Goal-based Operations: Leveraging Automated Planning for Space Exploration

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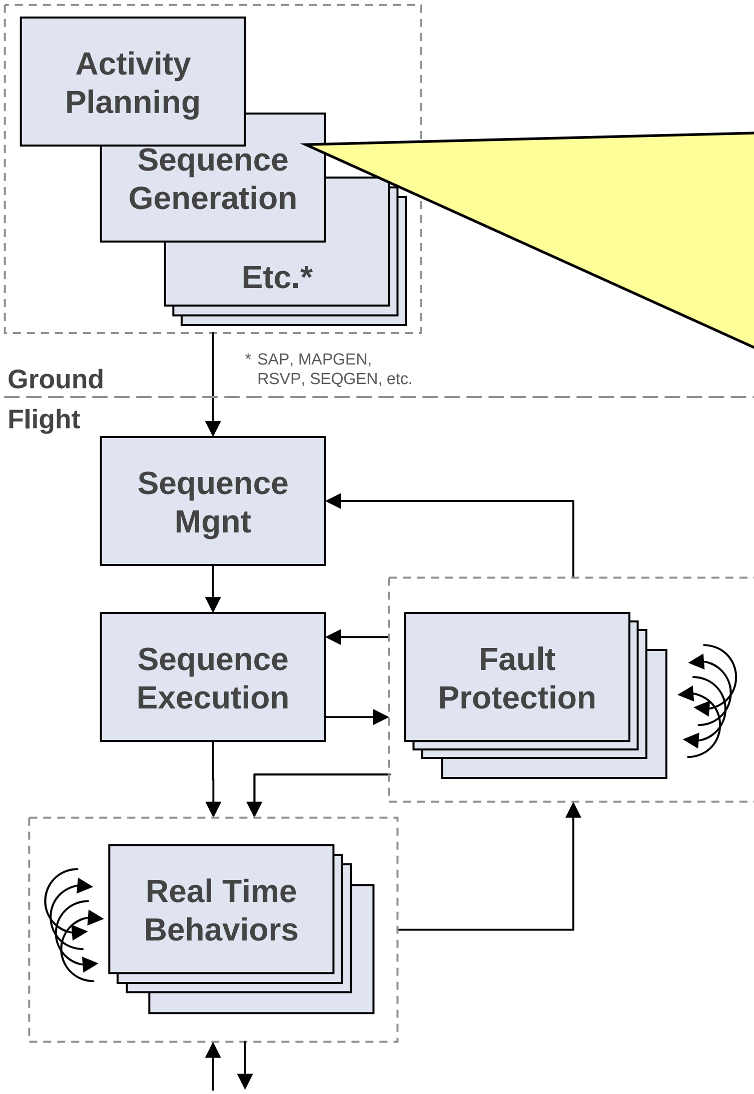
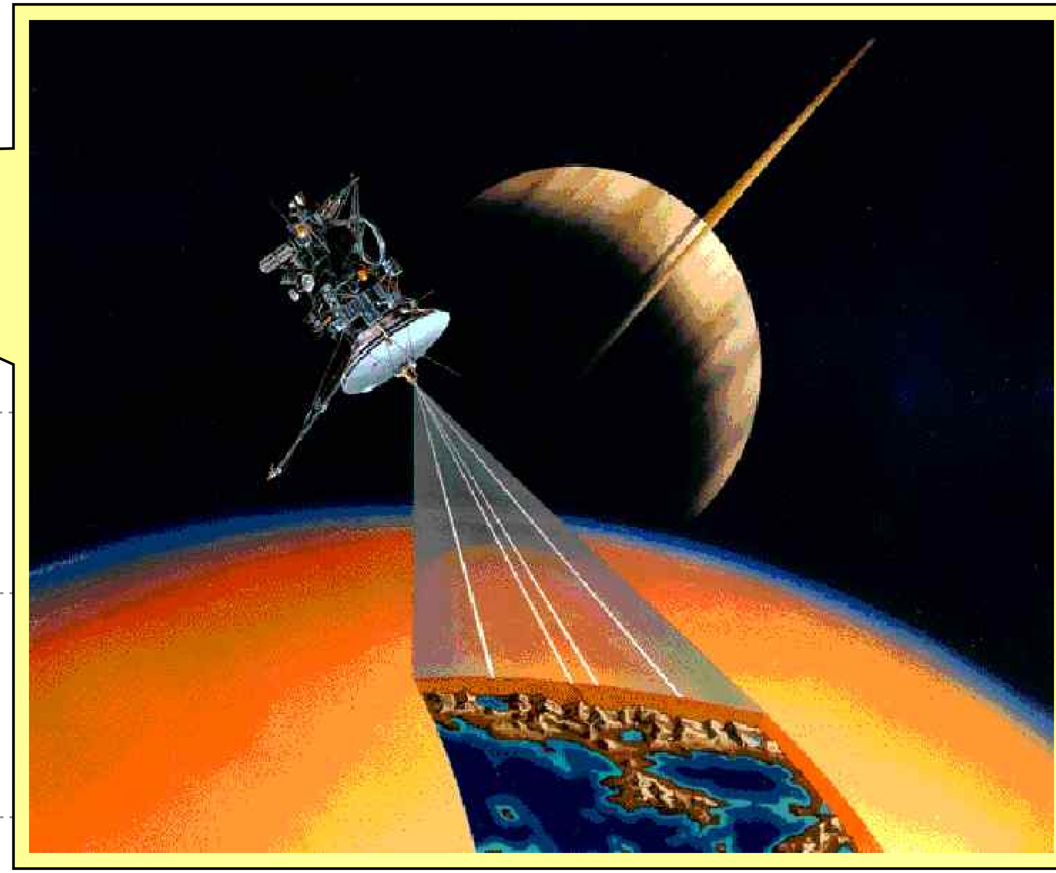
Outline

