Lecture 1

Optical systems for space-based scientific remote sensing

University of Arizona

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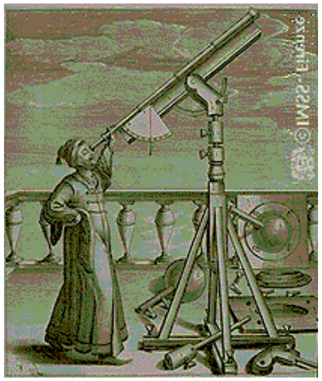
Who am I?

- PhD in Optical Science, College of Optical Sciences, University of Arizona, Tucson 1976
- 12 years at Kitt Peak National Observatory
- 34 years at JPL building instruments and developing optics technology
  - Developed space telescopes and instruments for astrophysics, earth and planetary remote sensing
  - Managed section of ~ 100 engineers for 12 years: optics technology and Flight Optical Systems for remote sensing: WF/PC2, Galileo and Cassini Imaging spectrometers & JPL Technologist for advanced imaging systems for Dod
  - NSF: Advanced Technology & Instruments Program Manager
  - NASA: Chief technologist of the NASA Exoplanet Program
- Teach the Optical Engineering class at CALTECH ('82-current)
- Just finished a book: <u>Basic Optics for the Astronomical Sciences</u>

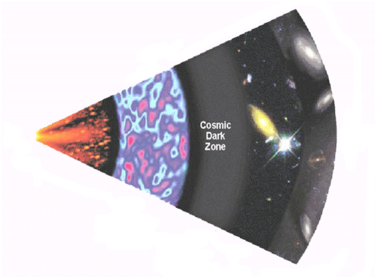
Tuesday, January 22, 2012



- The scientific method [Renaissance Europe]
- What can we measure?
- Analysis tools
- Optical system engineering
- How space optics differ from ground-based optics
- Projects move through time in three dimensions (cost, schedule, performance)

Thursday, January 24, 2013

- The NASA process
  - Technology
  - Mission development
  - Flight hardware approval & build
- Overview of large ground based telescopes
- Requirements development
  - Science measurements, technology risk map science into realized engineering
- Telescope system architectures
  - Filled, segmented, sparse, interferometers



Tuesday January 29, 2013

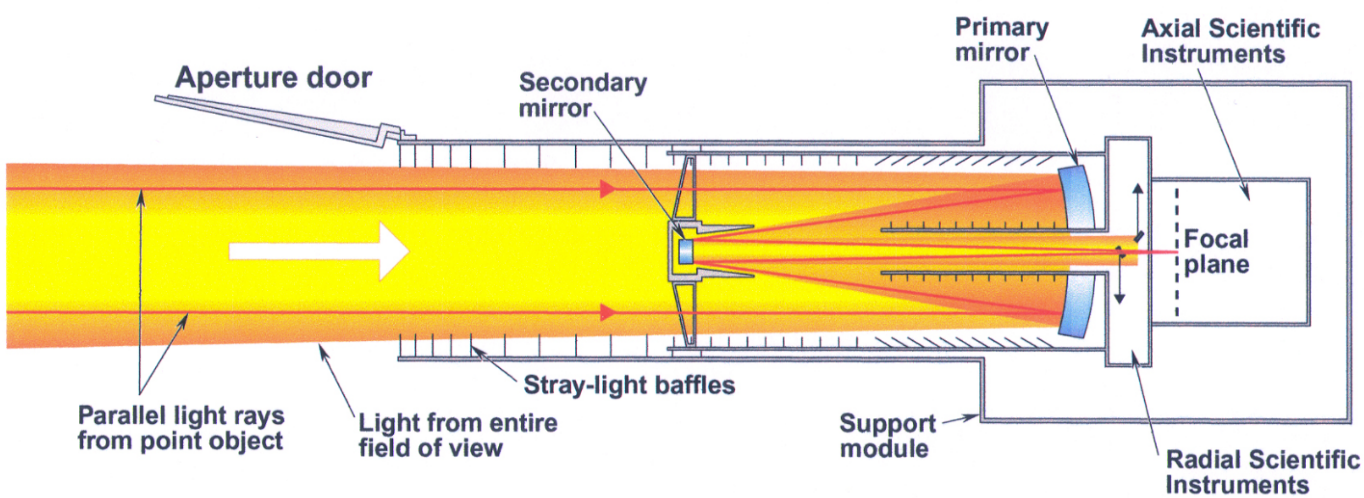
- How to build space telescopes and instruments?
- The work breakdown structure (WBS)
- Deliverables & milestones
- Technology development
  - Mission specific
  - Science measurement enabling
- Your design of space telescopes –In addition to optics
  - Radiation, electrostatics, thermal, launch vibration, pointing & control, scattered light (coronagraphs)
- Science in the noise
- The *DECADE* report

Thursday January 31, 2013

Case study of flight optical systems

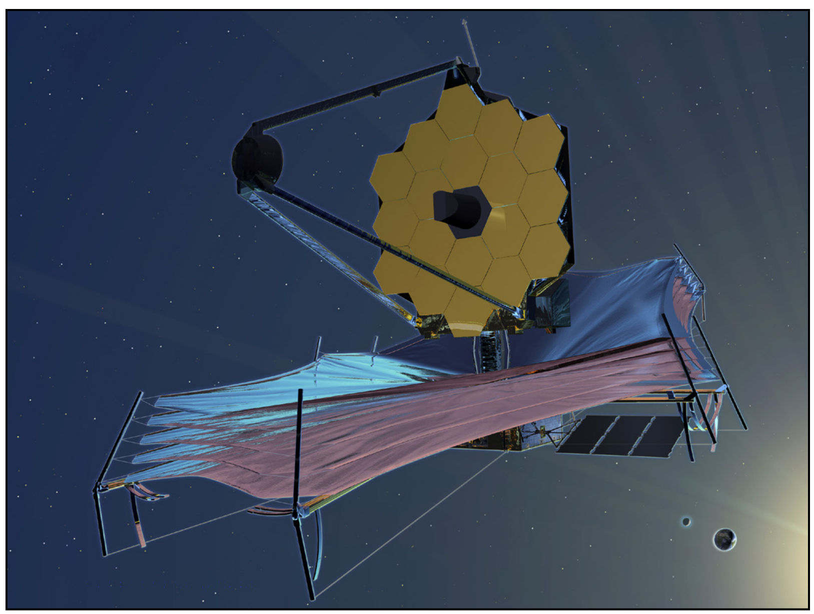
Figure D-2. RvNC interferogram of the primary mirror, taken in May 1981.

