Foreword

This Roadmap represents a long-term framework from which to establish and advocate the National Aeronautics and Space Administration (NASA) future research and technology-development program in fundamental physics. The Roadmap identifies two long-term goals of our research program (the “Quests”) and three sets of focused scientific investigations (the “Campaigns”), which comprise a scientifically rewarding, technologically challenging, flexible, and exciting program of fundamental physics research in space.

This document was prepared by a large team of scientists, technologists, and educators from the university community, industry, and government. Endorsement for the final product has been obtained from a broad spectrum of the physics community. The document will serve as a guide and an input to NASA strategic plans, which set priorities for flight experiments and technology developments, and which are updated every few years.

The charter for the Roadmap includes three primary elements:

- To promote a visionary and affordable mission and technology plan for performing groundbreaking research in fundamental physics in Earth-based and spaceborne laboratories in the 2000–2015 time frame.
- To include in this scientific pursuit a broad-based spectrum of stakeholders — scientists, technologists, and educators from the university community, industry, and government.
- To use the Science Plan developed in 1997 by the fundamental physics discipline working group as a guide in the Roadmap development.

The Roadmap development process began on 22 November 1997 with a meeting of the fundamental physics discipline working group, followed by JPL team meetings, a workshop on 20–22 March 1998, updates to the Roadmap based on recommendations from the workshop, and review and endorsement at a Principal Investigator meeting. Final updates to the Roadmap took place in fall 1998.

During preparation of this document, the scientific community believed that we should address the benefits that the space environment affords for all physics research without regard for which part of NASA is currently funding the activity. The Roadmap is focused mainly on the research program under development in the Microgravity Research Division of NASA (Code U) but also includes gravitational physics experiments under development by Code S. Research activities currently funded by Code S are explicitly labeled as such.

The Jet Propulsion Laboratory, California Institute of Technology, manages the Microgravity Fundamental Physics program for NASA.

Overview

Understanding the universe in all its vast and complex splendor seems a daunting and unimaginable task, yet human curiosity and wonder over centuries and civilizations have always led us to seek answers to some of the most compelling questions of all — How did the universe come to be? What is it made of? What forces rule its behavior? Why is it the way it is, and what will ultimately become of it?

In seeking such knowledge, scientists search for simple laws that not only describe the universe, but predict behavior within it, all the way from the smallest atom to the largest galaxies. Knowing basic laws is not enough, however, because simple rules do not necessarily produce simple outcomes. Just as an alphabet limited to 26 letters and a handful of grammatical rules can produce whole libraries of ideas, meanings, stories, and possibilities, fundamental physics laws give rise to complex tangles of phenomena in the universe. Understanding just how basic laws translate into the rich diversity we see in nature is therefore vital as well. That is why we have defined two **quests** for fundamental physics research —

- To discover and explore fundamental physical laws governing matter, space, and time.
- To discover and understand organizing principles of nature from which structure and complexity emerge.

The quests are our fundamental goals and the motivations behind our exploration. Each quest is driven to pursue a set of research destinations, answer a series of research questions, and yield the potential for societal benefits.