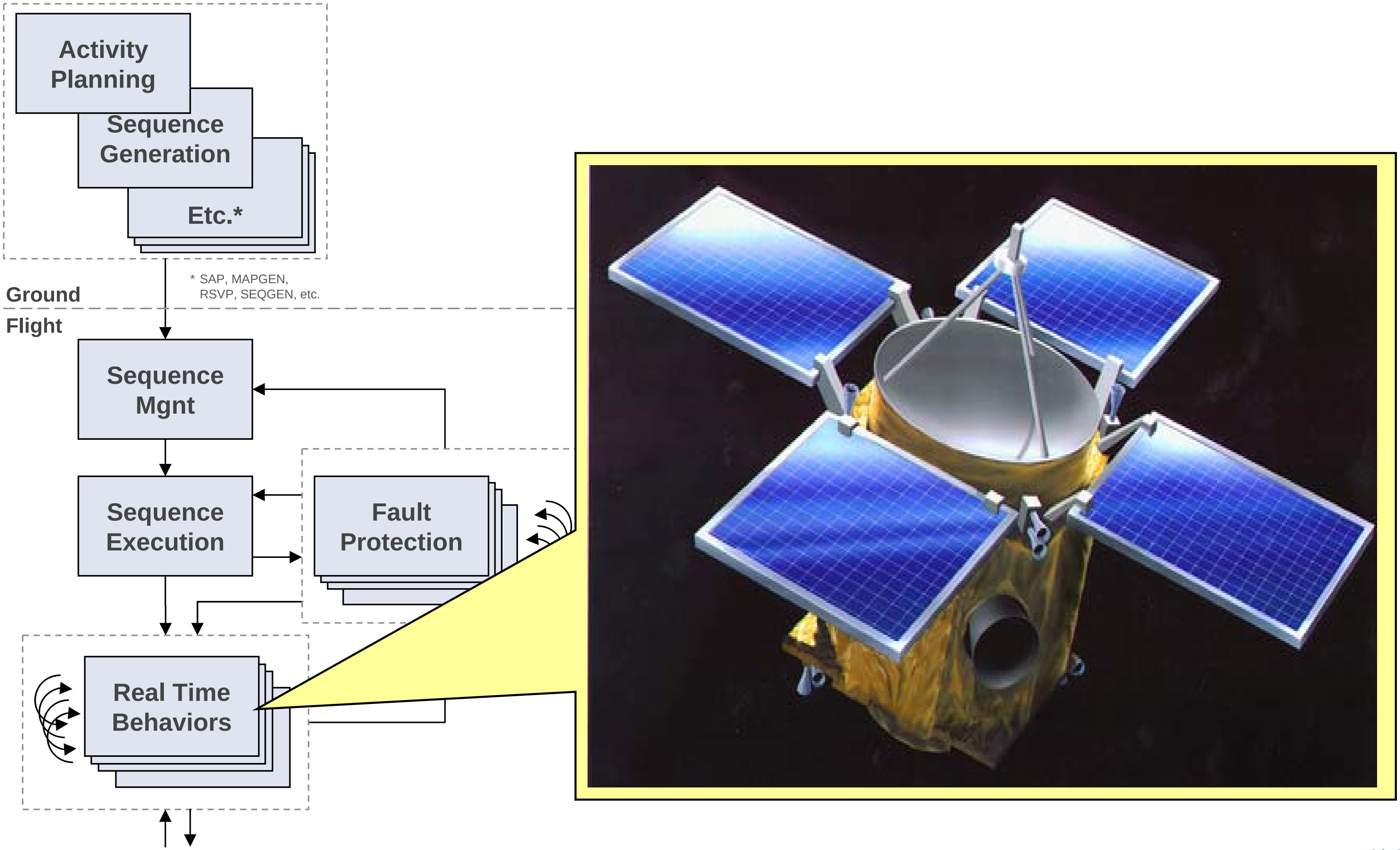
- State of the Practice
- Goal-based Operations
- Steps in the Right Direction
- Reaping the Benefits
- Challenges

