aircraft



Ultra-Efficient
Commercial Vehicles



Transition to Alternative
Propulsion and Energy



Real-Time System-Wide
Safety Assurance



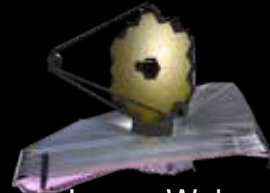
Assured Autonomy for
Aviation Transformation



NASA: We're Out There



Hubble Space Telescope



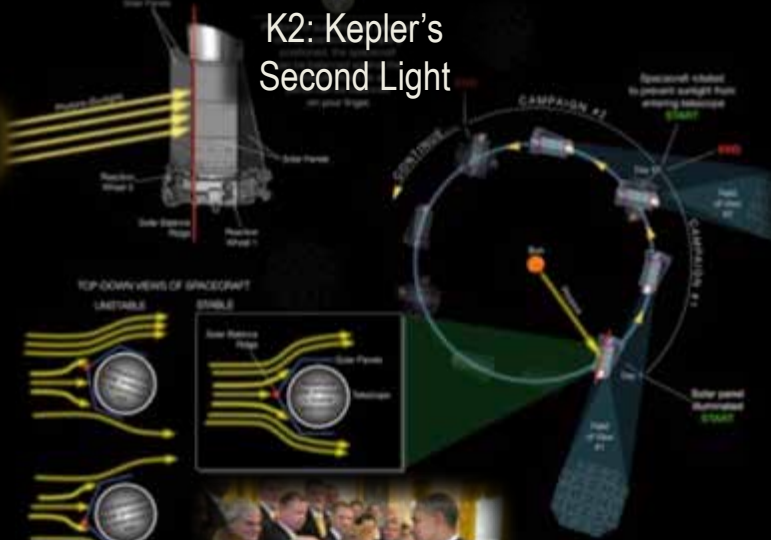
James Web
Space Telescope



Icy Worlds:
Habitability and
Life Detection



K2: Kepler's
Second Light

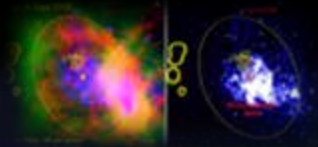


Origin and Nature of
Life, Co-evolution
with Planet Earth

Mars: Habitability
of Early Mars



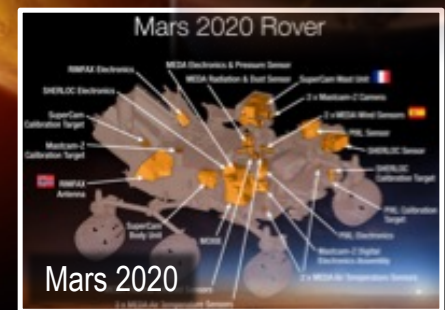
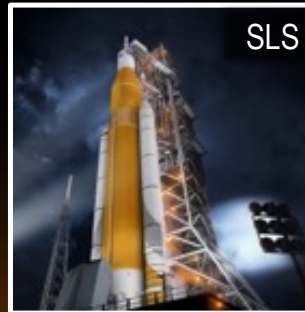
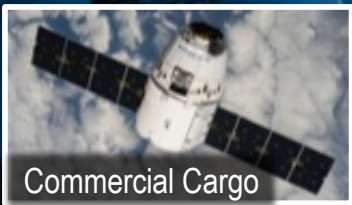
TESS



SOFIA



Join Us on the Journey



INTERNATIONAL SPACE STATION

SCIENCE
OPERATION
TECHNOLOGY

COMMERCIAL CARGO AND CREW












ORION CREWED SPACECRAFT
DEEP SPACE HABITAT

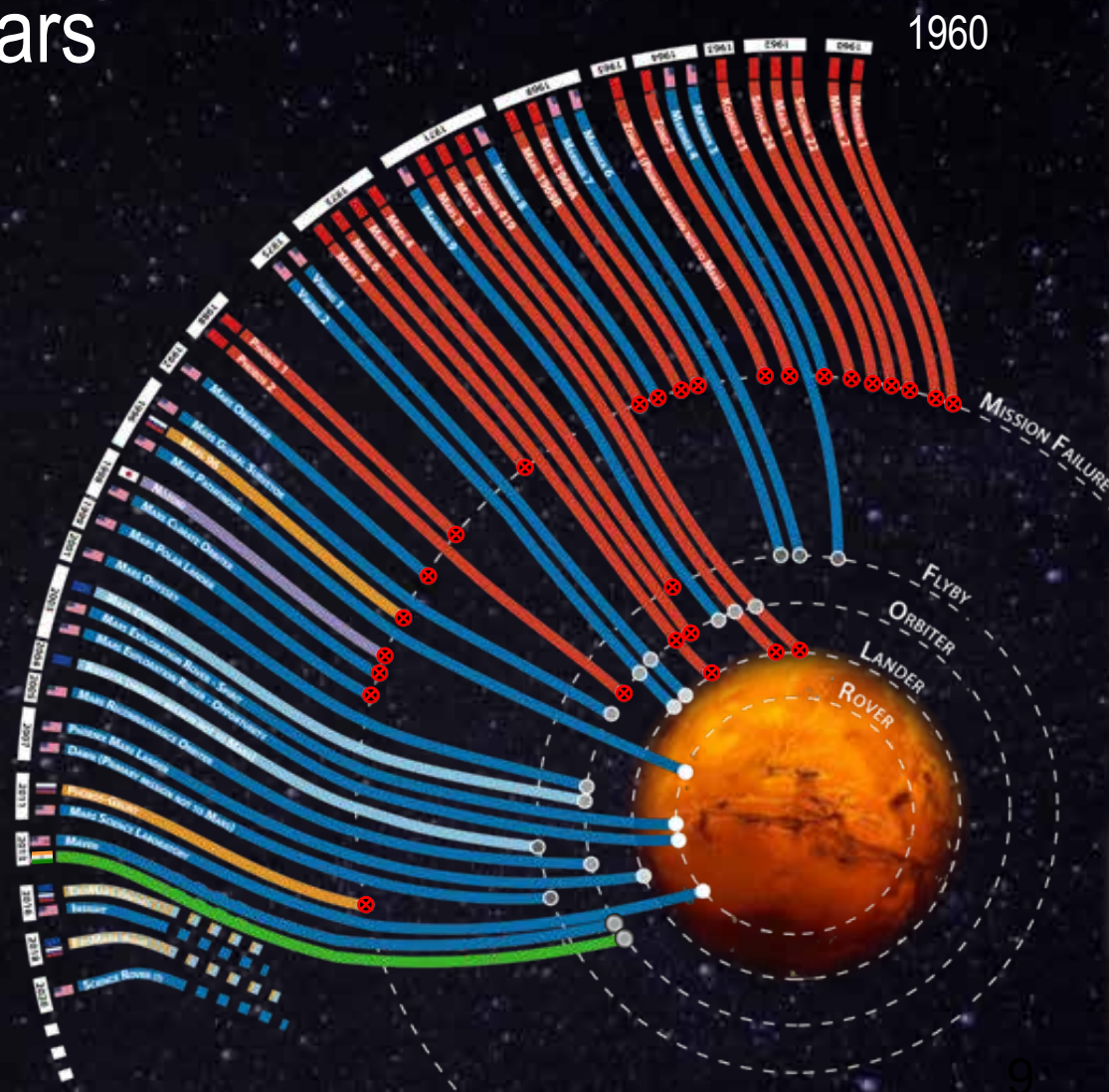
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION

ORBITERS
ROVERS AND LANDERS



60 Years of Mars Exploration

-  Soviet Union
-  United States
-  Russia
-  Japan
-  ESA
-  India
-  MISSION FAILURE
-  FLYBY
-  ORBITER
-  LANDER
-  ROVER





Ames is One of the Early NACA Laboratories



Joseph S. Ames



NACA

Langley

Ames

Lewis

Dryden

NASA

1915

1939

1940

1946

1958



NASA Centers and Installations



Glenn Research Center

Ames Research Center

Goddard Space Flight Center

Headquarters

Jet Propulsion Laboratory

Armstrong Flight Research Center

Johnson Space Center

Stennis Space Center

Kennedy Space Center

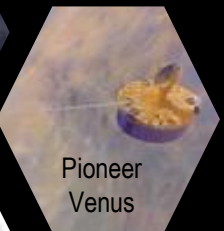
Langley Research Center

Marshall Space Flight Center

78 Years of Innovation



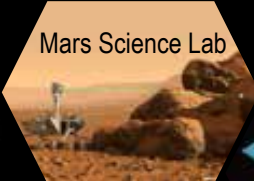
2015



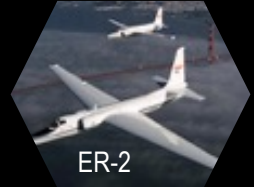
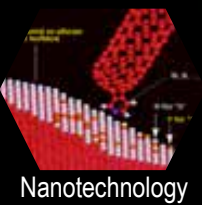
1980

1990

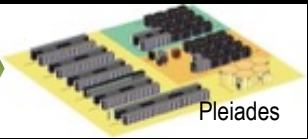
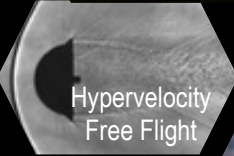
2000