- Hubble space telescope 1990-today (23 years)
  - Telescope and instrument system overview
  - Fabrication of the optics
  - Search for the optical prescription
  - Implementing the fix

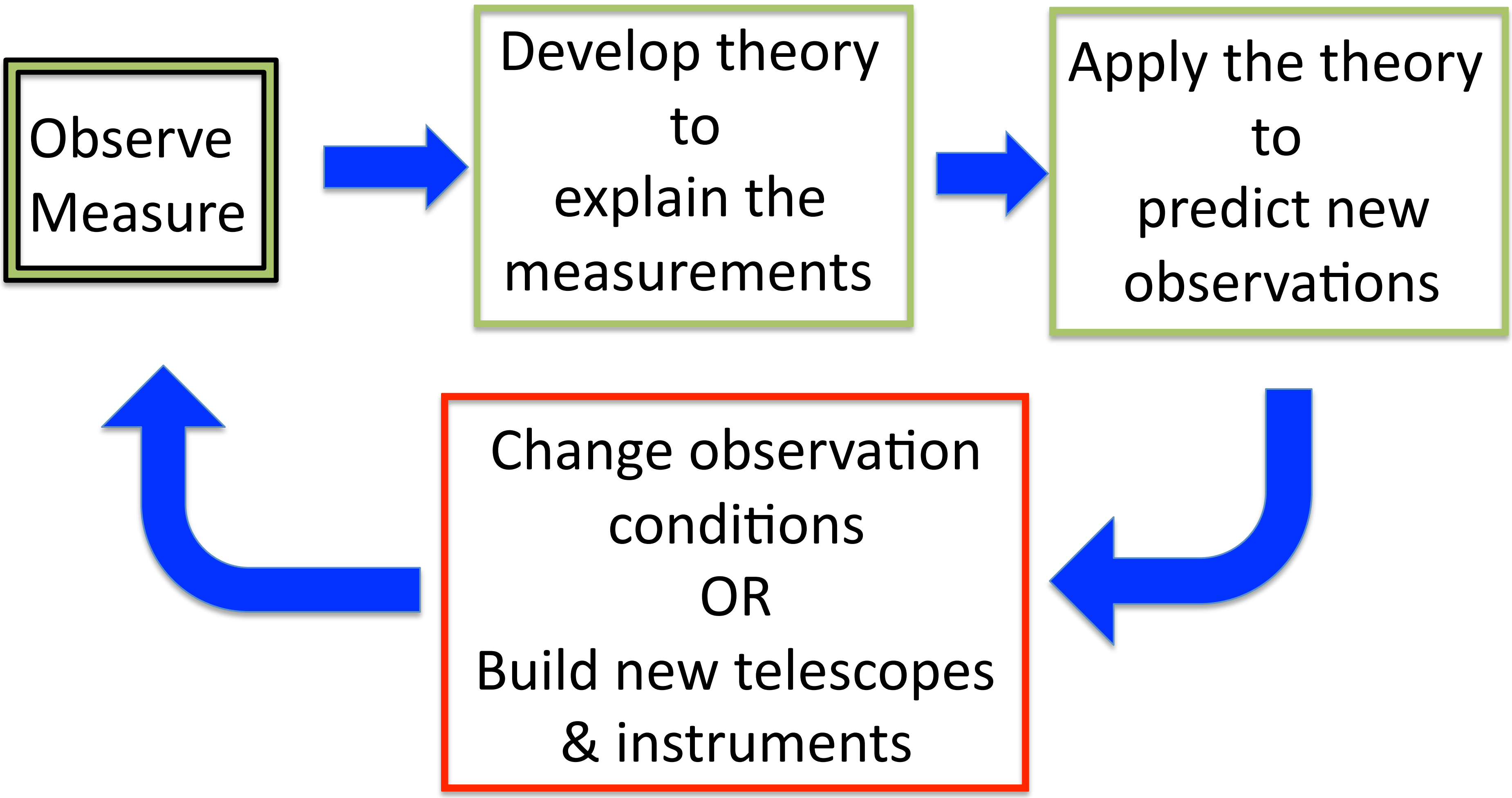


Today

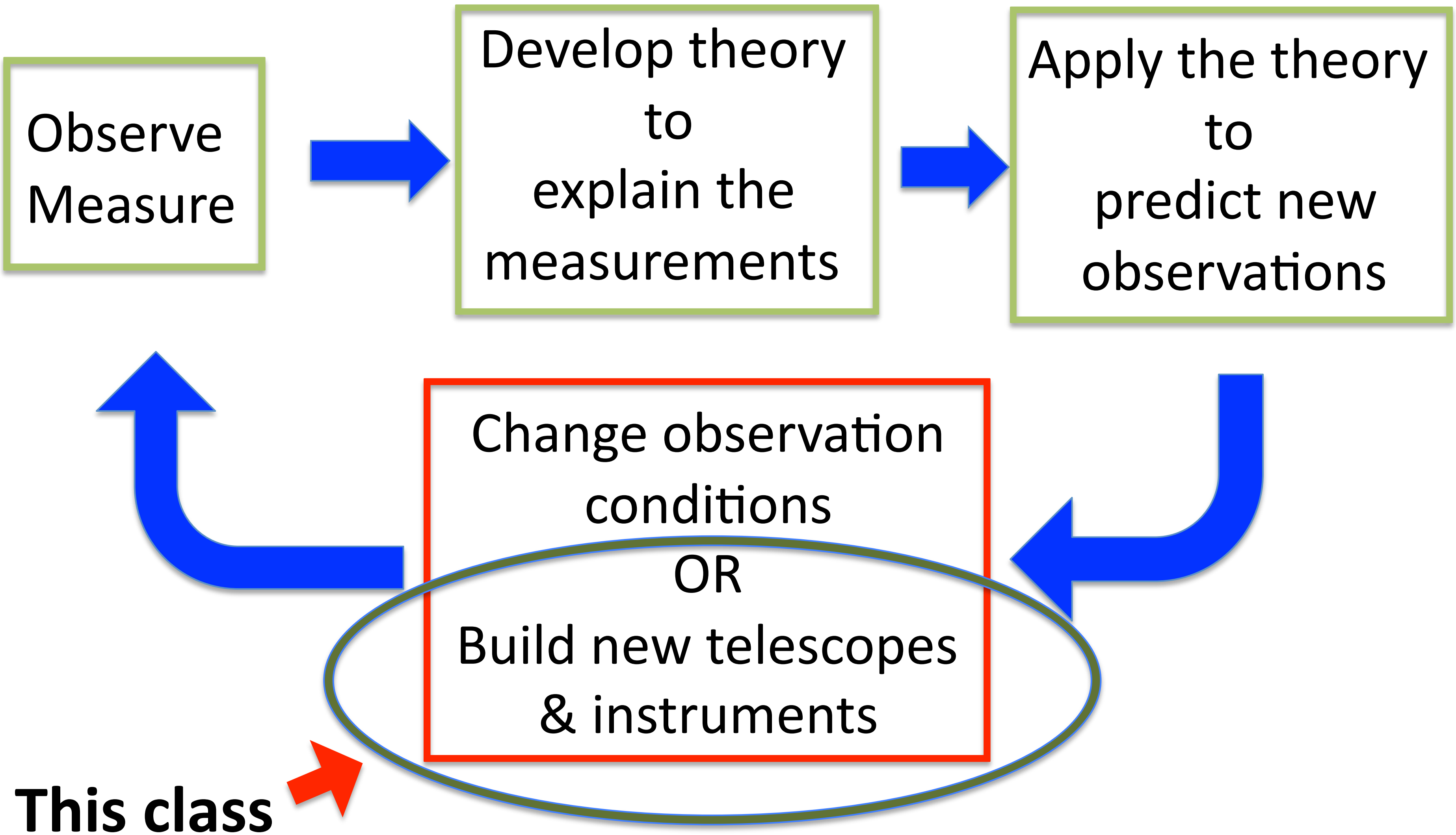
- The scientific method
- What is a space optical system?
- Why build a new telescope/instrument
- Optics for astronomy