Current State of the Practice

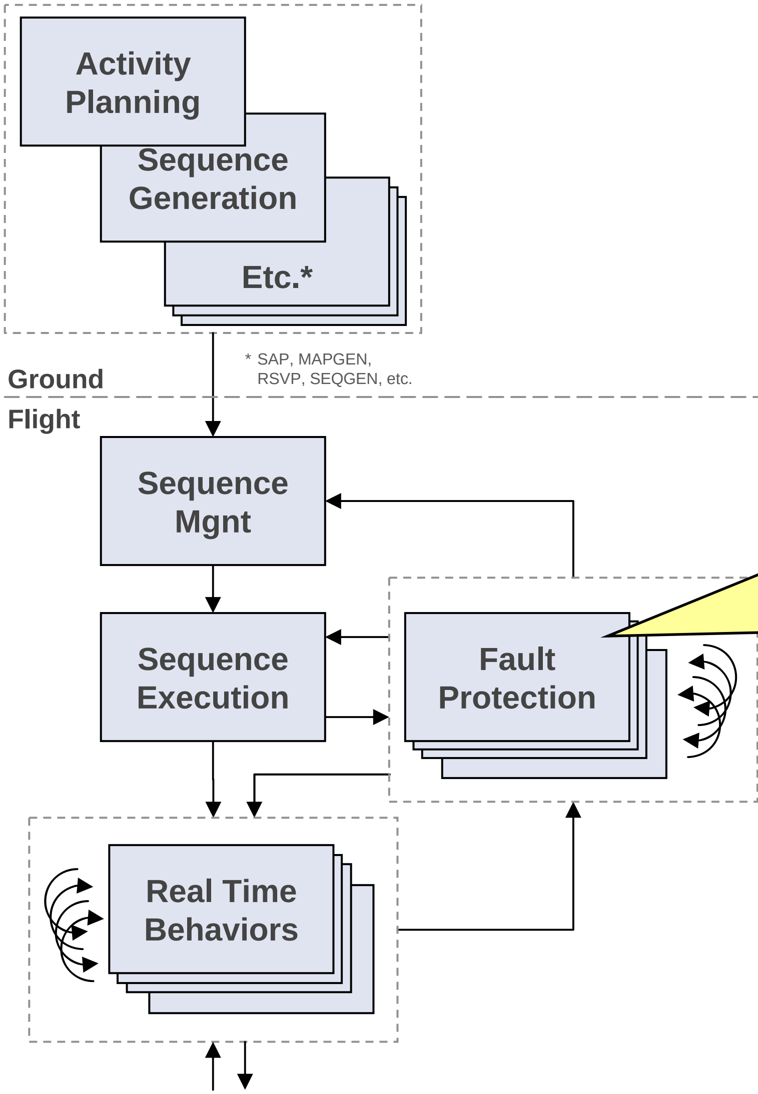




Current State of the Practice



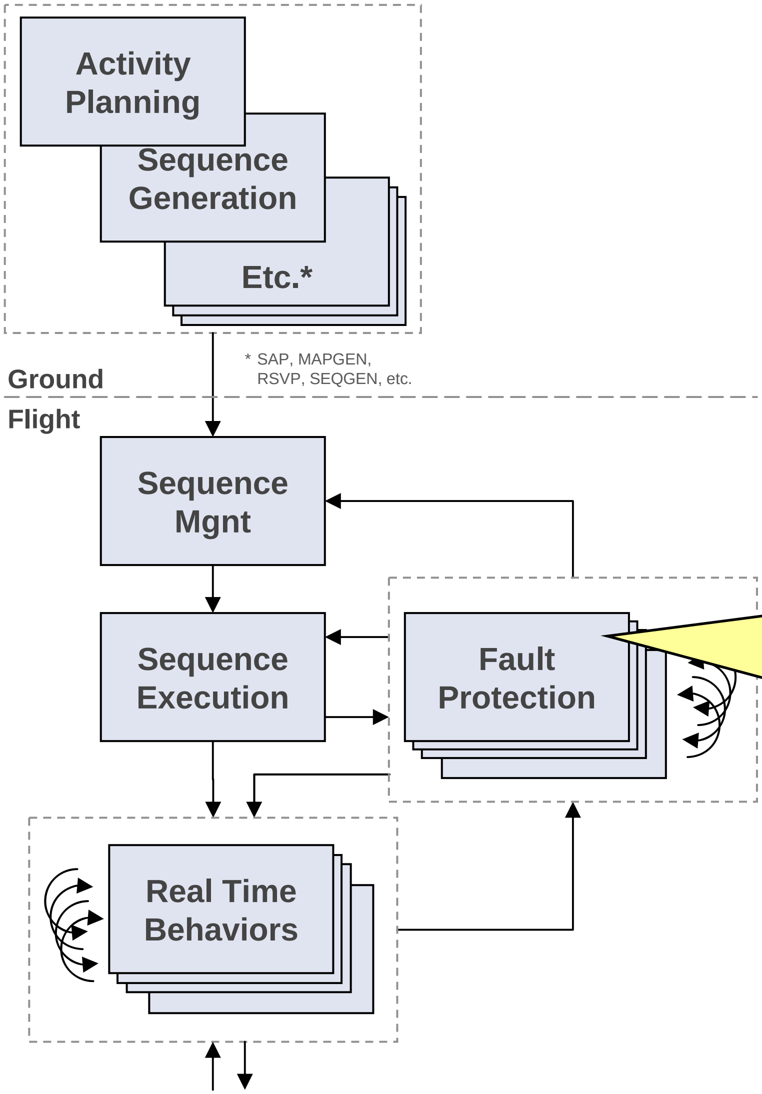
Current State of the Practice

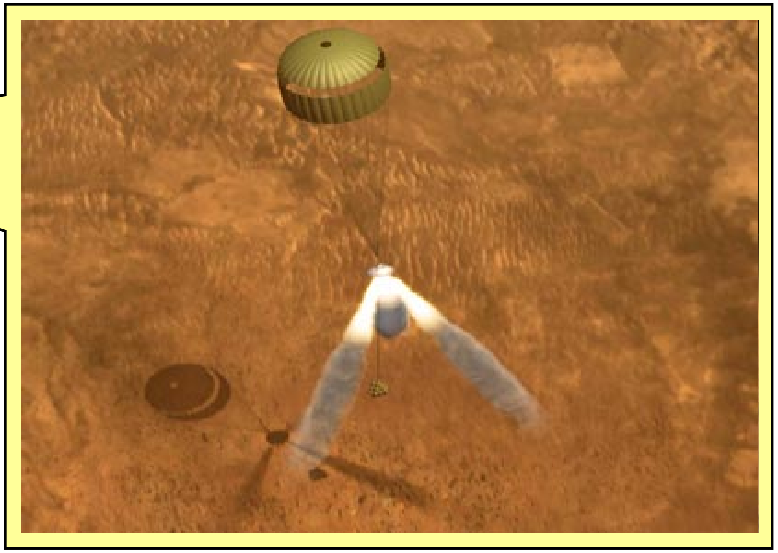


Fault protection software running in parallel, ready to "take over" from nominal sequence execution when a fault monitor is triggered. The usual off-nominal response is "safe mode":

- **costly ground ops**
- **lost science opportunities**

Current State of the Practice





Commands vs. Goals

- All commands direct momentary *changes* of state, …
  - But many commands are open-loop
    - Examples: open a valve; select an antenna; set a mode…
  - Typically depend only on intrinsic state stability
    - Persistence of effects is assumed, not enforced
    - Failure to effect or sustain a change may go unnoticed until subsequent dangers trigger a fault response