1970




1950



1940

Ames Research Center

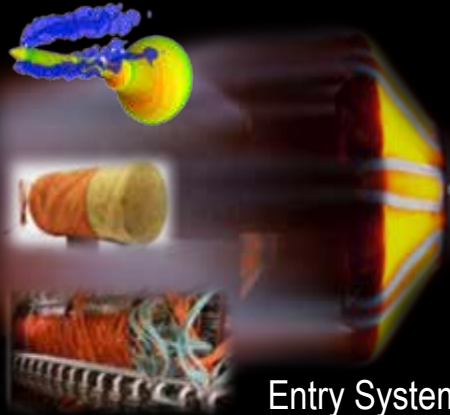


- Occupants:
 - ~1130 civil servants; ~2,100 contractors; 1,650 tenants
 - 855 summer students in 2016
- FY2016 Budget: ~\$915M (including reimbursable/EUL)
- ~1,900 acres (400 acres security perimeter); 5M building ft²
- Airfield: ~9,000 and 8,000 ft runways

Core Competencies at Ames Today



Air Traffic Management



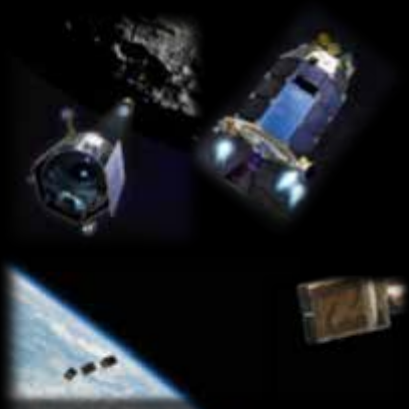
Entry Systems



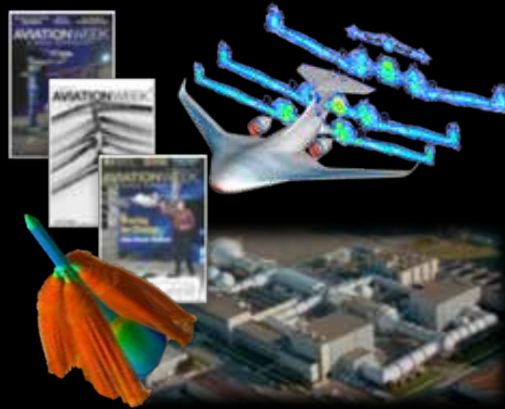
Advanced Computing & IT Systems



Intelligent/ Adaptive Systems



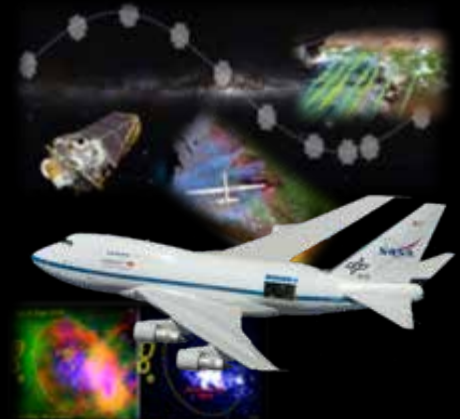
Cost-Effective Space Missions



Aerosciences



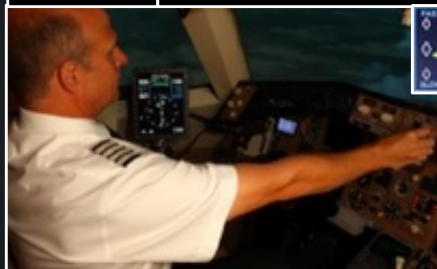
Astrobiology and Life Science



Space and Earth Sciences

Air Traffic Management

FIM Flight Deck Interval Management for Arrival Operations



CMS Controller-Managed Spacing in Terminal Airspace



HEAVEN	1234567890	01
HEAVEN	1234567890	02
HEAVEN	1234567890	03
HEAVEN	1234567890	04
HEAVEN	1234567890	05
HEAVEN	1234567890	06
HEAVEN	1234567890	07
HEAVEN	1234567890	08
HEAVEN	1234567890	09
HEAVEN	1234567890	10
HEAVEN	1234567890	11
HEAVEN	1234567890	12



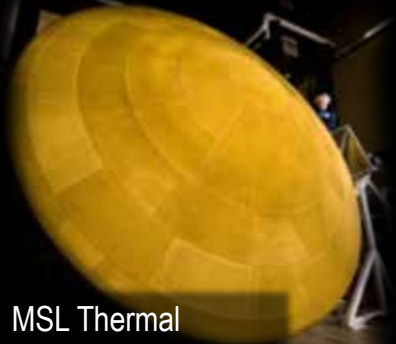
TMA-TM Traffic Management Advisor with Terminal Metering



UAS Traffic Management

Air Traffic Demonstration – ATD-1

Entry Systems



MSL Thermal Protection System

PICA



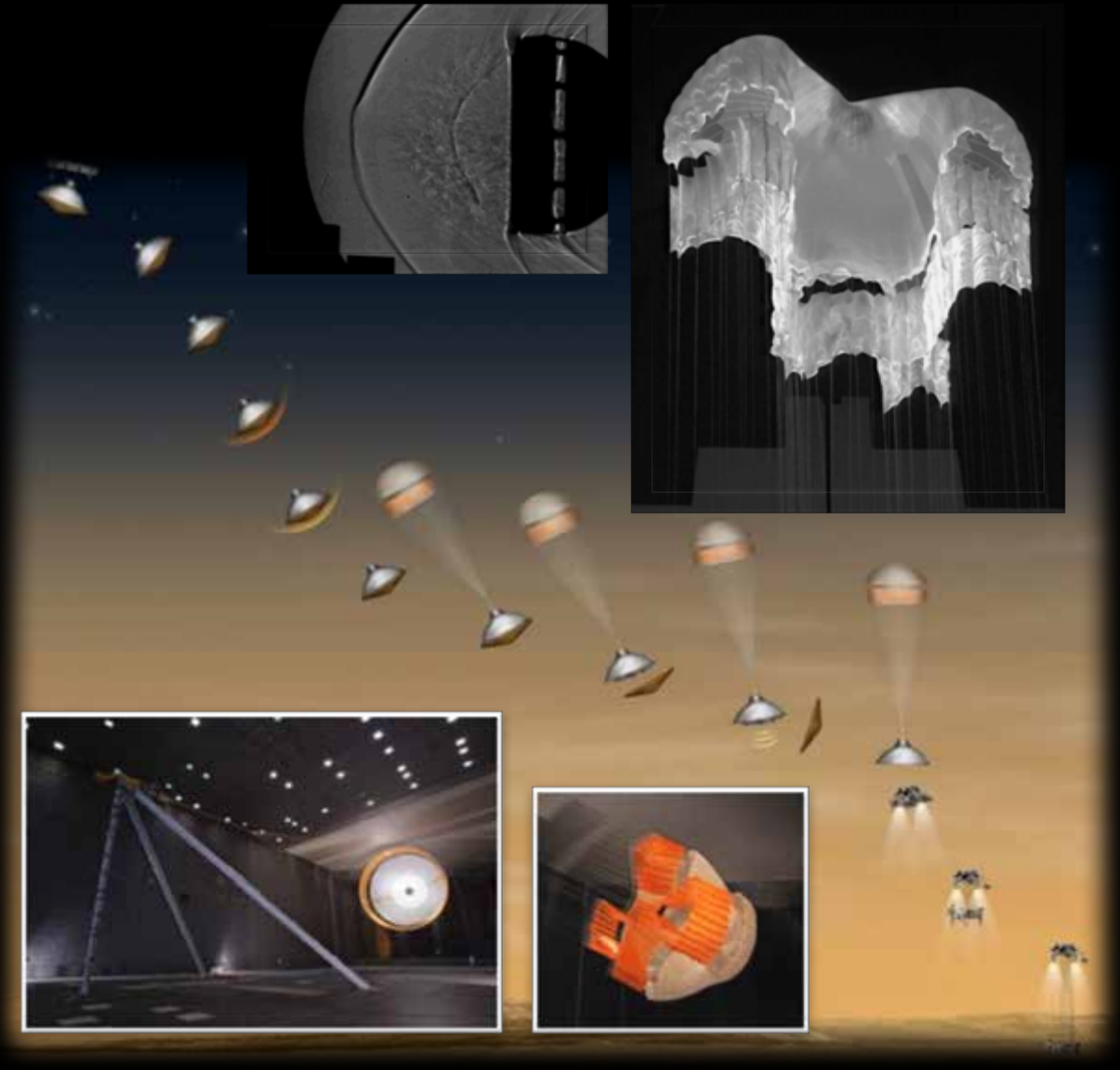
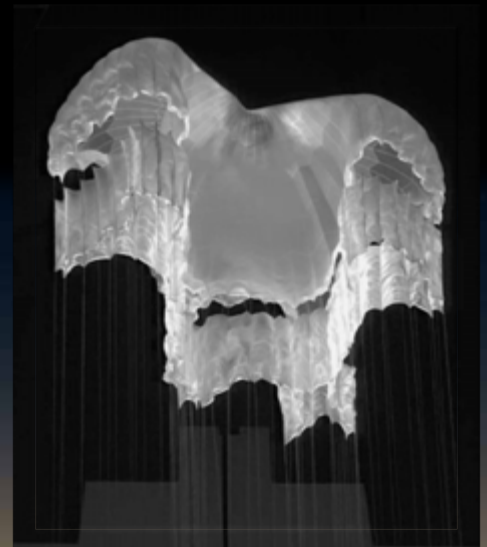
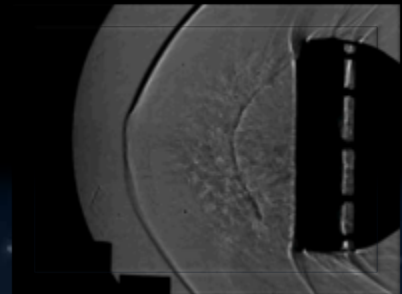
ADEPT



MEDLI



Interaction Heating Facility



Intelligent Adaptive Systems



Activity Mission Planning For **Mars**



Planning And Scheduling For **Human Robotic Teams / Future**



Astronauts Self-scheduling And Planning

Payload & Drill Subsystem



Planetary Lake Lander

Adaptive science for dynamic phenomena in deep-space missions. Field testing in Chile.