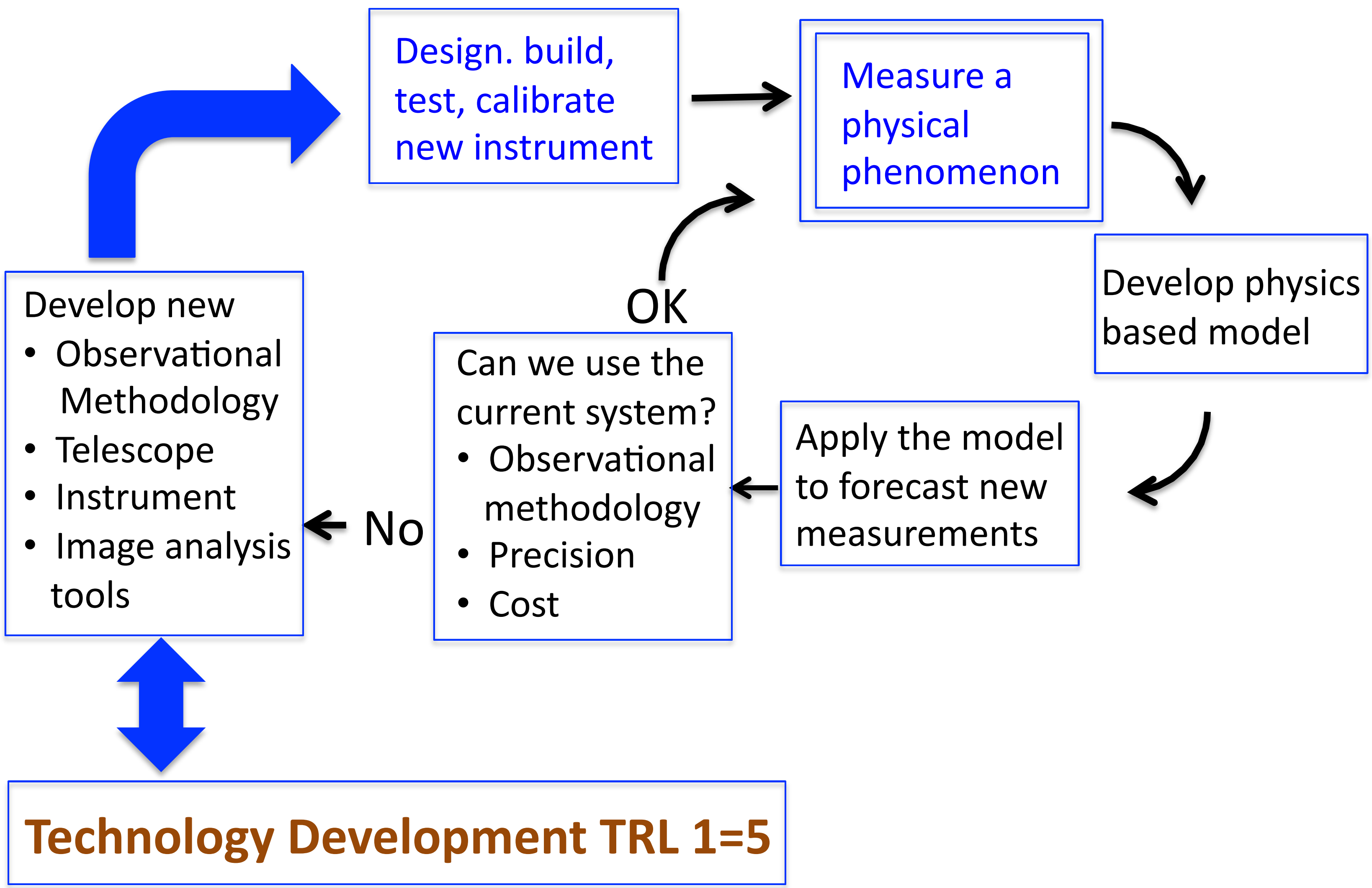
The scientific method



The scientific method

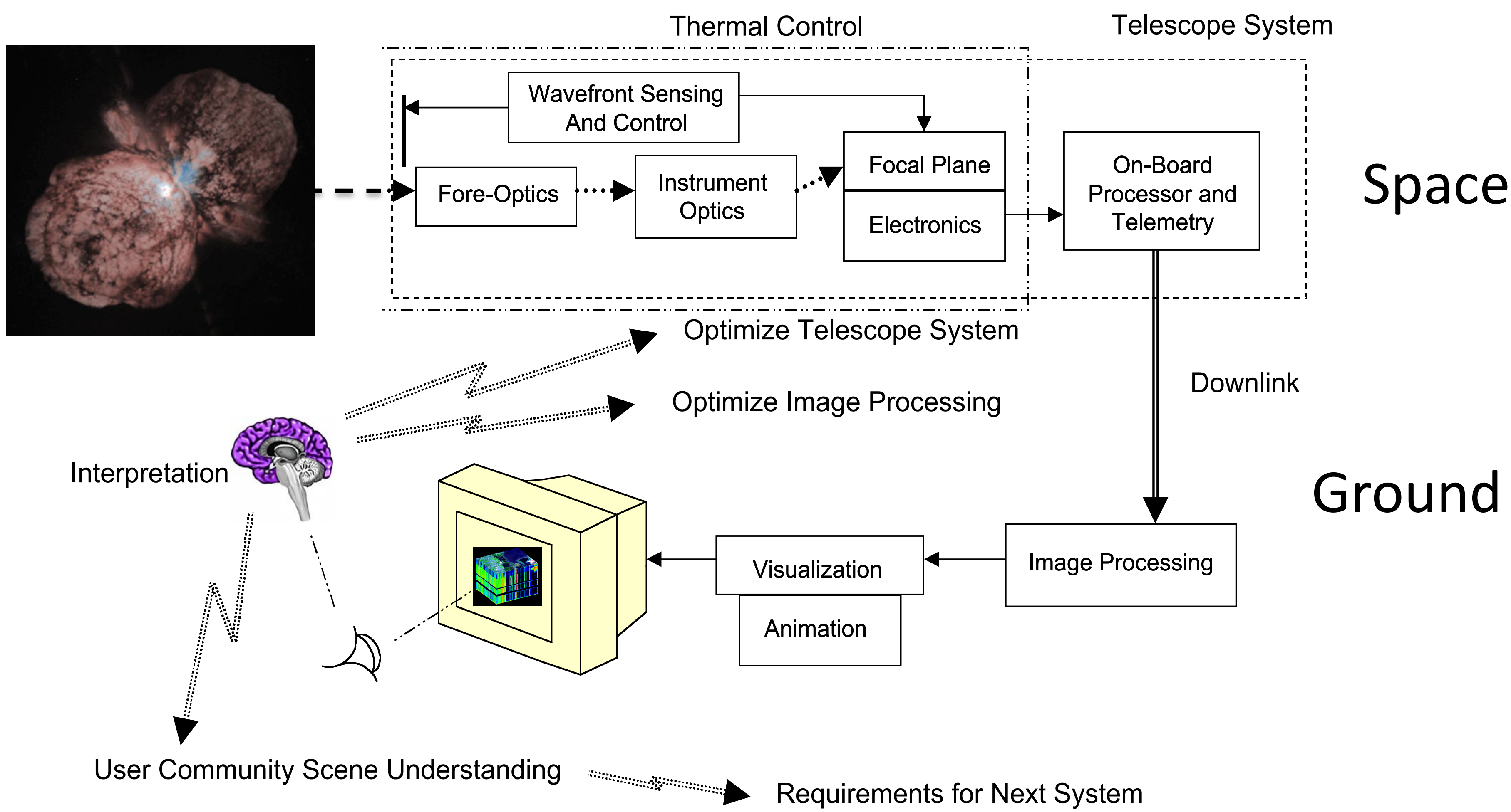


The scientific method
“engineering meets science”



Space Telescope Optical System:

The optical system scientist works from the source through the interpretation



Applications for space optics

- Earth remote sensing
  - Watershed management
  - Land management & urban planning
  - Weather models & CO_2 “global warming”
- Planetary science
  - Geology (Mars, Venus, satellites/asteroids)
  - Atmospheric science (Mars, Venus, Four giant planets)
- Astrophysics
  - Cosmology
  - Stars and stellar systems
  - ExoPlanets: radial velocity spectrometers & precision radiometers & coronagraphs
- Heliospheric science

Optics roles for remote sensing

- Optical science
  - Study of the generation, propagation, imaging, measurement and analysis of electromagnetic radiation from ~200 nm to ~50 micron wavelength
- Optical engineering
  - Understand requirements, identify system approach, design telescopes & instruments, specify, test components integrate, align, test and calibrate an optical system to a fixed cost.
- Optics Technology
  - Technology development to enable new scientific or engineering measurements
    - Devices (detectors, A/O, wavefront sensors, optical metrology)

Where is the science? What can we measure?