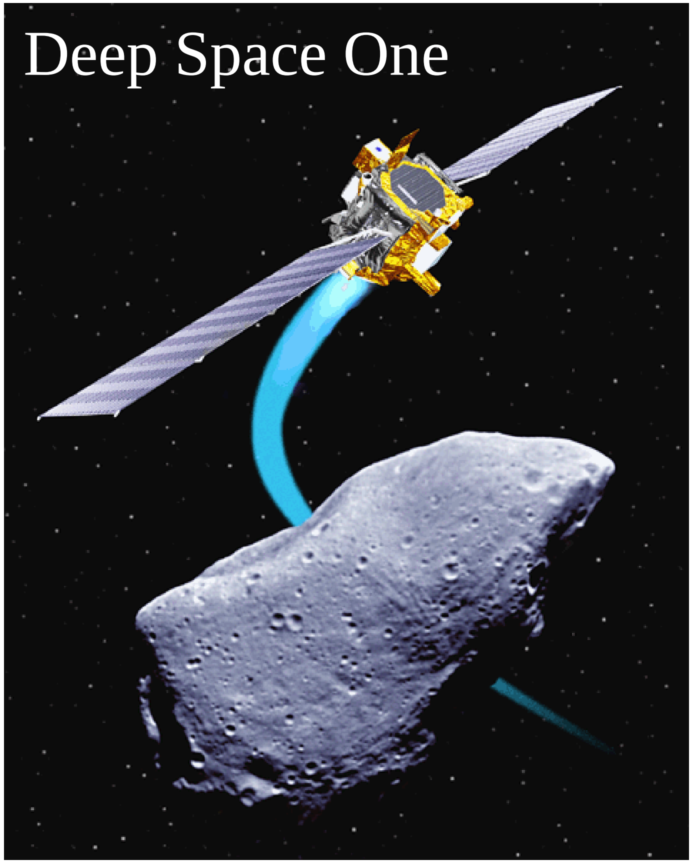
Commands vs. Goals

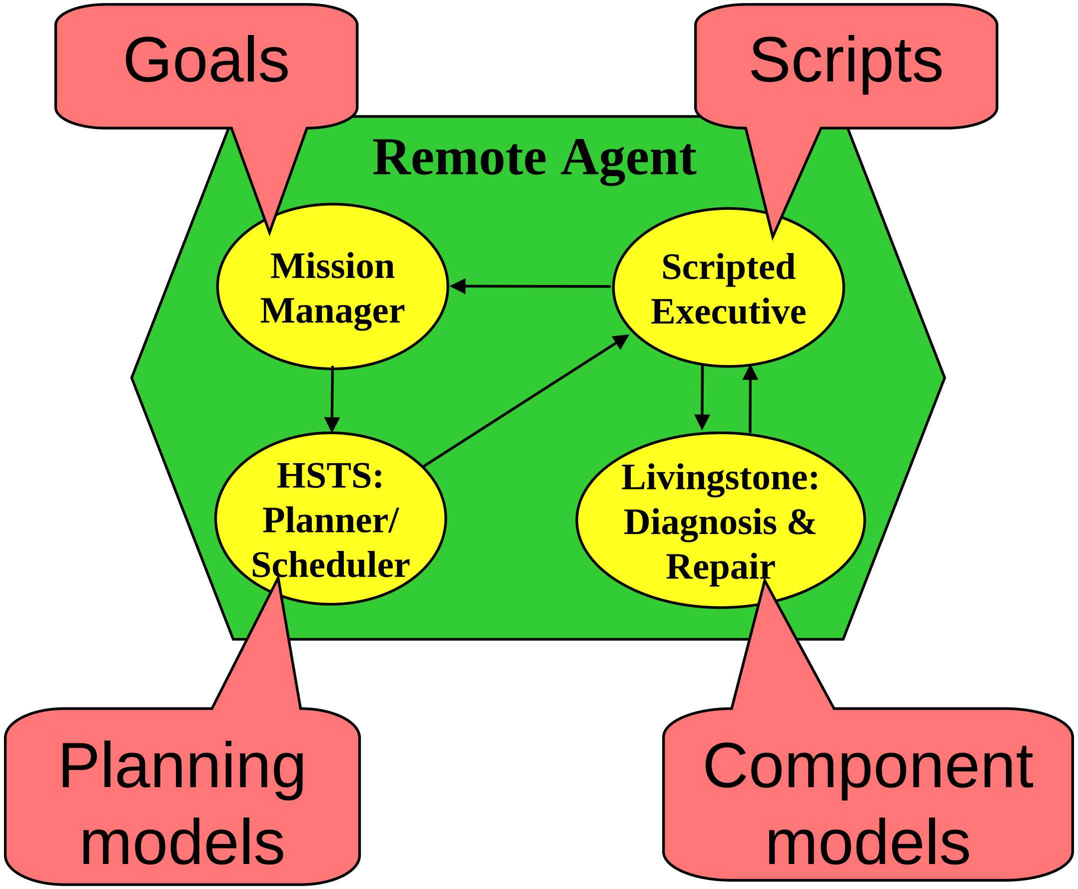
- Goals, a.k.a. closed-loop commands, change *objectives* on state
  - Common in most space systems, but not the norm
    - Examples: Track the earth; take a picture; drill a hole…
  - Subsequent action monitors and sustains the objective
    - Playing out over time is a defining characteristic
    - Failure to achieve an objective is overt and recognized early
  - More general representation
    - A goal can mimic *any* open-loop command
    - No hidden assumptions, so easier to construct, schedule, and verify robust sequences
  - Goals can also specify passively achieved behavior
    - Flight rules and constraints, resource management, fault monitoring can use same representation as nominal “sequence”