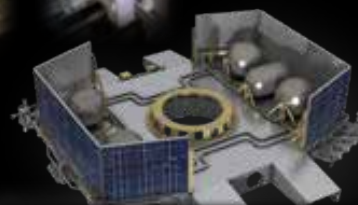


Activity Mission Planning For **Crew On ISS**

Distributed Ops Testing



Partnering Lander Concept



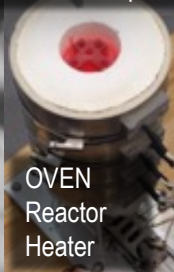
Self Driving Car

Adapt space robotics technology to "fleet management" use.

Synchronized Position Hold, Engage Reorient, Experimental Satellites



OVEN Reactor Heater



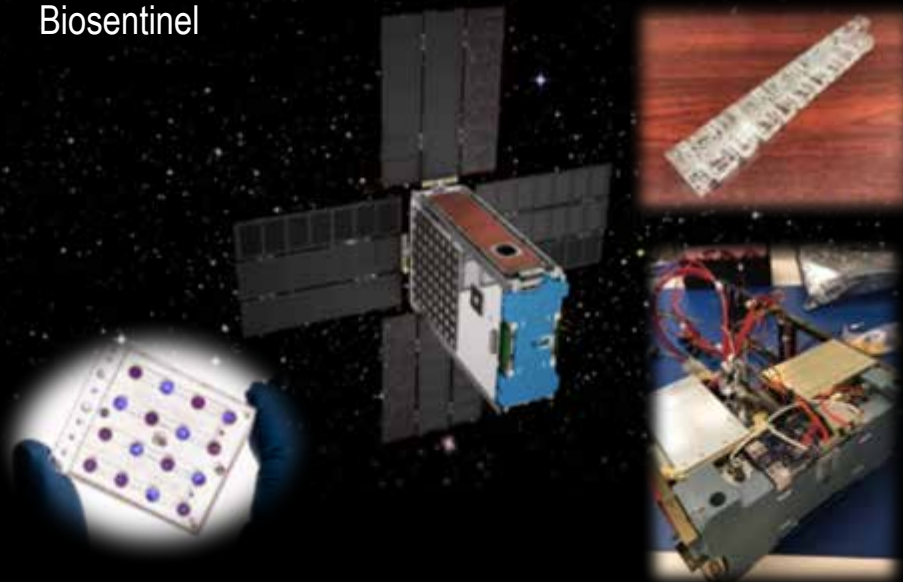
Astrobee Free-Flyer

Autonomous nav, docking and recharge, and mobile sensor IVA work on the ISS

Cost-Effective Space Missions @ Ames



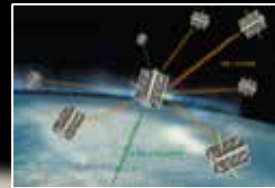
Biosentinel



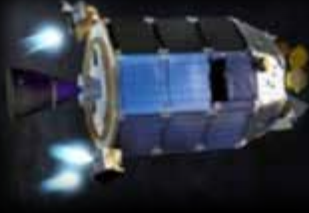
TechEdSat-4



TechEdSat-5



LCROSS (2009)



LADEE (2013)



PhoneSat (2013), EDSN (2013)

Aerosciences



Astrobiology and Life Sciences



Dry Electrode ECG System



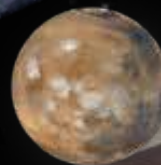
GeneLab



Experimental cassette for Seedling Growth-2



Origin and Nature of Life, Co-evolution with Planet Earth



Mars: Habitability of Early Mars

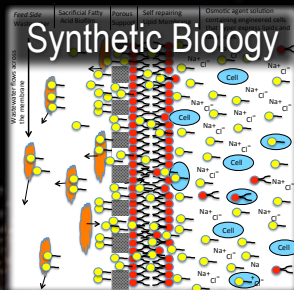


Icy Worlds: Habitability and Life Detection

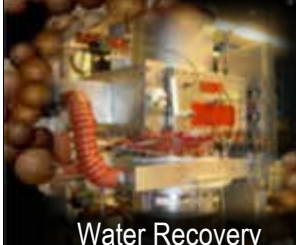


Rodent Research-1 (SpaceX-4)

Advanced Life Support Technologies



Regenerable water processing membrane



Water Recovery



Air Revitalization



Waste Recovery



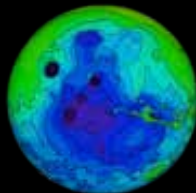
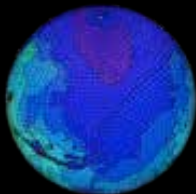
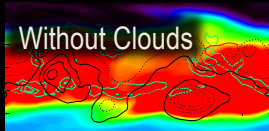
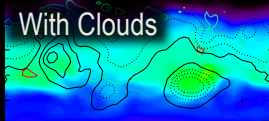
Technology: Technology Drives Exploration
Global Partnerships Employing Collaborative Technologies

NASA Astrobiology Institute

LIFE IN THE UNIVERSE

Space and Earth Sciences

Understanding Mars Climate



Global Circulation Model



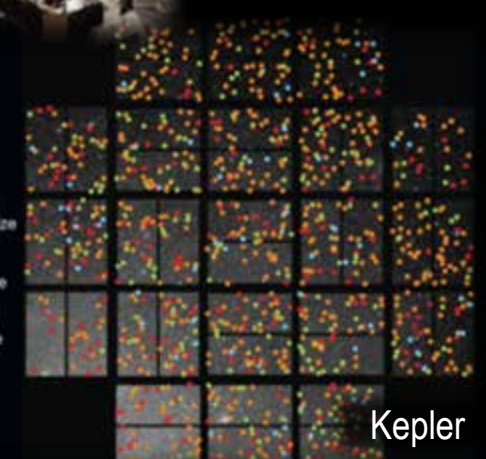
Field Studies in Antarctica



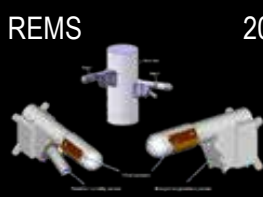
Kepler-37c, Mercury, Mars, Kepler-37c, Earth, Kepler-37d



- Earth-size
- Super-Earth size
1.25 - 2.0 Earth-size
- Neptune-size
2.0 - 6.0 Earth-size
- Giant-planet size
6.0 - 22 Earth-size



Kepler

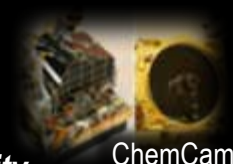


REMS

2007: CheMin installed in MSL



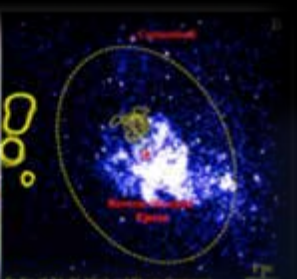
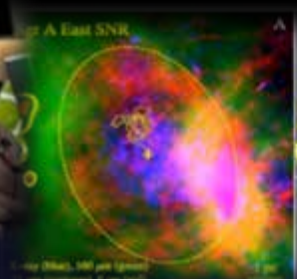
In Support of *Curiosity*



ChemCam



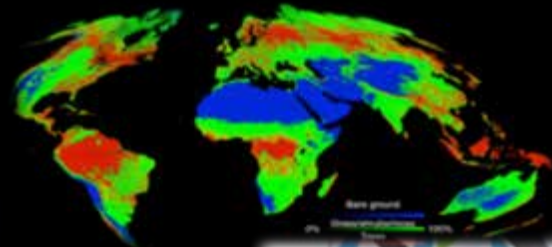
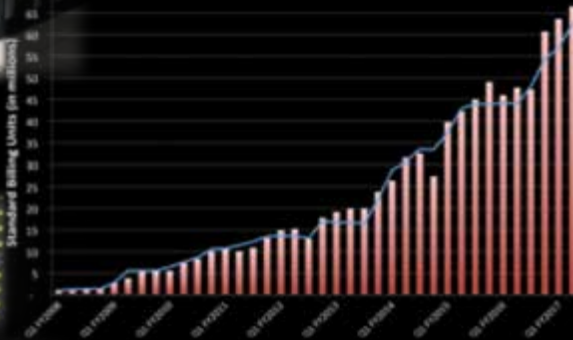
SAM