- Intensity as a function of
  - A single point $I = f(x_0, y_0)$
  - An image $I = f(x,y)$
  - Wavelength $I = f(x,y;\lambda)$ or $I = f(x,y;\sigma)$
  - Time $I = f(x,y;\lambda;t)$
  - Polarization $I = f\{I,Q,U,V;x,y;\lambda;t\}$
  - The total number of variables is:

    $7+n$ where n is the number of spectral channels

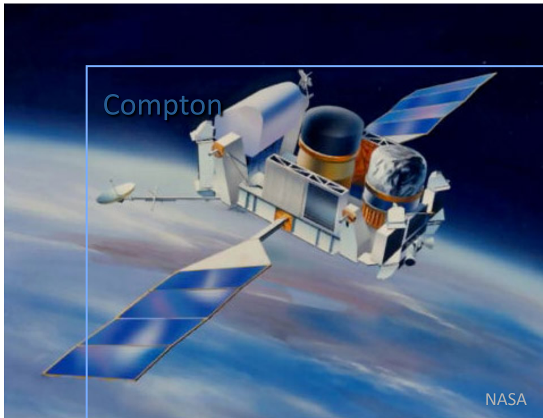
This information needs to fit onto a 2d spatial + time detector => the instrument!

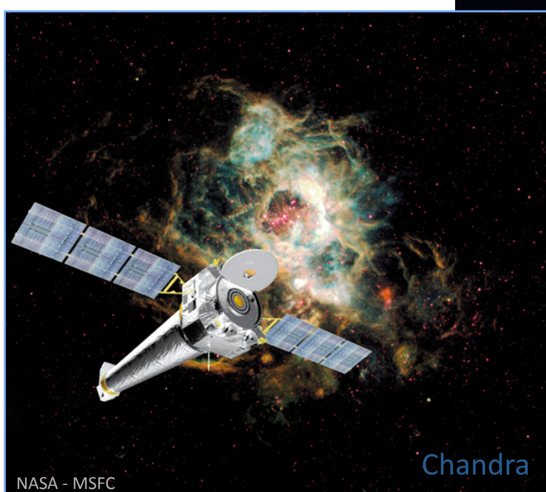
Optics for space vs. ground

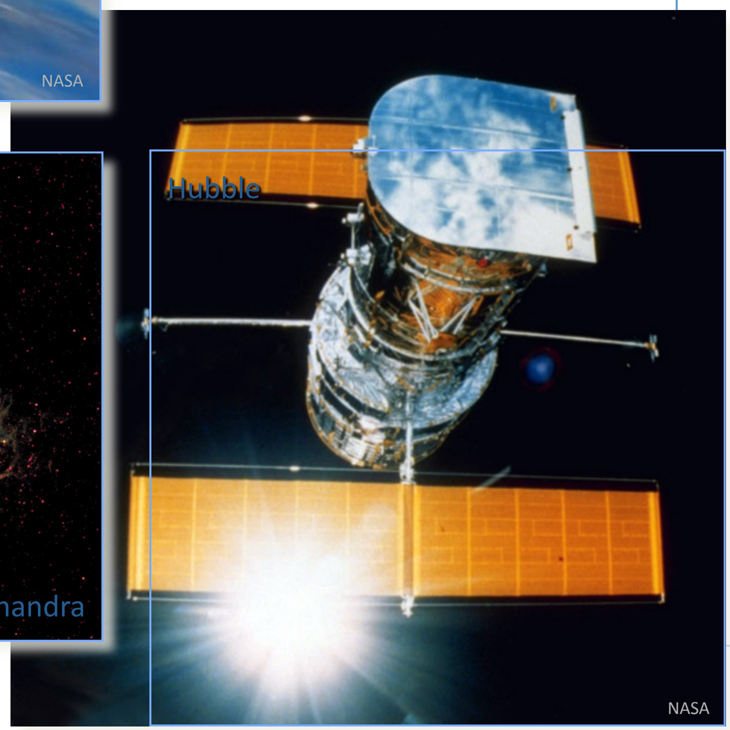
	Ground Observatories	**Space Observatories**
Wavelength coverage	400 nm to 50 μm with absorption windows	γ-ray to long-wave radio waves
Scattered light for coronagraphs	Atmosphere limited to $>10^{-8}$	Unknown, limited by technology; probably $<10^{-15}$ contrast
Angular resolution	2×10^{-4} arcsec (500-m @ 500 nm)	Unknown; may be $<10^{-7}$ arcsec (10-km baseline)
Thermal environment	~230 to 310 K	Extreme: ~20 K with sunshade
Gravity	1-g; The vector changes during the night.	0-g
Accessibility	Easy-to-fix hardware	Telescope inaccessible after launch
Operation cost	Keck ~24 M/year	~10 times as much

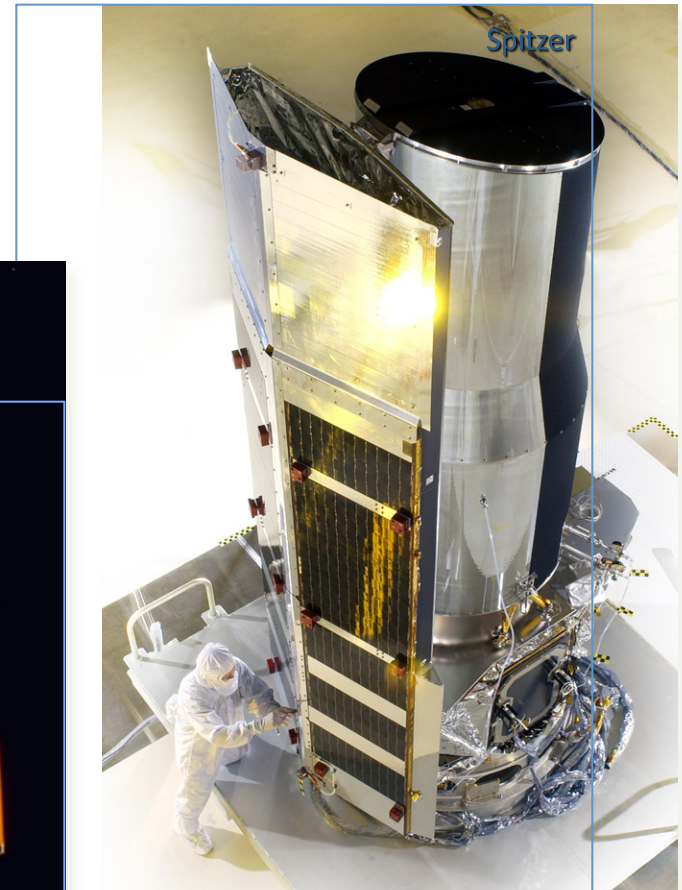
The Great Observatories

- Compton
- Hubble
- Spitzer
- Chandra









Tools for space optics, engineering and technology

- Geometrical ray trace (Light pencil - normal to a geometric wave)
  - Image location, size, orientation and brightness
- Scalar diffraction (Light is a wave)
  - Image quality – diffraction spectrometers
- Vector diffraction (Light is a vector wave)
  - Image intensity and quality – diffraction spectrometers
- Radiometry (Power transfer - Watts)
  - Image intensity and background noise.
- Statistical theory (Light is represented by random fluctuations)
  - Detection process, image quality, physical properties of the source, interferometry, polarization, spectroscopy
- Quantum theory (Light is quantized, Lasers)
  - Detection process, Image intensity, image quality and physical properties of the source/intervening matter.