Goal-based Operations

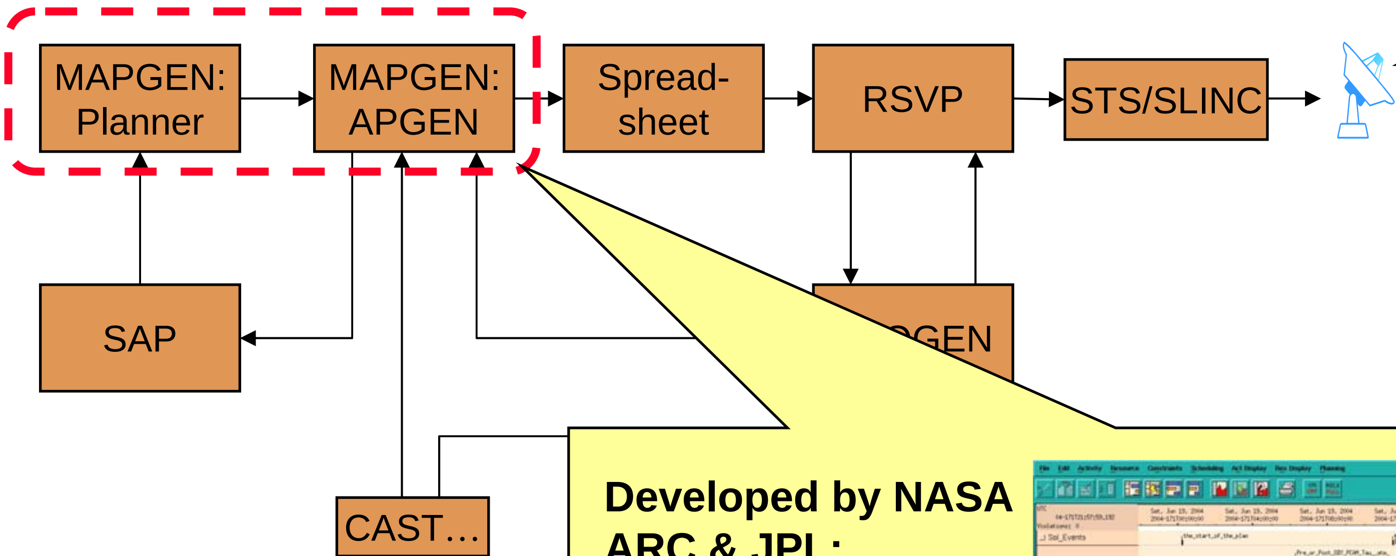
- Say WHAT to do, not HOW to do it
  - Operator's intent is explicit
  - More compact and inspectable
  - Easier to see interactions and conflicts between activities
- Allows for both time- and event-driven execution
- Allows for hierarchical expansion
- Bottom-line motivation:
  - Reduce ops costs (decrease comm bandwidth needed for control, enable use of onboard autonomy)
  - Reduce risk (facilitate integral fault protection)

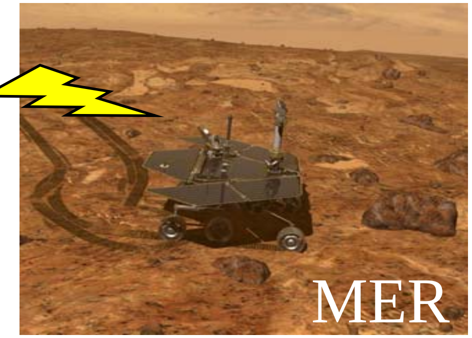
Steps in the Right Direction (1)





Steps in the Right Direction (2)

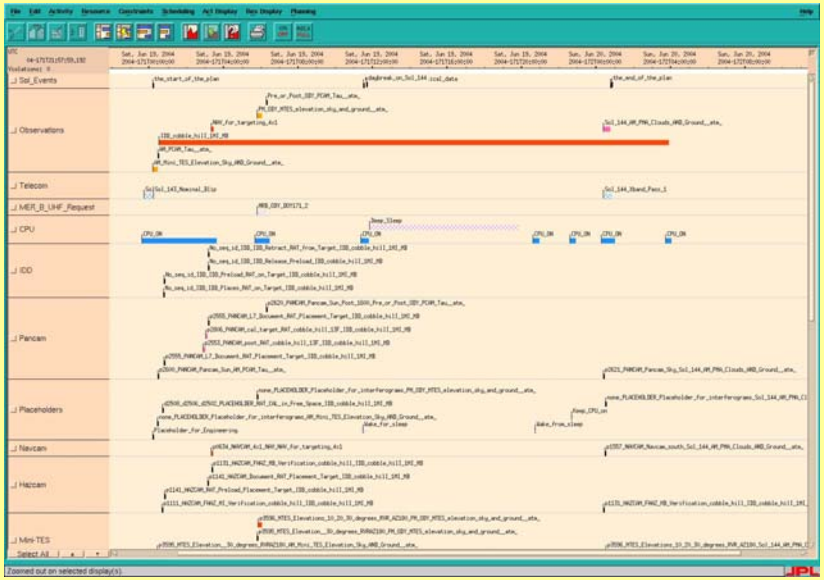




Developed by NASA ARC & JPL;

MER Ops personnel use MAPGEN to:

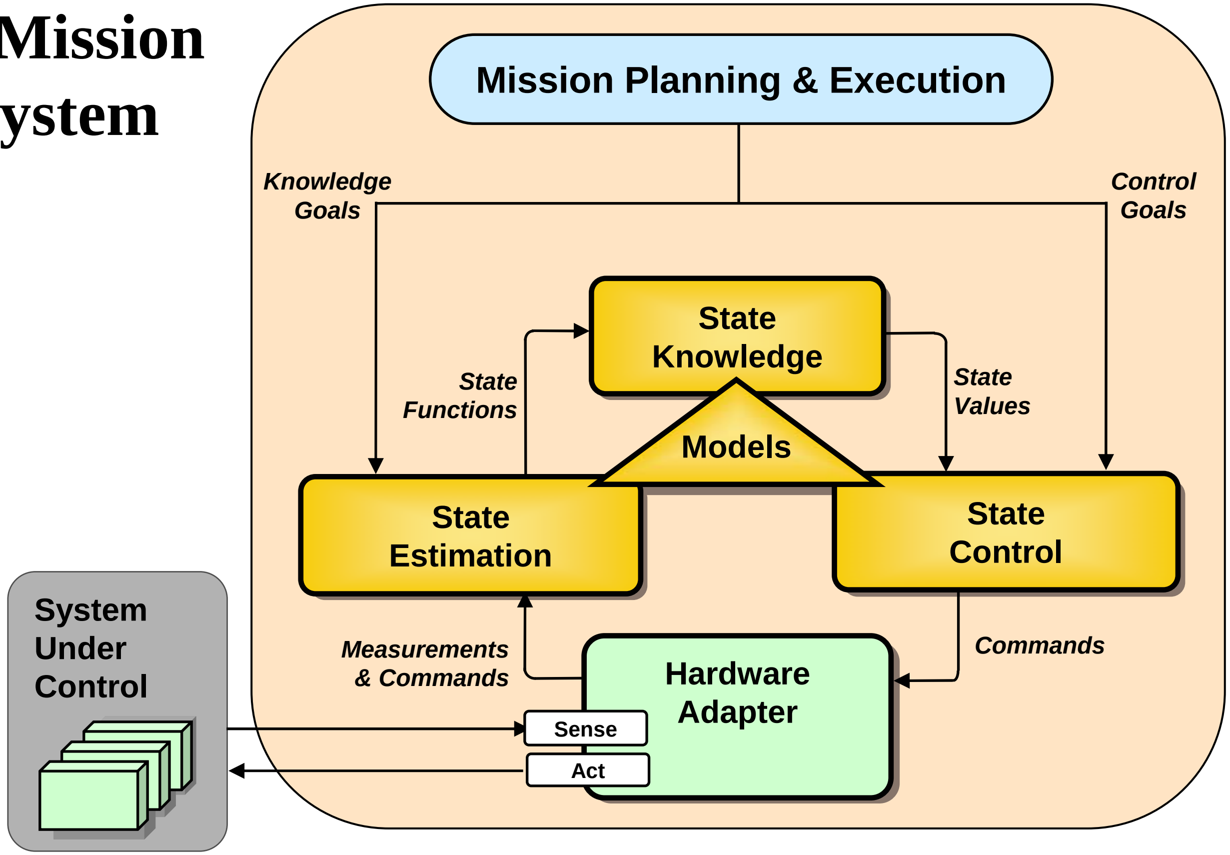
- **Plan Goals**
- **Analyze Resources**
- **Edit Plans**



Reaping the Benefits: Robustness

- Control layer has flexibility in achieving goal
- Enables integration of tiered fault management capabilities