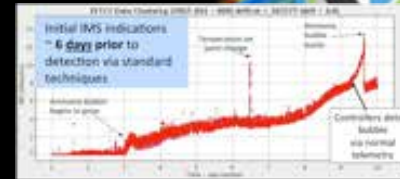
SOFIA

Advanced IT and Computing Systems

Supercomputing Systems



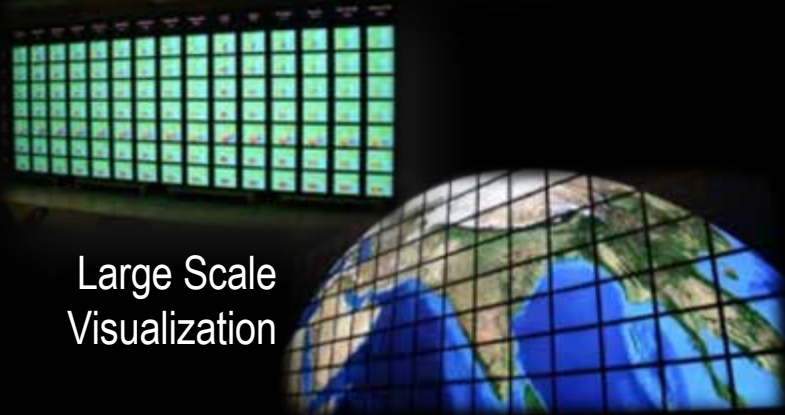
Big Data Analytics



NEX

Quantum Computing

Large Scale Visualization



Enterprise Managed Cloud Computing

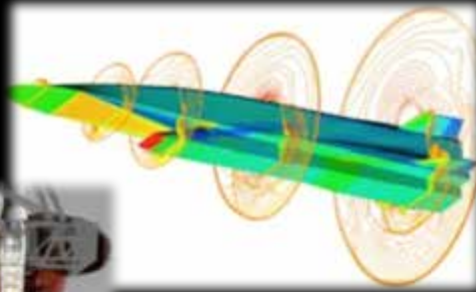
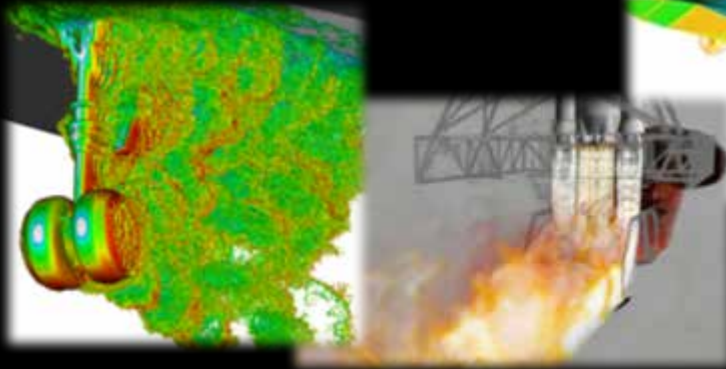


Disruptive Technologies

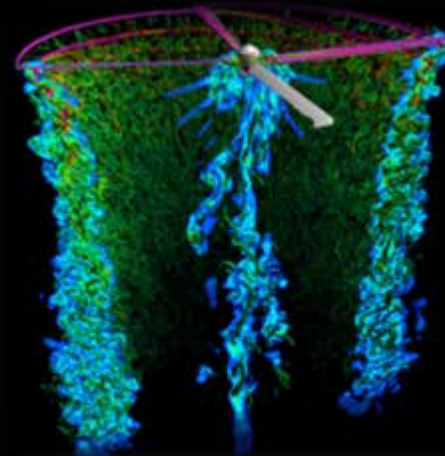


Modeling and Simulation

Advanced IT and Computing Systems



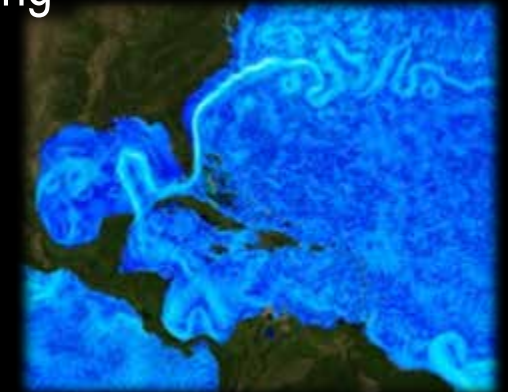
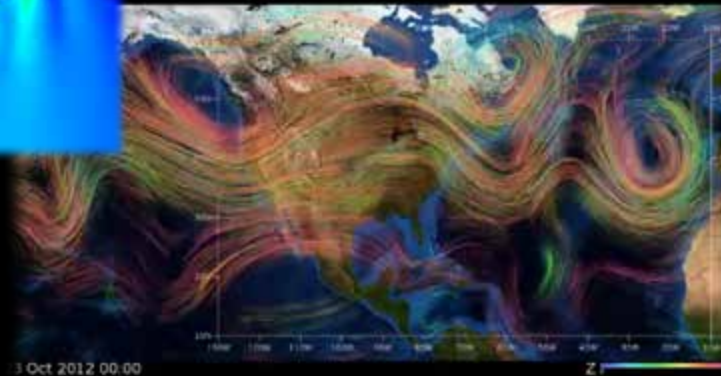
Capacity
Computing



Time Critical Computing

Capability
Computing

KEPLER

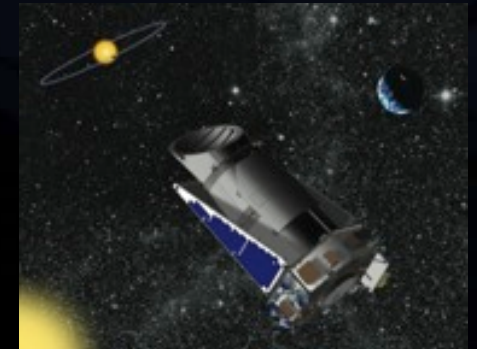




Need for Advanced Computing

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

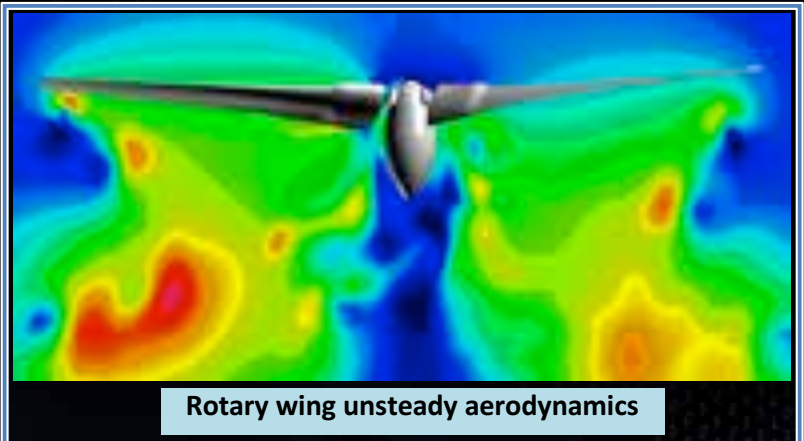
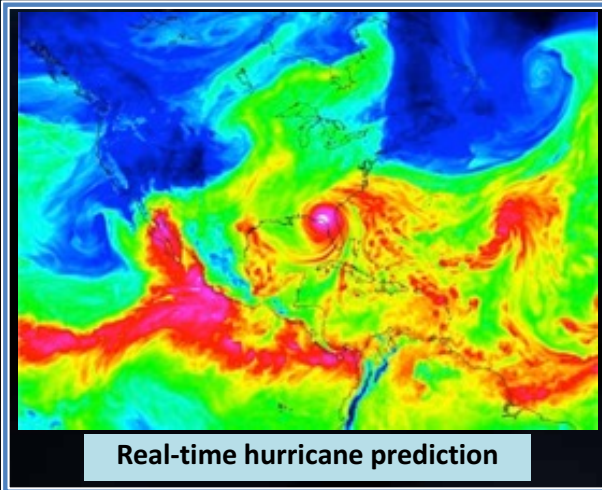
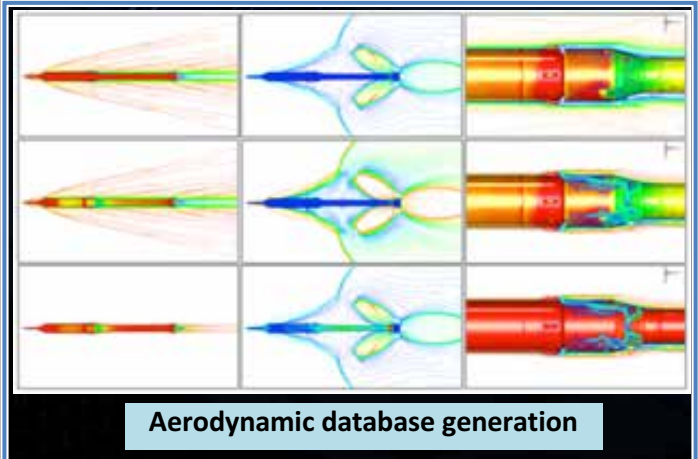
Advanced Computing Environment





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**)



Balanced HPC Environment



Computing Systems

- **Pleiades**: 246K-core SGI Altix ICE (now HPE) with 4 generations of Intel Xeon (64 nodes GPU-enhanced: Nvidia M2090, K40; 32 nodes have Phi 5110P); 938 TB RAM; 7.25 PF peak (#15 on TOP500, #10 on HPCG)
- **Electra**: 32K-core Altix ICE with Intel Broadwell; modular container; 147 TB RAM; 1.24 PF peak
- **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 (240M pixels)