Tools used to model optical systems

Tools	Image Location	Image Size	Image Orientation	Image Intensity	Image Quality	Physical Properties of the Source
Ray Trace	Yes	Yes	Yes	Yes	No	No
Scalar Diffraction	No	No	No	No	Yes	No
Vector Diffraction	No	No	No	Yes	Yes	Yes
Radiometry	No	No	No	Yes	Yes	Yes
Statistical Theory	No	No	No	Yes	Yes	Yes
Quantum Theory	No	No	No	Yes	Yes	Yes

A new telescope/instrument system is designed and built to

- Provide new scientific data
- Open a new temporal frequency window
  - Kepler (occultation science)
- Open a new spatial frequency window
  - Interferometry
  - wide FOV
- Open a new spectral window
- Collect more photons
  - Measure more accurately (characterize after discovery)
  - Peer deeper into the cosmos
- Reduce cost

How do we build a large, complicated system?

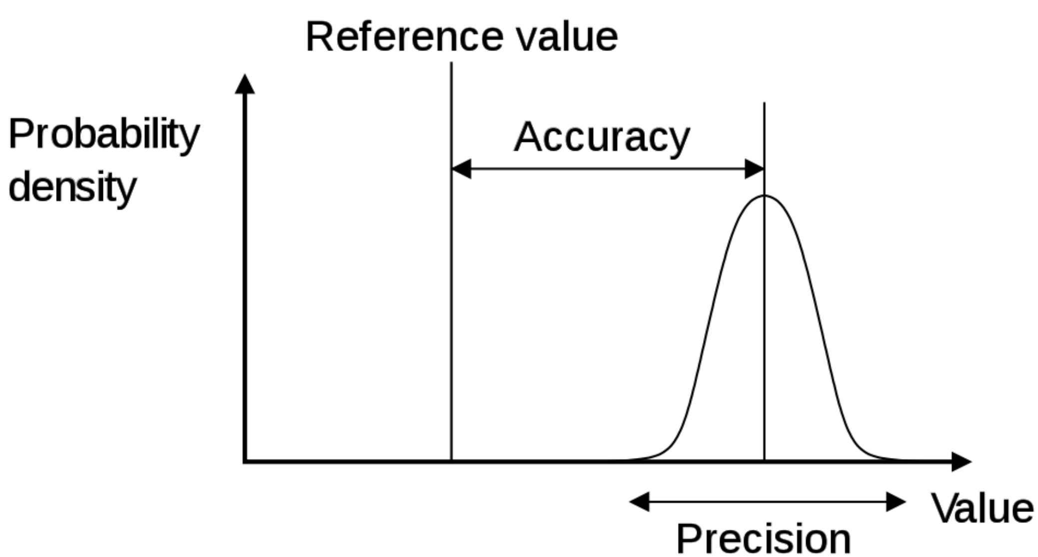
- Understand the job
- Develop functional requirements
  - *Measure polarization as a function of wavelength on stars to V = 5*
- Define and develop new technology
  - *Invent low noise spectra-polarimeter*
- Develop engineering requirements
  - *Telescope aperture 3.6 meter, Cassegrain,* $A\Omega$ ….
- Divide the problem into manageable parts
  - *Consistent with talents and skills available*
  - *Consistent with available facilities & equipment*

System development process

- Science
  - “Determine the scope of global warming”
- Science measurement objectives
  - “Measure the annual abundance of CO_2 to an accuracy of 0.1%”
- Functional requirements (constraints on the instrument & system)
  - “the needed signal to noise is 60:1, global measurements, season…”
- Create a System architecture
  - “Telescope with spectrometer, low earth orbit, down link capacity……. ”
- Develop a point design
  - “Grating or Fourier transform spectrometer, spectral resolution, $A\Omega$..??”
- Model source, telescope/instrument and data processing to demonstrate the science measurement objectives have been met.
- Is new technology needed?

Example of a science measurement requirement

- Mission studies
  - Science measurement requirement
    - *Measure the wavelength position of a line in the spectrum of a 26^{th} magnitude star with 10% accuracy at the 95% confidence level*

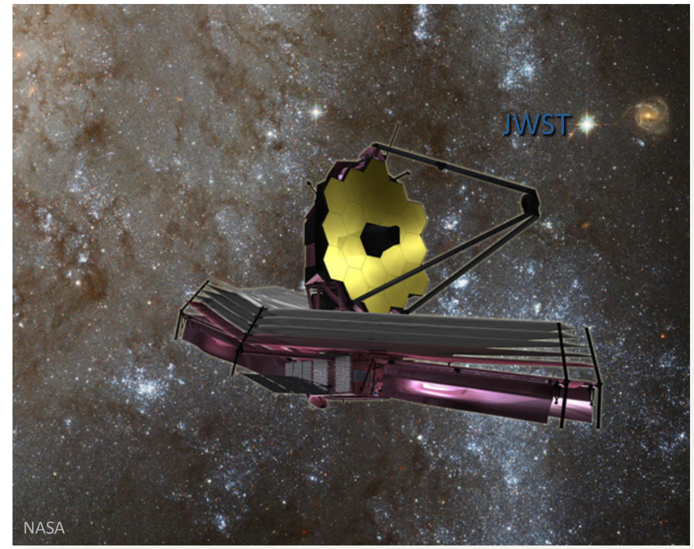


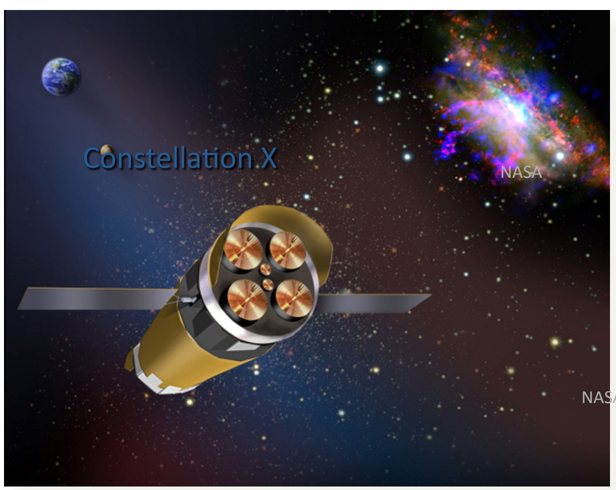
How do we build a large, complicated system?