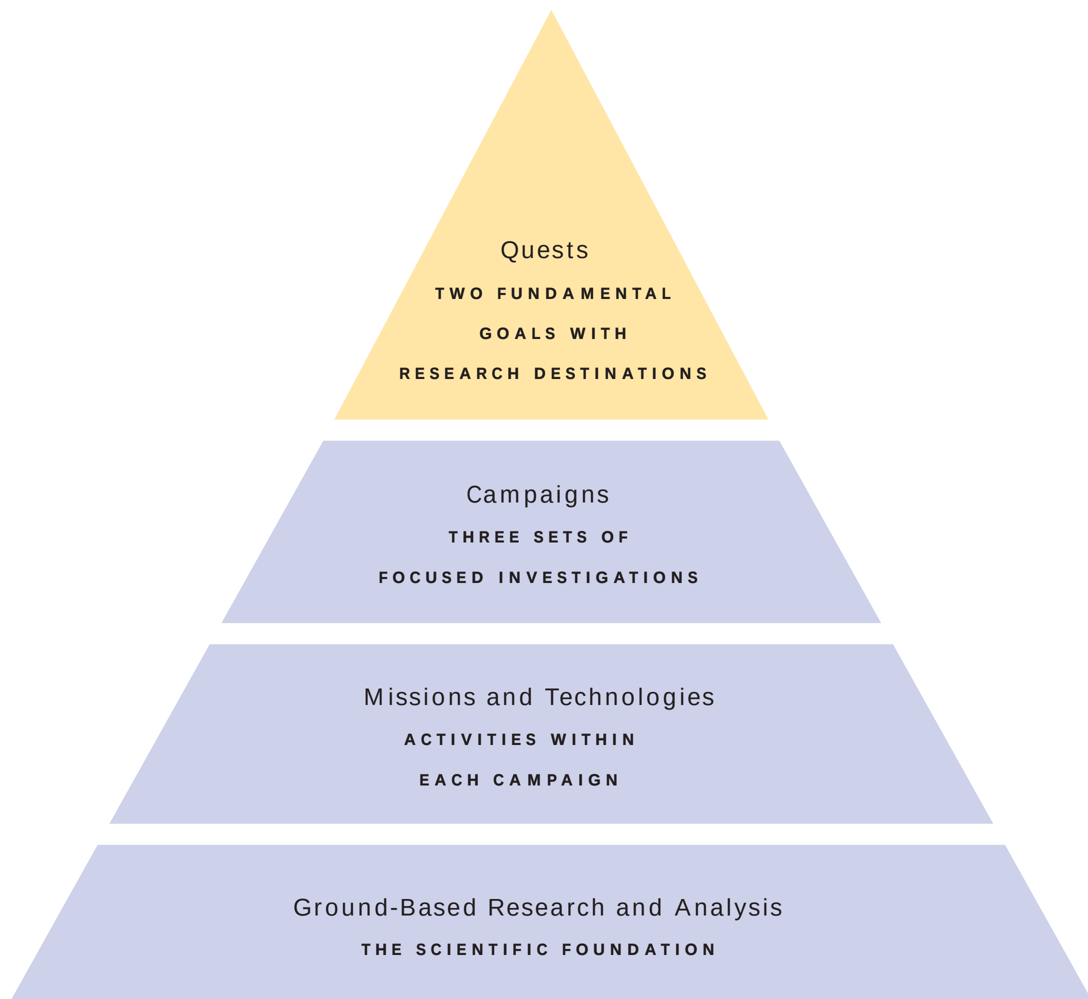
To satisfy these two quests, we have embarked on three **campaigns** that define what we will study, organized in sets of focused investigations. Each campaign contributes to both quests. There is significant scientific and technological overlap among the three campaigns, which are:

- Gravitational and relativistic physics
- Laser cooling and atomic physics
- Low-temperature and condensed-matter physics

Experiments in gravitational and relativistic physics will test current physical theories on how gravity influences the way the universe looks and behaves. These experiments will contribute to a deeper understanding of the beginning, development, and fate of the universe, and may even discover long-range forces beyond those currently known. Experiments in gravitational and relativistic physics might also lead to the long-sought unification of physical laws, revealing a powerful order at the heart of the universe.

Our ability to understand and to manipulate nature depends on the precision of our measurements. Experiments in laser cooling and atomic physics will provide unprecedented accuracy, setting new world standards for use in physical theories as well as in computing, navigation, and communications here on Earth. Cooling atoms with lasers away from the pull of Earth's gravity will also give scientists better opportunities to measure fundamental atomic forces and symmetries that may well hold clues to how things work at macroscopic levels as well.

Low-temperature and condensed-matter physics can reveal how organizing principles result from basic laws. Experiments will show how adding stress (e.g., heating or cooling) to uniform systems will produce variations in which identifiable patterns can emerge. Studying states of matter (e.g., solid, liquid, gas) and the transition from one phase to another, especially in elements like helium, will help us understand how similar changes might have occurred in the early universe, as well



Research and analysis form the foundation, missions and technologies implement the campaigns, and the campaigns — the sets of focused investigations — are designed to satisfy our two quests.

as improve such human activities as weather modeling, metallurgy, and oil field recoveries.

To implement the campaigns, we will conduct **missions** and develop **technologies** — these are what we will measure, how we will proceed, and what tools are required. Selections of these missions are done using a peer review process.