Data Storage

- 49 PB of RAID over 7 Lustre filesystems
- 490 PB of tape archive

Networks

- InfiniBand interconnect for Pleiades 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 (16 Broadwell-based racks)
- External air fan cooling; switch to adiabatic evaporative cooling when needed
- PUE of 1.03 resulting in 93% power savings and 99.4% water use reduction over our traditional computer floor
- Pad has 2.5 MW of electrical power and can accommodate 2 modules
- In production use since Jan '17
- Second module being added with 4 E-Cells, bringing Electra to 4.78 PF peak

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



Prototype MSF hosting



Artist's rendering of future



Integrated Spiral Support Services

NASA Mission Challenges

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



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

Performance Optimization



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

Data Analysis and Visualization



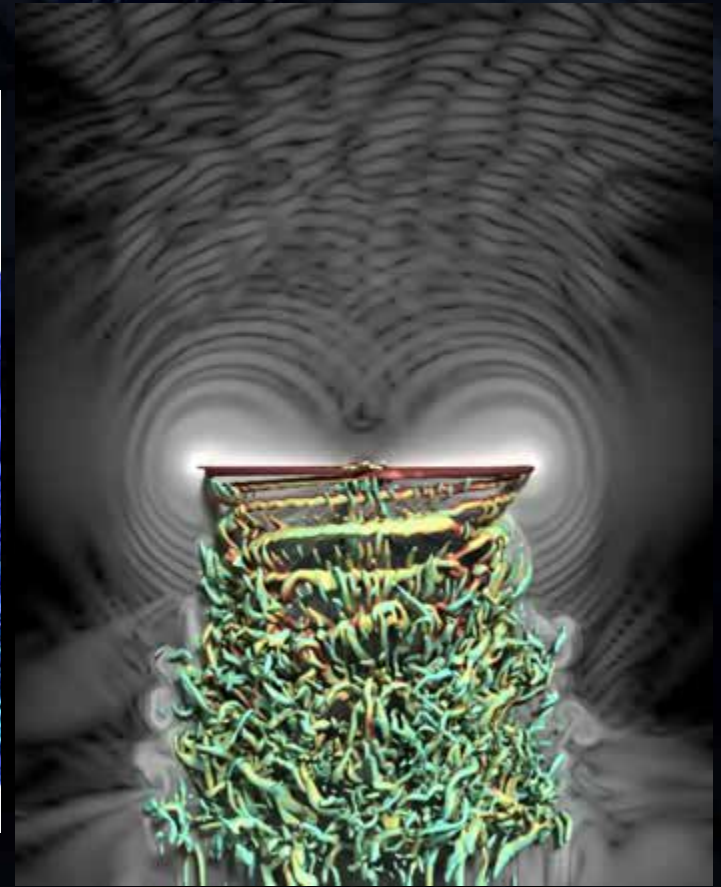
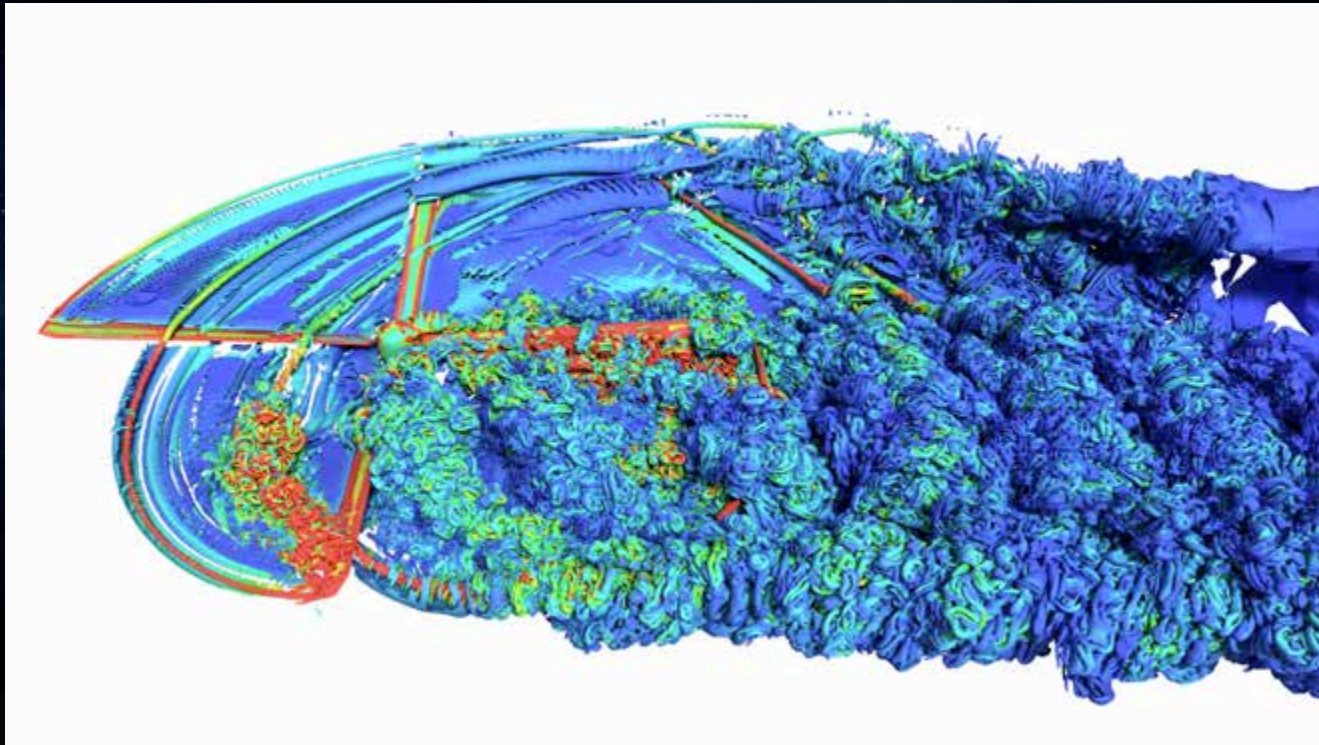
NAS visualization experts apply advanced data analysis and rendering techniques to help users explore and understand large, complex computational results

Computational Modeling, Simulation, and Analysis

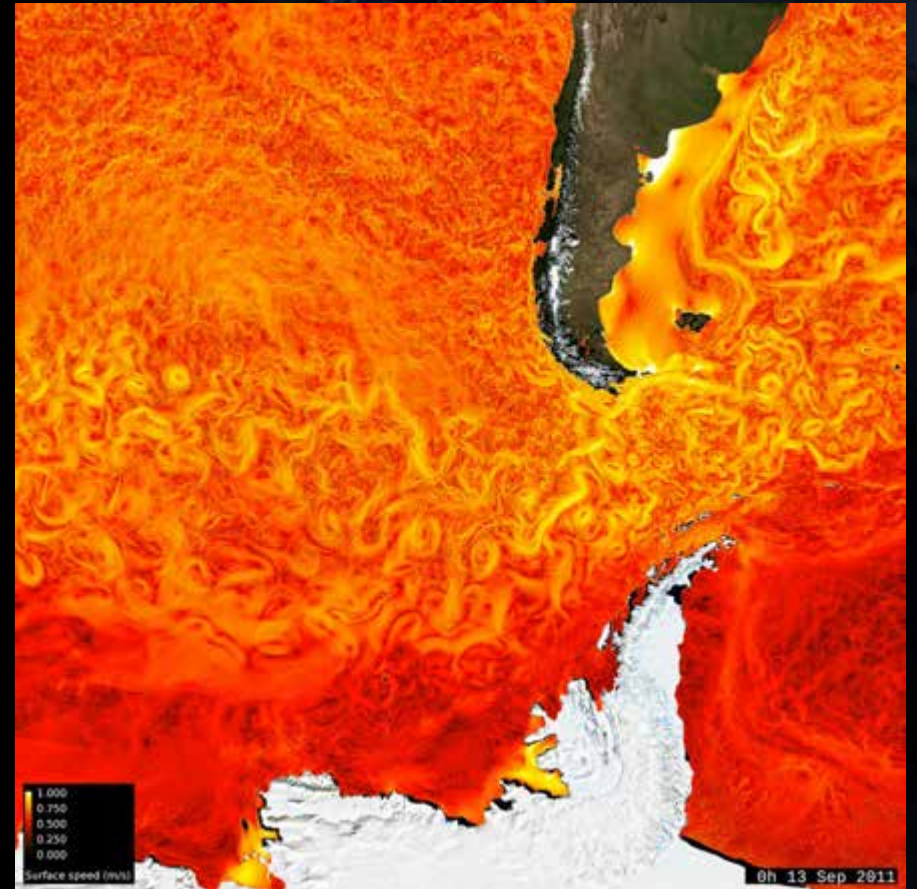
NAS support staff help users productively utilize HPC resources (hardware, software, networks, and storage) to meet NASA's needs