- Create a work-breakdown structure (WBS)
- Assign personnel to jobs in the WBS you know they can do
- Prepare proposal and work plan with schedule and cost
- Be funded
- Re-plan the job to meet funding constraints
- Accept the requirements and start work

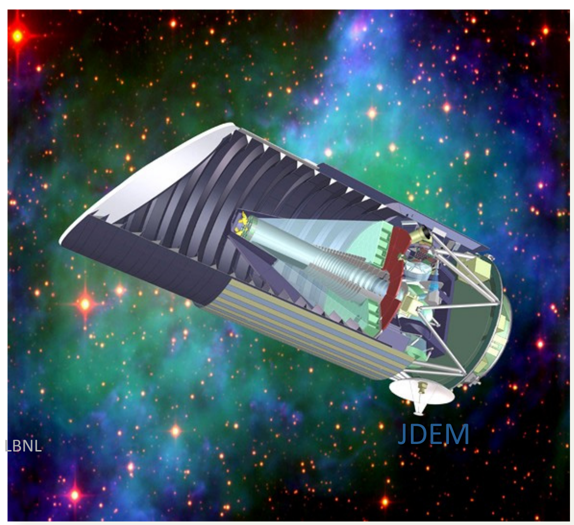
New NASA Missions

- Constellation X
- James Webb Space Telescope
- LISA – Gravity Wave Experiment
- Joint Dark Energy Mission (JDEM)
  - WFIRST

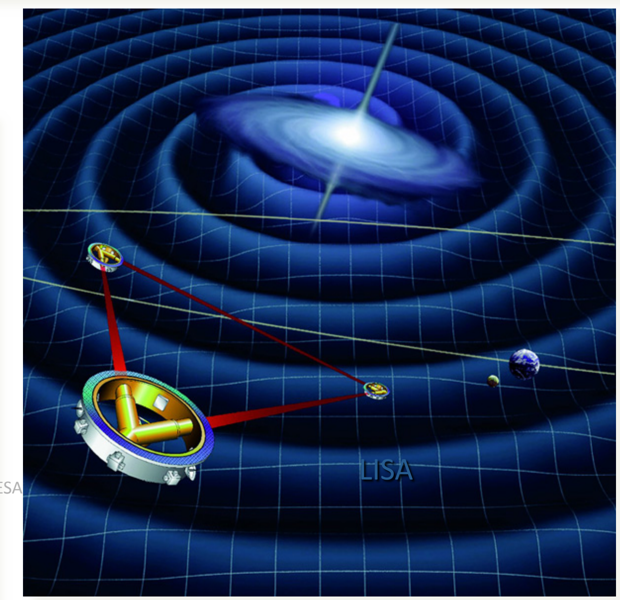




NASA, LBNL



ESA



Definitions "speak the language"

- Program
  - Typically 4 to 10 people
- Several projects exist within a program
  - Perhaps 2 to 6 projects
  - Typically 50 to 2000 tasks for each project
- Several tasks exist within a project
  - Requires 1 to 10 technical people

Definitions

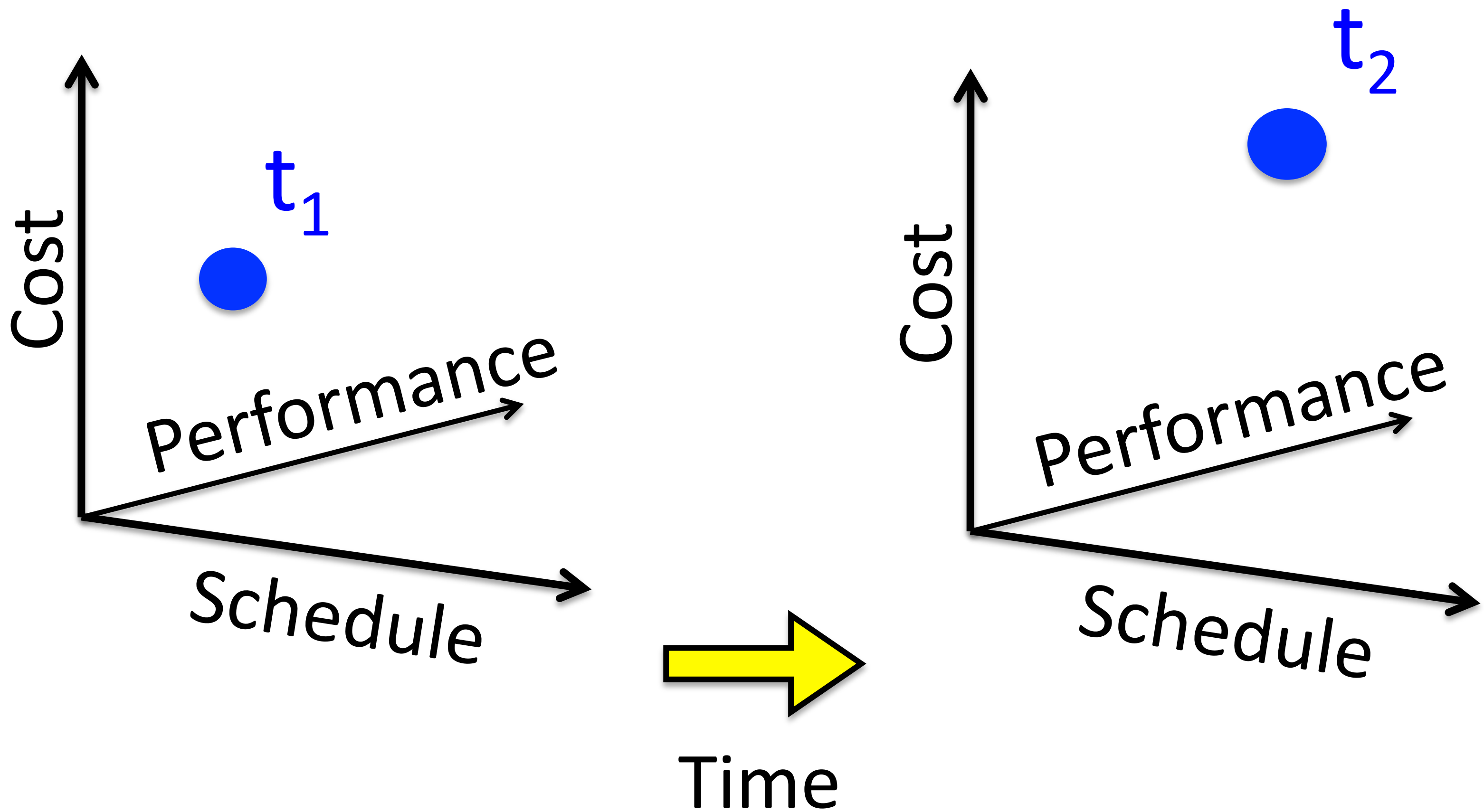
- Spacecraft
  - Hosts a telescope system – a payload
- Telescope system (payload)
  - Hosts several optical/IR instrument subsystems
- Optical/IR Instrument
  - Contains: mirrors, lenses, structure (optical bench), filters, focal planes, preamplifier, baffles, control computer and other sub-subsystems.
- We also use level 1, level 2, level 3, ...

Projects move through time in 3 dimensions

- Cost
  - As time passes is the cost consistent with the budget, schedule & performance?
- Schedule
  - Are tasks and hardware delivered on schedule?
  - How to avoid “standing around” waiting
  - “marching army”- salaries paid but no work!
- Performance
  - Requirements being met?
  - Negotiate performance to keep cost and/or schedule obligation (promise)

How do we build a large, complicated space or ground optical system?