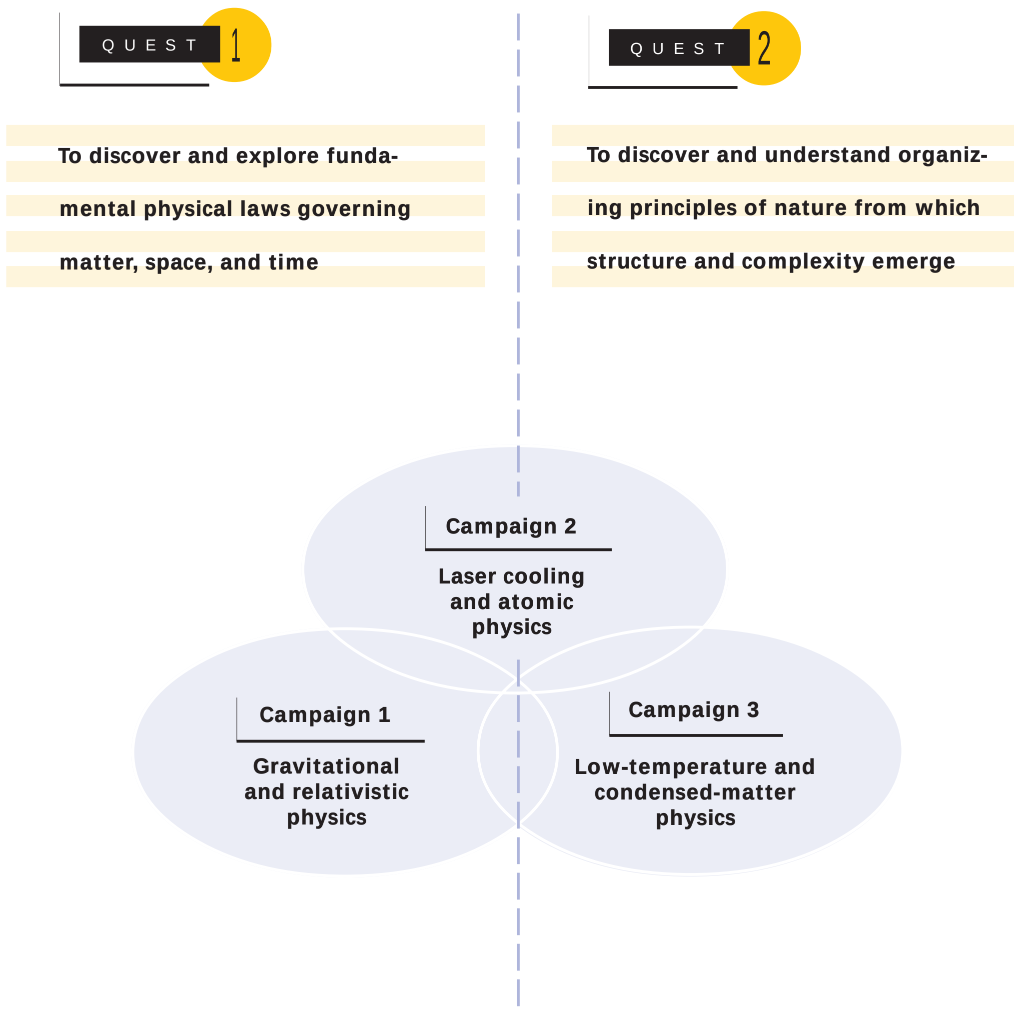
The Roadmap identifies about 20 example missions and experiments that can address campaign objectives during the years 2000–2015. The missions are technologically challenging, possess high science value, and are exciting and inspiring. The missions serve as the context for identifying key technology needs. The actual missions to be flown will be selected periodically as a part of the ongoing strategic/program planning process. Factors include:

- Microgravity benefit and rationale
- Programmatic considerations and budgets
- Scientific discoveries and analysis
- Technology development progress
- International opportunities

To sustain the missions and technologies, we perform ground-based **research and analysis** — using modeling, simulations, and laboratory demonstrations to understand what we have learned and to determine what we should measure next. These selections are done using a peer review process.

Campaigns

To accomplish our two quests, we have identified three campaigns, each determining what we will study in a set of focused investigations. Each campaign contributes to both quests, and significant scientific and technical overlap exists across all campaigns.



Missions

These example missions and experiments were selected to address campaign objectives during 2000–2015, and are the context for identifying key technology needs. In succeeding sections of this Roadmap, the technology needs are listed for each campaign as Key Capability Requirements. For all campaigns, technology needs include remote teleoperations, advanced detectors, autonomous “smart” control software, and lightweight electronics.

Campaign 1 — Gravitational and Relativistic Physics

- Satellite Test of the Equivalence Principle (STEP)
- Gravity Probe-B (GP-B) (Code S)
- Superconducting Microwave Oscillator (SUMO)
- Gravitational Wave Missions (Code S and ESA)
- Spacetime Mission (STM)
- Laser Interplanetary Ranging Experiment (LIRE)
- Alpha Magnetic Spectrometer (AMS) (NASA/DOE)

Campaign 2 — Laser Cooling and Atomic Physics

- Laser-Cooled Clock Experiments (LACE)
- Electron Dipole Moment Experiment (EDM-X)
- Bose–Einstein Condensation (BEC)
- Space Atom Laser (SAL)
- Space Matter-Wave Gyroscope (SMW-G)

Campaign 3 — Low-Temperature and Condensed-Matter Physics

- Critical Dynamics in Microgravity Experiment (DYNAMX)
- Microgravity Scaling Theory Experiment (MISTE)
- Superfluid Universality Experiment (SUE)
- Experiments Along Coexistence Near Tricriticality (EXACT)
- Boundary Effects on the Superfluid Transition (BEST)
- Superfluid Hydrodynamics Experiment (SHE)
- Kinetics of the Superfluid Helium Phase Transition (KISHT)