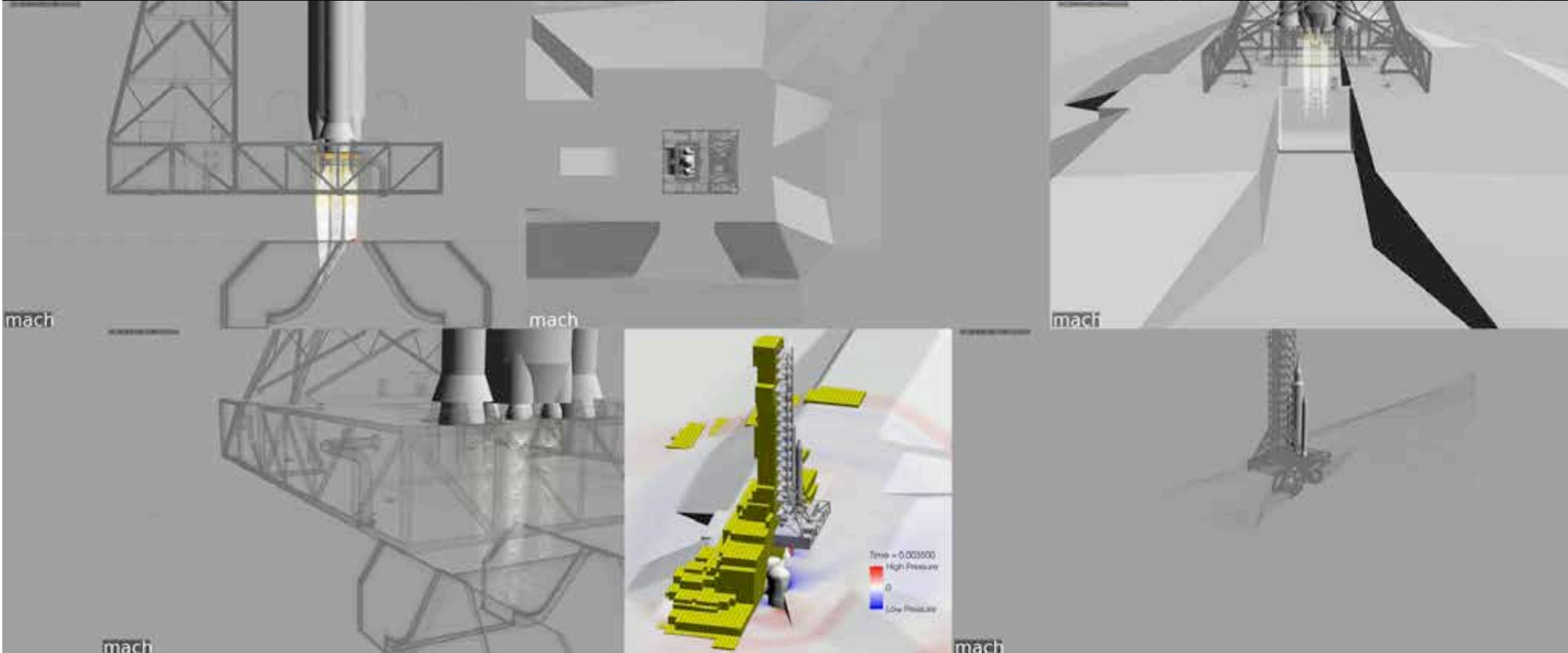
Helicopter Rotor Aerodynamics & Aeroacoustics



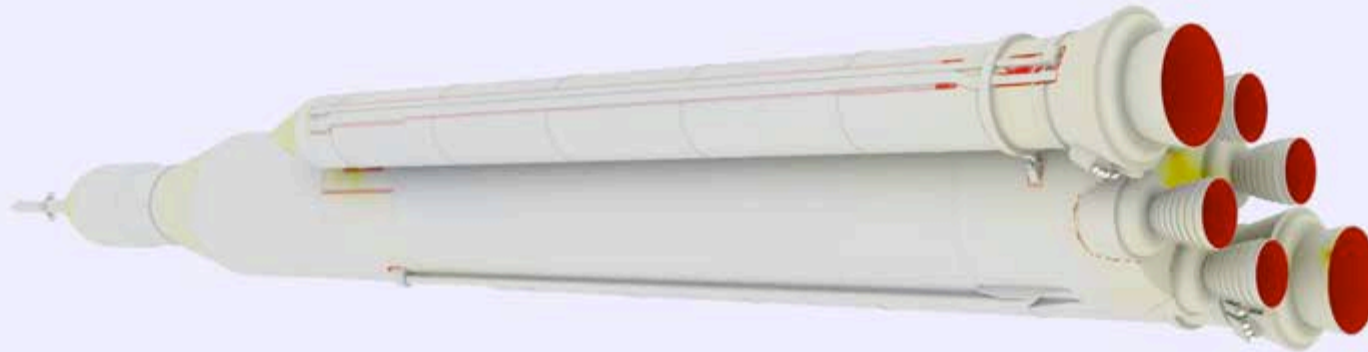
Time-Evolving Global State of Ocean



Launch Environment

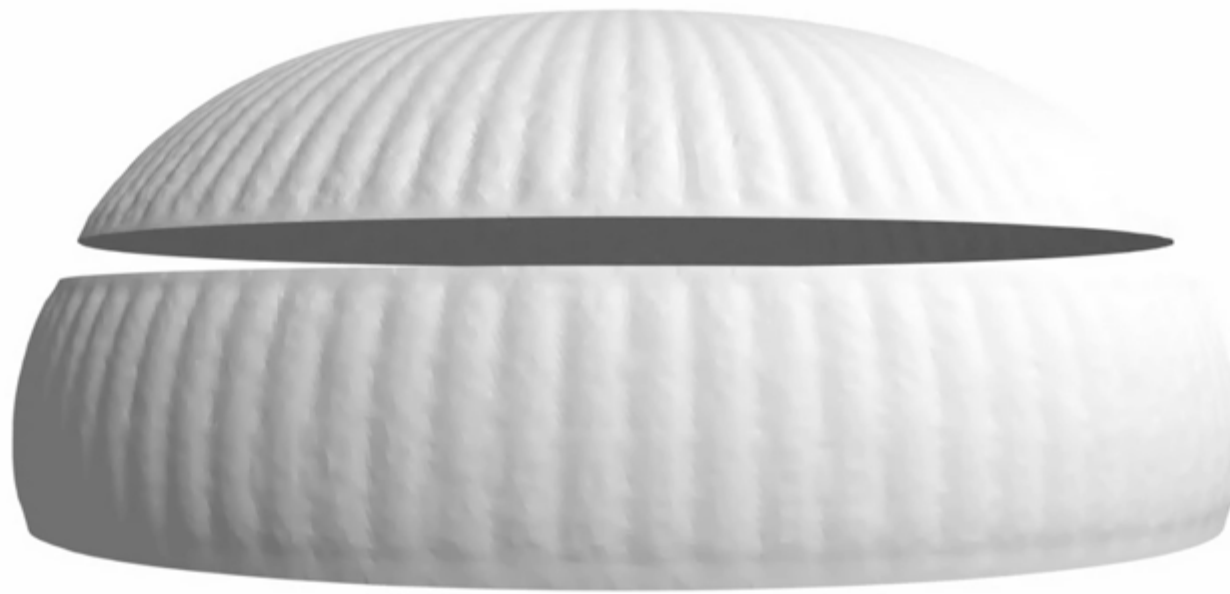


SRB separation from SLS



0' 0"

Low Density Supersonic Decelerator





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



SCALABLE COMPUTING

Heterogeneous and remote,

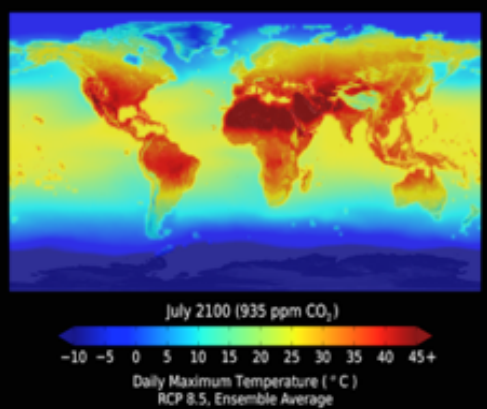


KNOWLEDGE

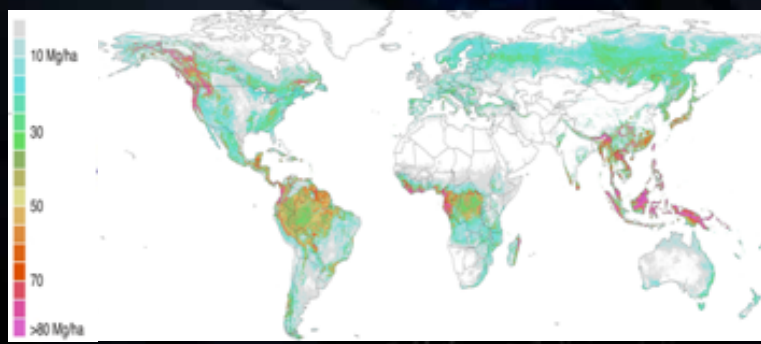
Workflows, virtual machine images



Science via NEX



High-resolution projections for climate impact studies



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



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



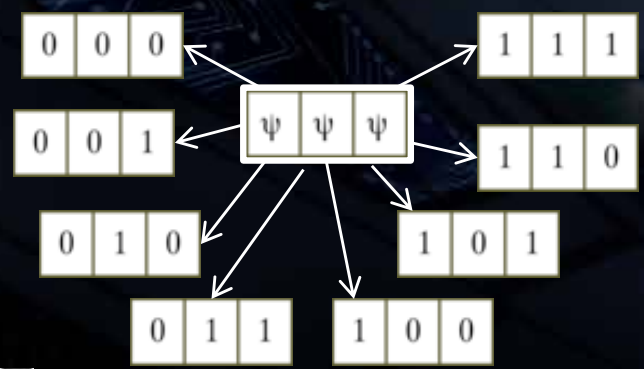
Sample publication using NEX environment: *Nature* 532.7599 (2016):