- Tasks and Projects progress through time in three dimensions



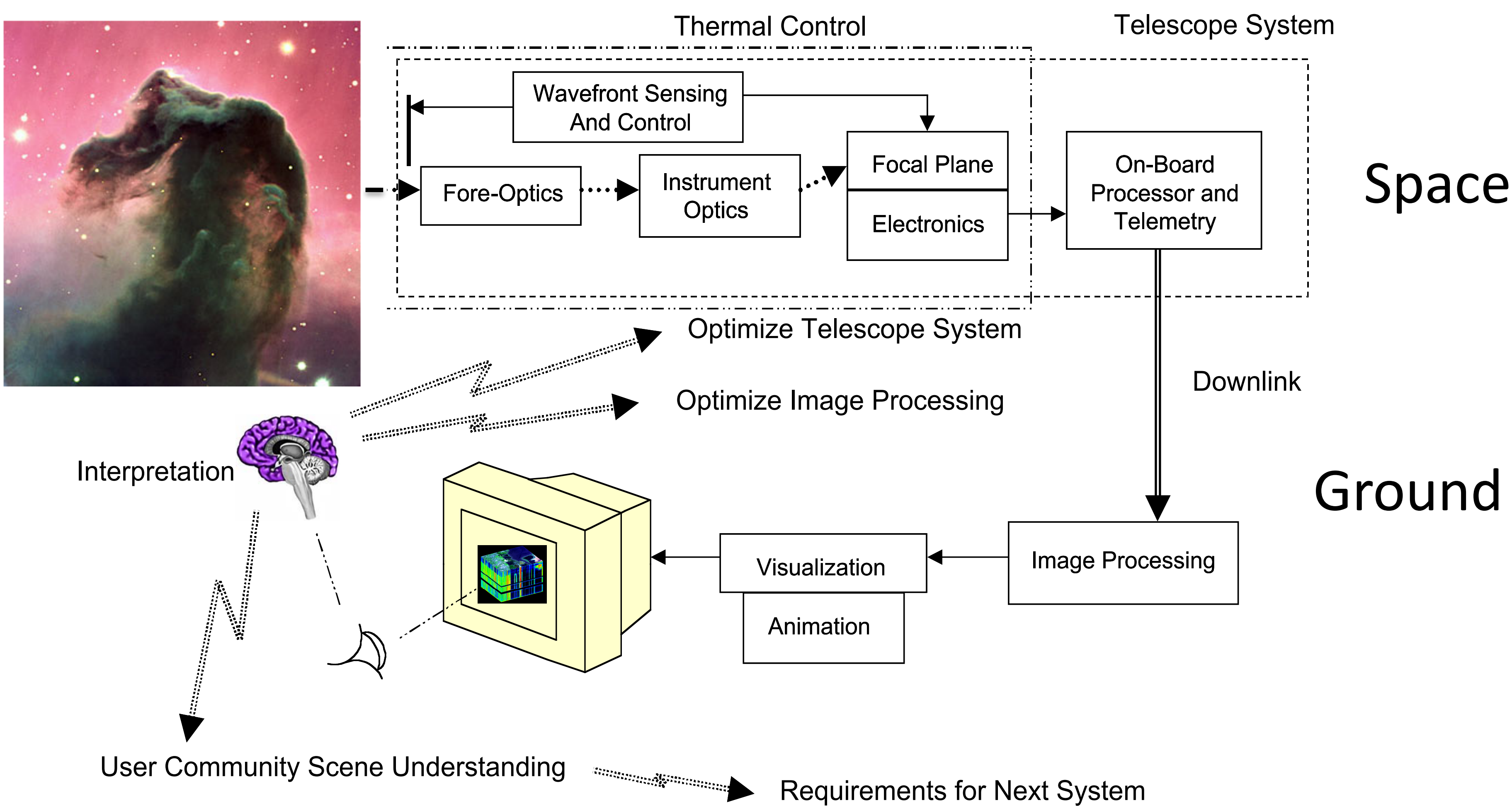
Optical system engineering integrates:

- Optical design: first order layout, aberrations
- Physical optics: materials, coatings, scalar & vector diffraction, image formation and unwanted radiation control & mitigation.
- Solid-state physics & electronics: conversion of photons to electrons, detectors, packaging, low-noise amplifiers and electronics
- Radiative transfer: transfer of power from object space, through the telescope/instrument system and onto the detector at the plane detector.
- Mechanical and mechanisms engineering: optical metrology
- Wavefront sensing & control: sense and correct wavefront aberrations in telescope systems – wavefront PSF.
- Structures and dynamics: Active and passive damping.
- Thermal engineering: coatings, heaters, mechanical coolers & cryogens
- Spacecraft engineering – orbital mechanics
- End-to-end optical system characterization, verification, validation & calibration & modeling

The successful observational astronomer understands how all these affect the quality of his data.

Space Telescope Optical System:

The optical system scientist works from the source through the interpretation



The optical engineer is responsible for

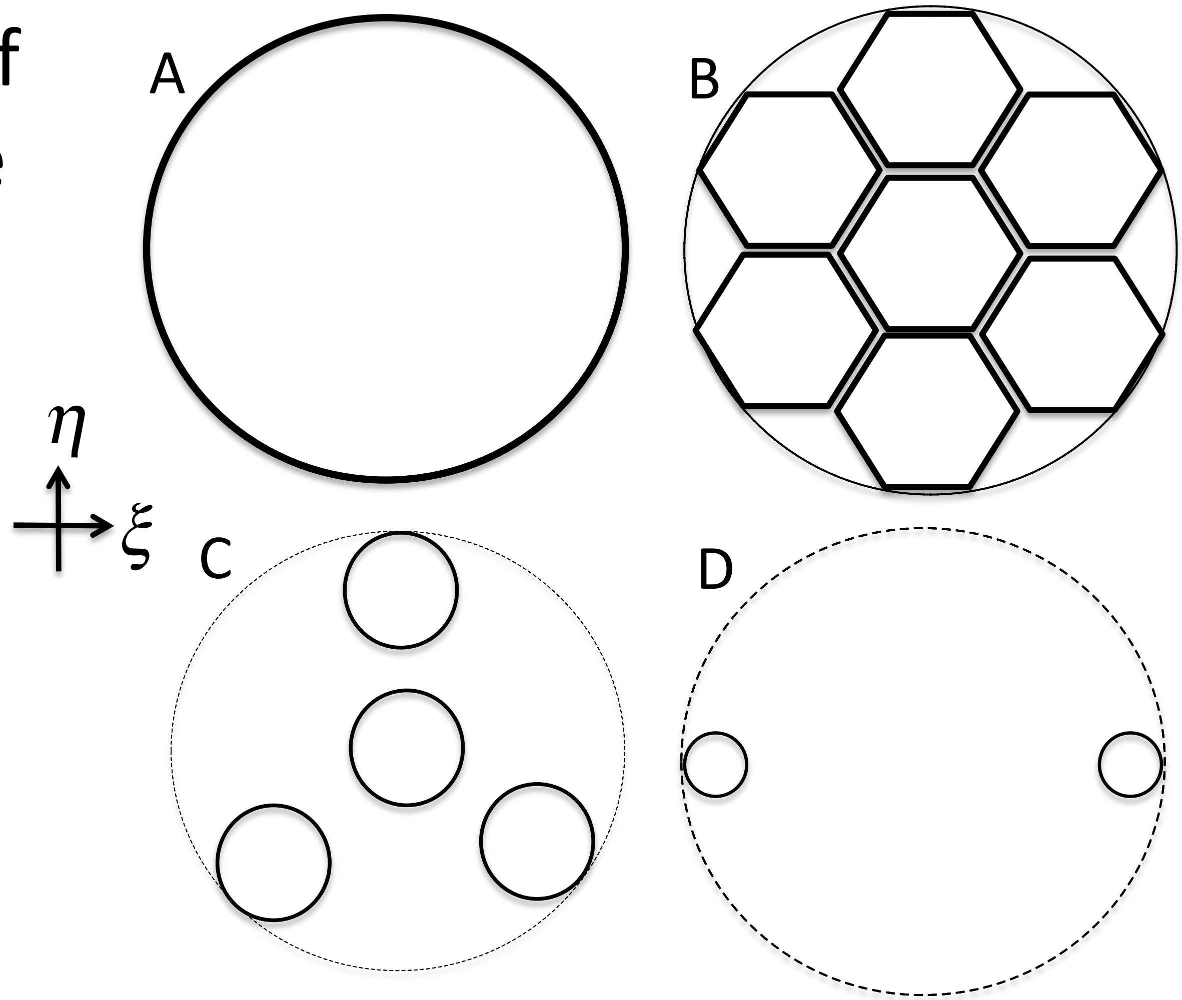
- The quality of the wavefront across the field of view at the focal plane
- The efficient conversion of image photons to an electronic signal
- Minimum unwanted radiation
  - Scattered light & emission
- Extraction of signal from noise
  - Image processing