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

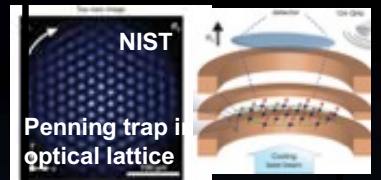
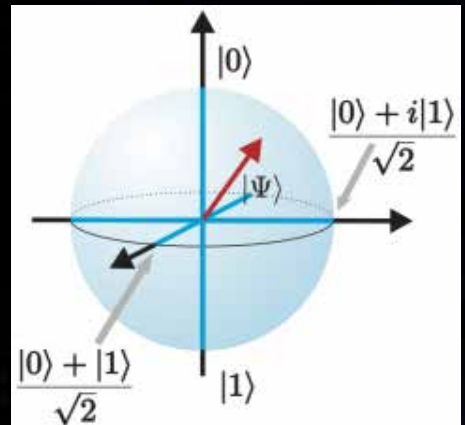
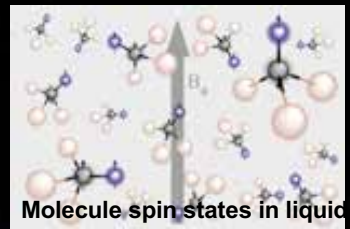
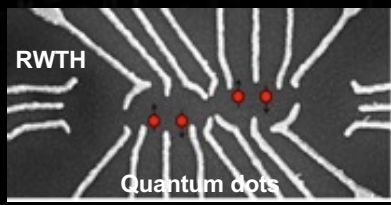
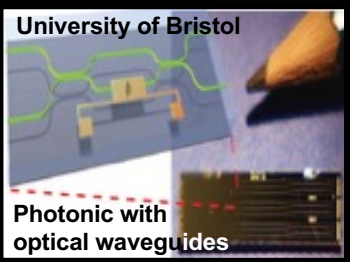


Quantum Computing 101

- 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

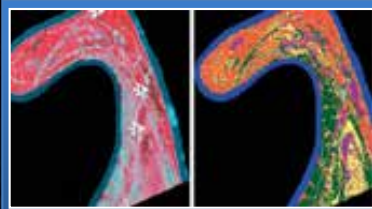
Nanoelectronics, NMR, Diamond Chips,

Quantum Computing for NASA Applications



Objective: Find “better” solution

- Faster
- More precise
- Not found by classical algorithm



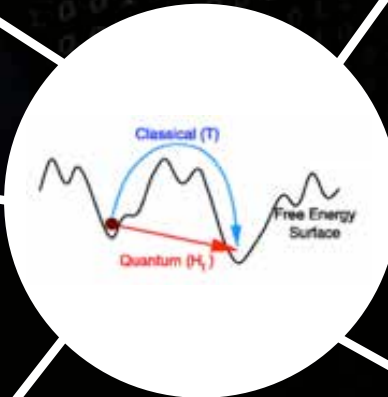
Data Analysis and Data Fusion



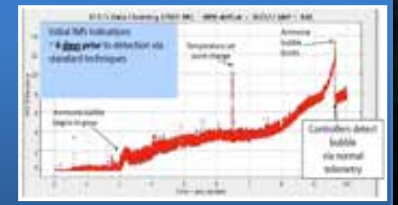
Air Traffic Management



Mission Planning, Scheduling, and Coordination



Anomaly Detection and Decision Making



V&V and Optimal Sensor Placement



Topologically-aware Parallel Computing



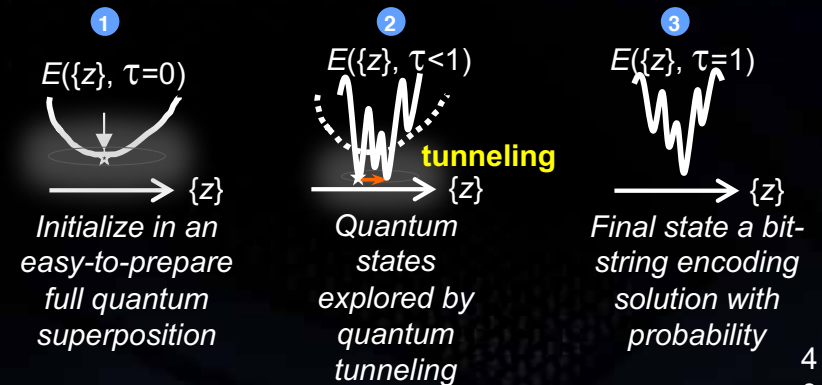
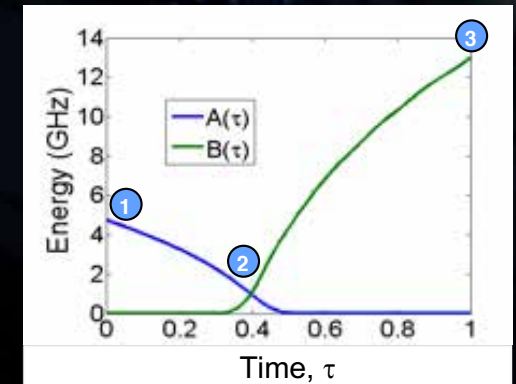
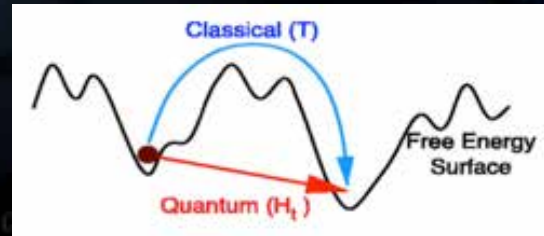
Common Feature: Intractable (NP-hard / NP-complete) problems!

Quantum Annealing

A physical technique to solve combinatorial optimization problems

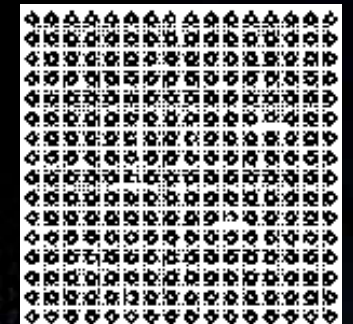
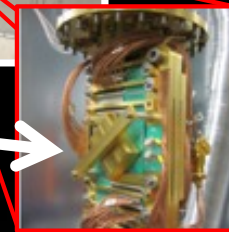
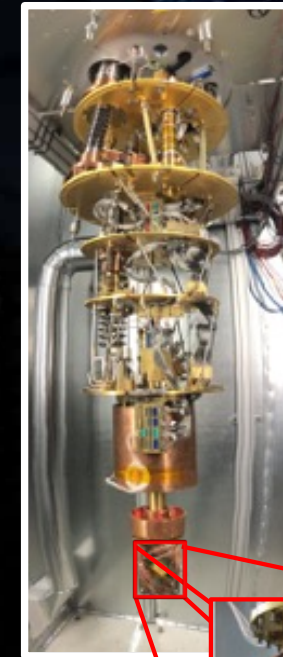
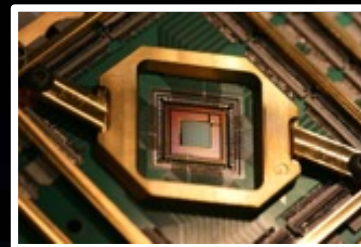
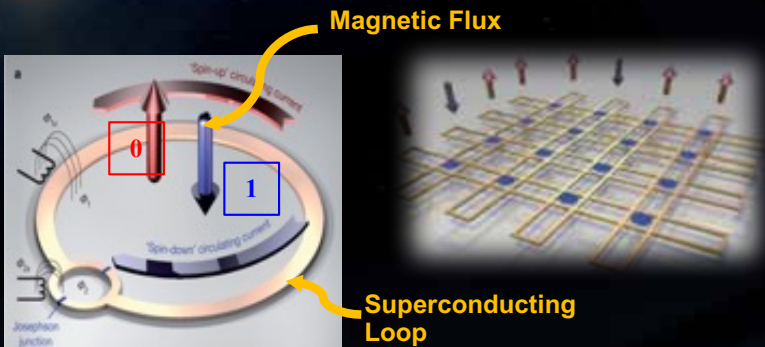
$$E(z_1, z_2, \dots, z_n) = \underbrace{\left(1 - \frac{t}{T}\right) H_0(\{z\})}_{A(t)} + \underbrace{\frac{t}{T} H_P(\{z\})}_{B(t)}$$

- 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



D-Wave System Hardware

- Collaboration with Google and USRA via Space Act Agreement 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 μ s
- Typical run of 10K anneals (incl. reset & readout takes ~4 sec)
- Uses 15 kW of electrical power



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.)

$\alpha_{ijk} z_i z_j z_k$

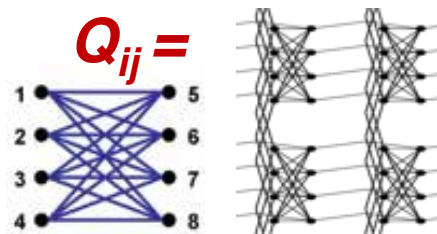
$\alpha_{ijk} y_{ij} z_k + \beta_{ijk} (3y_{ij} - 2z_i y_{ij} - 2z_j y_{ij} + z_i z_j)$

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

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

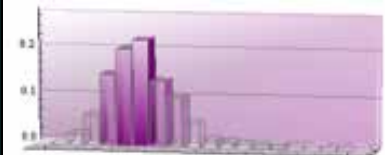


Embedding not needed for native Chimera problems

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

Probability



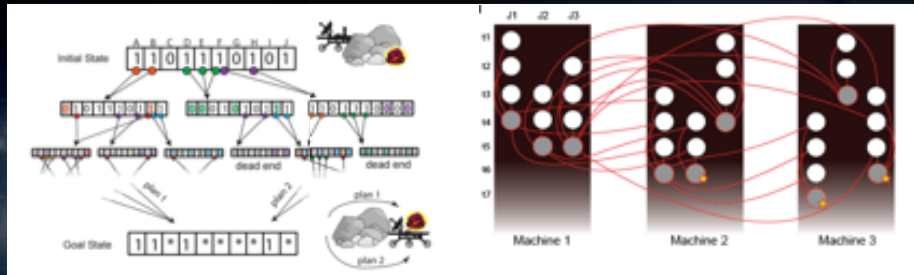
Solution's energy/cost

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

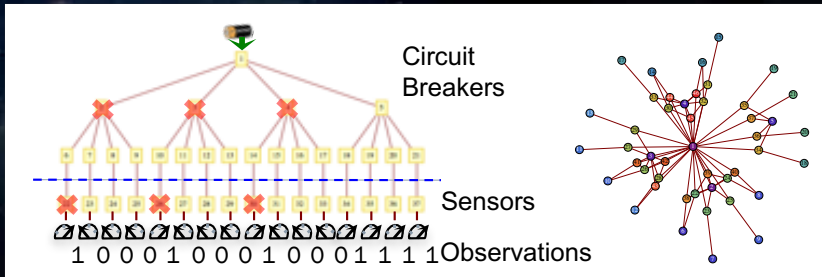
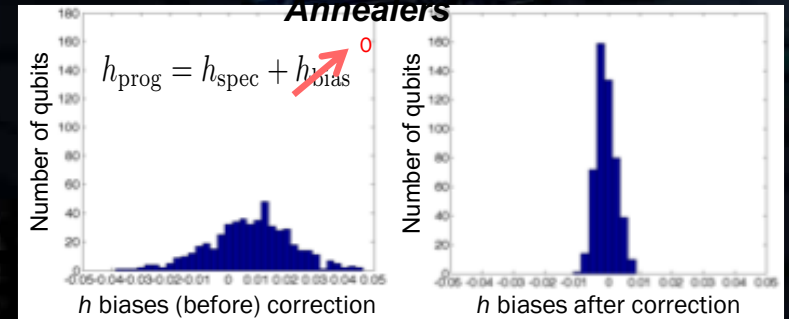
Current NASA Research in Quantum



Complex Planning and Scheduling

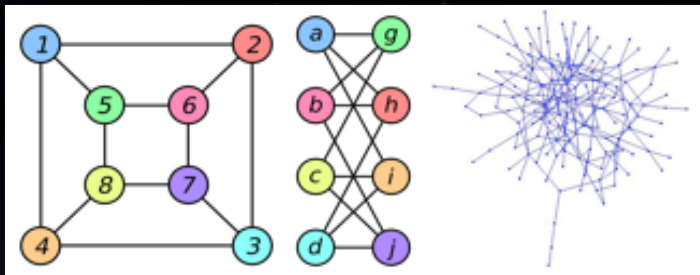
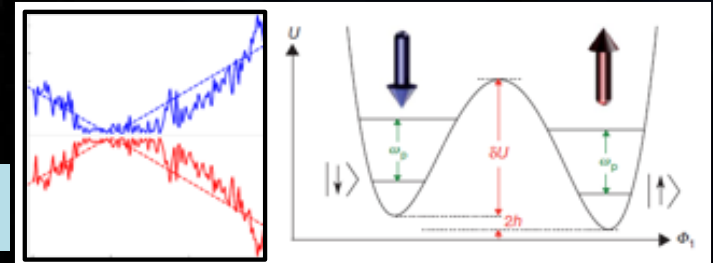


Calibration of Quantum Annealers



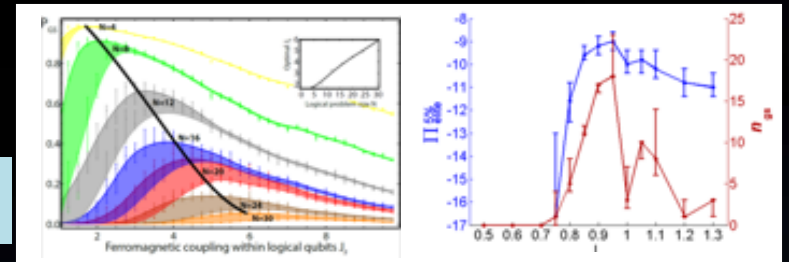
Graph-based Fault

Effect of Noise on Quantum



Graph Isomorphis

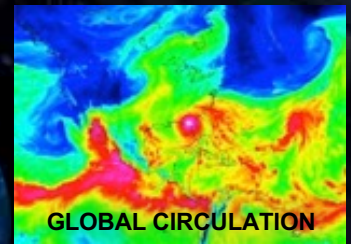
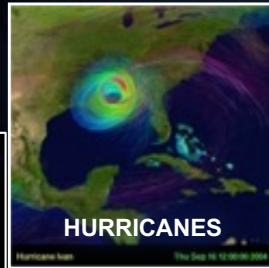
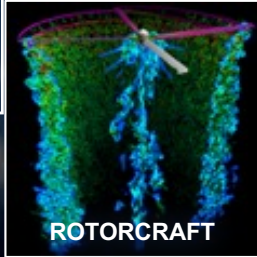
Optimal Embedding and Parameter





Advanced Computing Mission

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



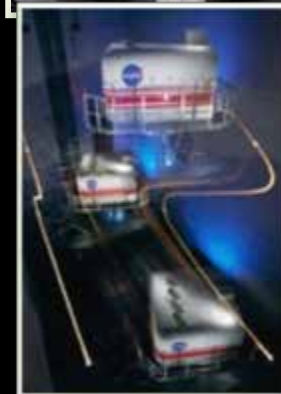
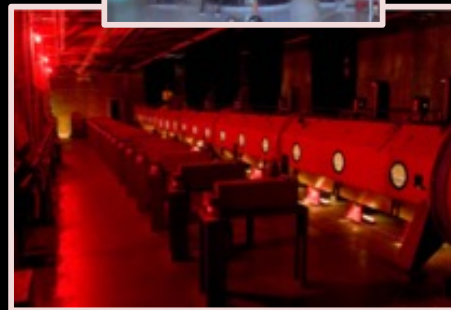
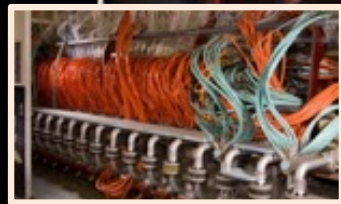
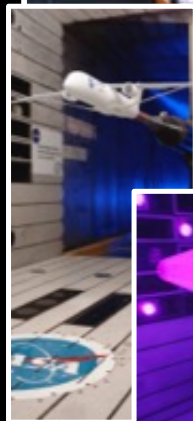
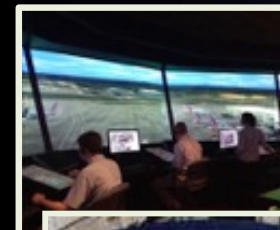
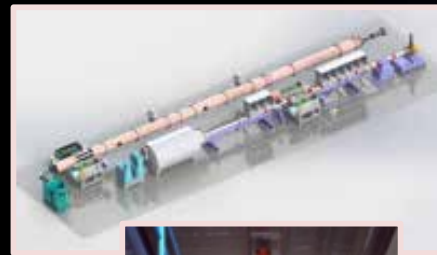
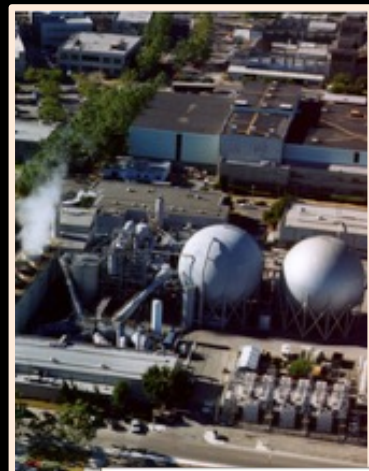
Effective, stable, production-level HPC environment



Advanced technologies to meet future goals



Major Research Facilities



Wind Tunnels

ARC Jet Complex

Range Complex

Simulators

Advanced Supercomputing

Partnerships at Ames

Commercial



Academia



Virtual Institutes



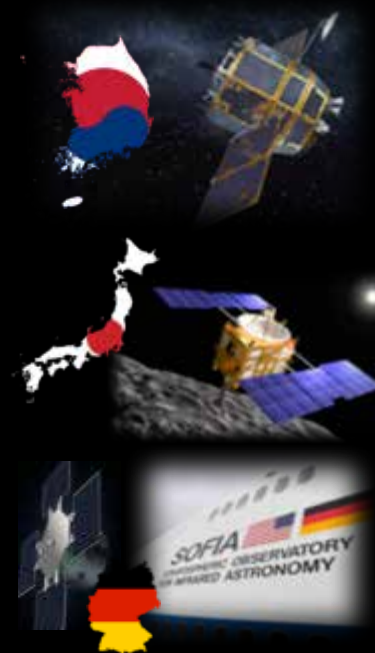
Inter-Agency



NASA Research Park



International





Questions?