Telescope aperture architectures

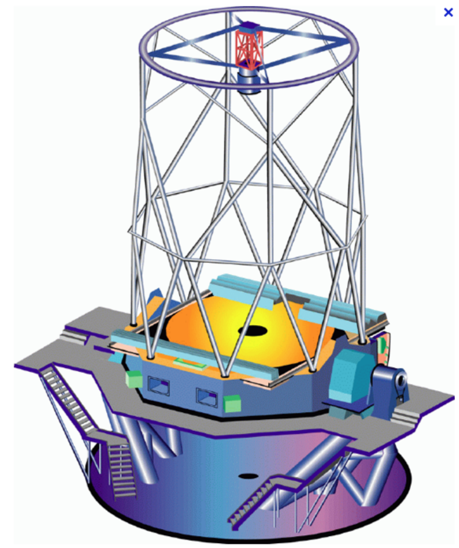
- Larger - monolith
  - diameter increases angular resolution
  - area increases radiation collected
- Filled
- Segmented
- Sparse
- Interferometry
  - Spatial interferometry

Filled, segmented, sparse and interferometer apertures

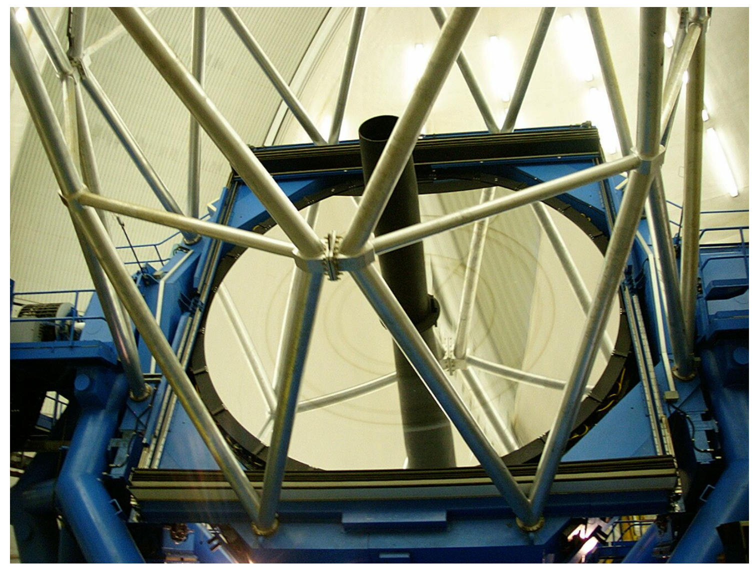
- What kind of aperture are you going to build?
- a<8 m
- 8>a>30 m
- a>50m

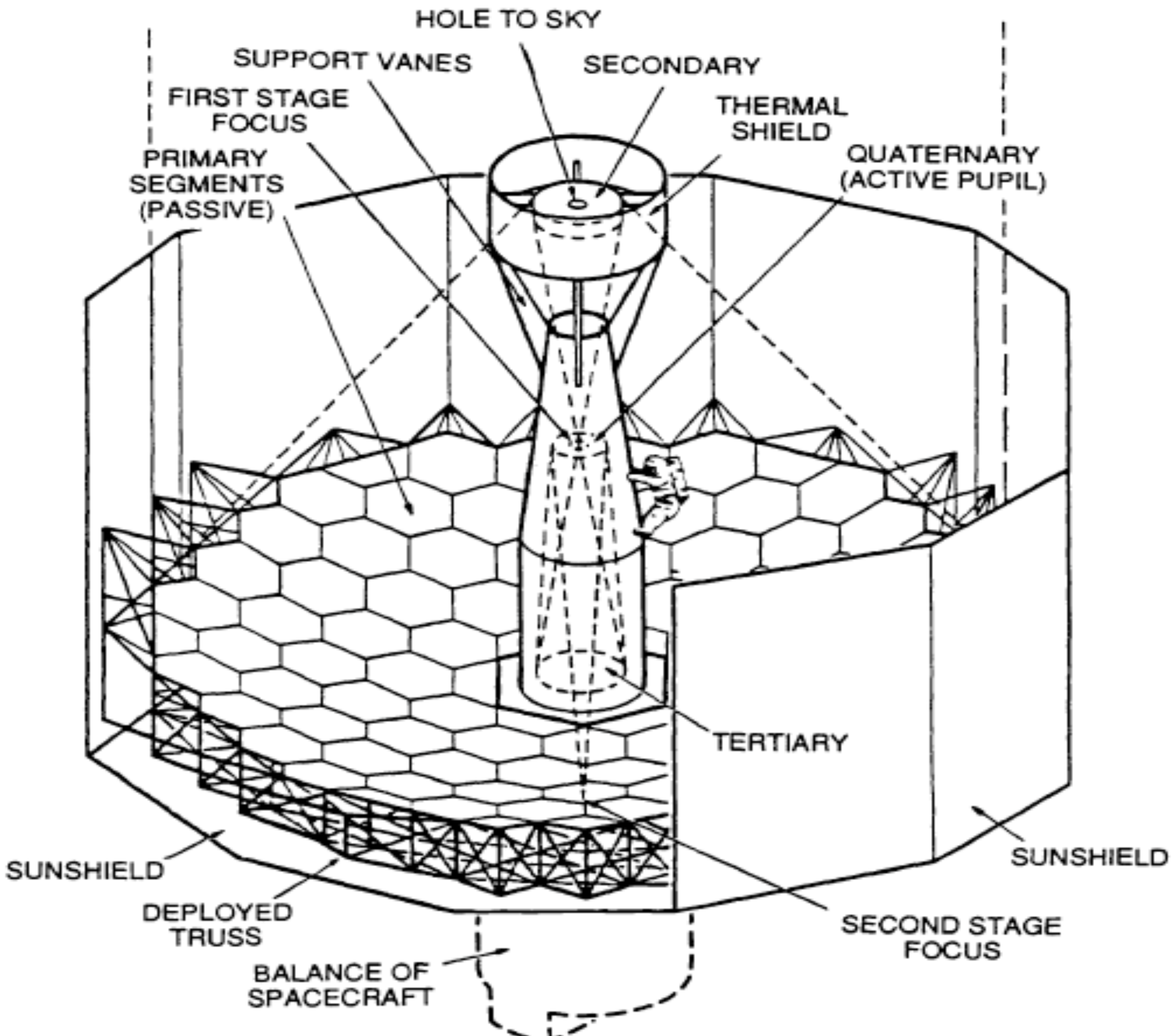


Monolithic mirrors



- Gemini (N & S)
  - 8 meter mirror
  - Alt-Az Mounted
  - Instruments at the Nysmith focus
- ESO Very Large Telescope (VLT)




HOLE TO SKY
SUPPORT VANES
SECONDARY
FIRST STAGE FOCUS
THERMAL SHIELD
QUATERNARY (ACTIVE PUPIL)
PRIMARY SEGMENTS (PASSIVE)
TERTIARY
SUNSHIELD
SUNSHIELD
DEPLOYED TRUSS
SECOND STAGE FOCUS
BALANCE OF SPACECRAFT

Tuesday, January 22, 2012

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