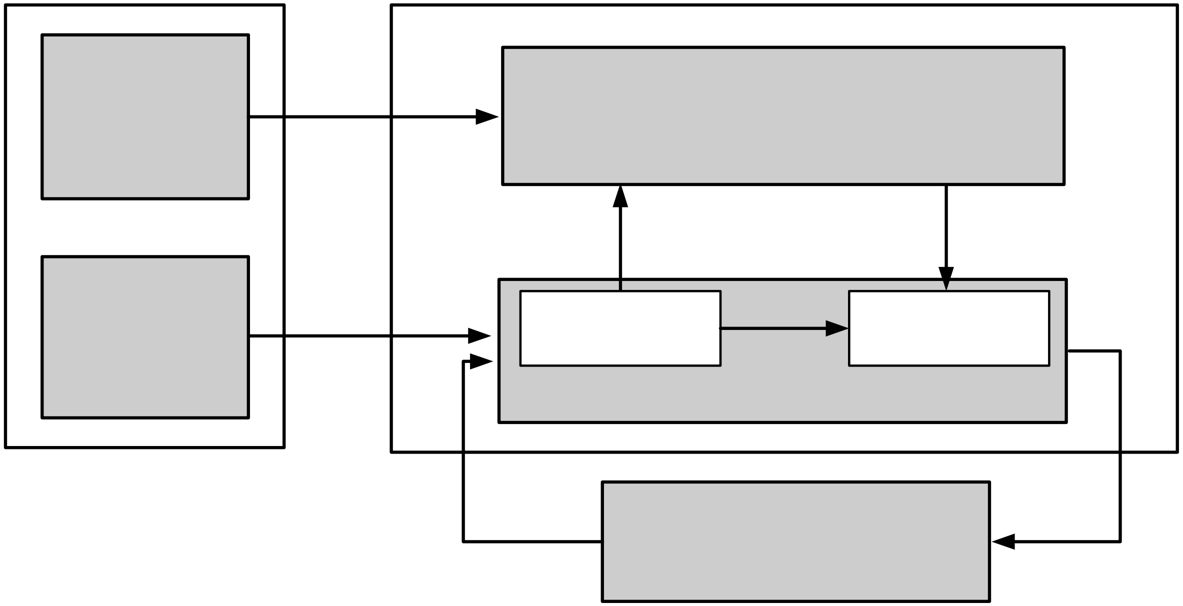
JPL's Mission Data System



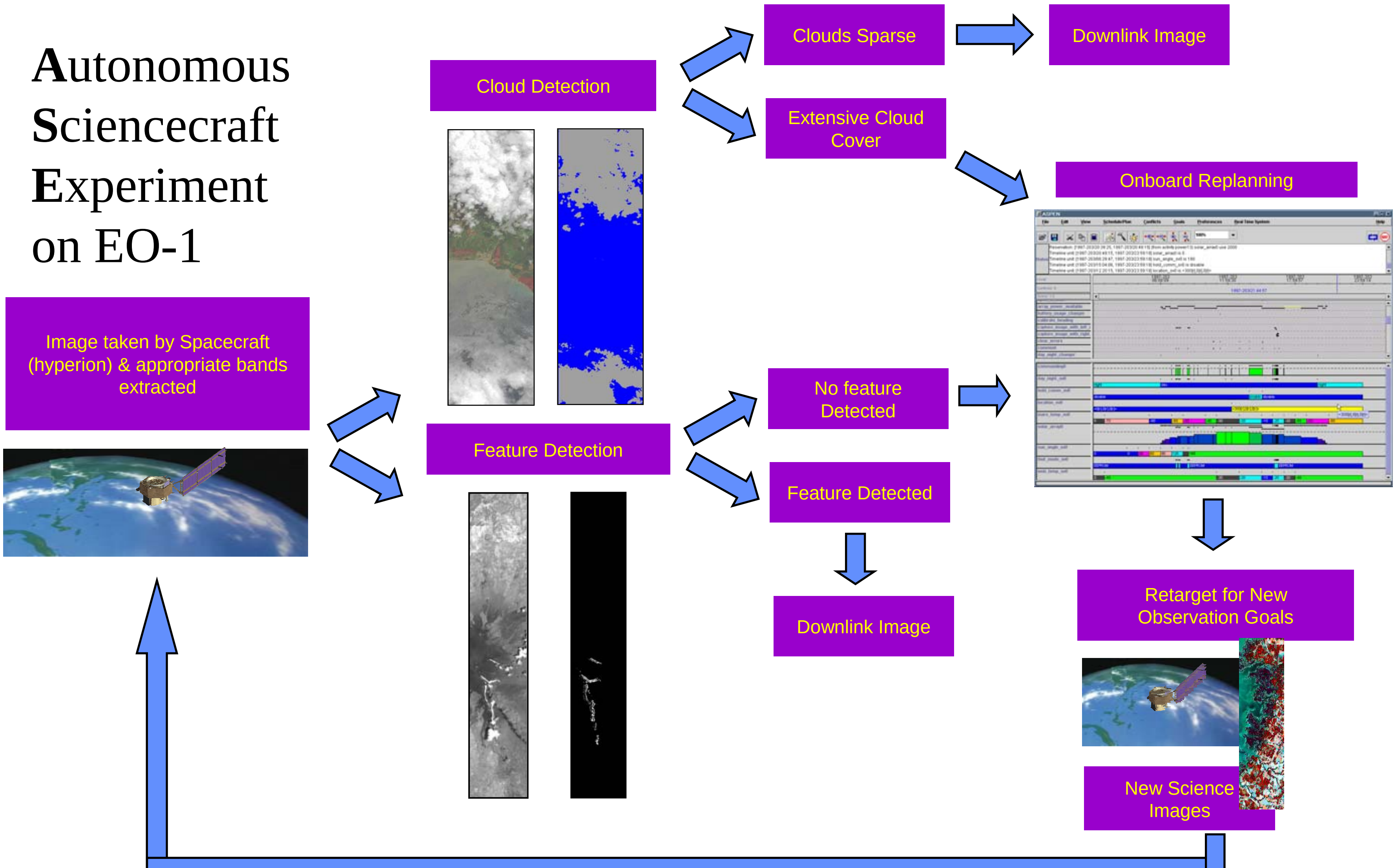
Reaping the Benefits: Robustness

- Control layer has flexibility in achieving goal
- Enables integration of tiered fault management capabilities
- Enables integration of state-of-the-art autonomy software

MIT's Titan Model-based Executive



Reaping the Benefits: Greater Science Return



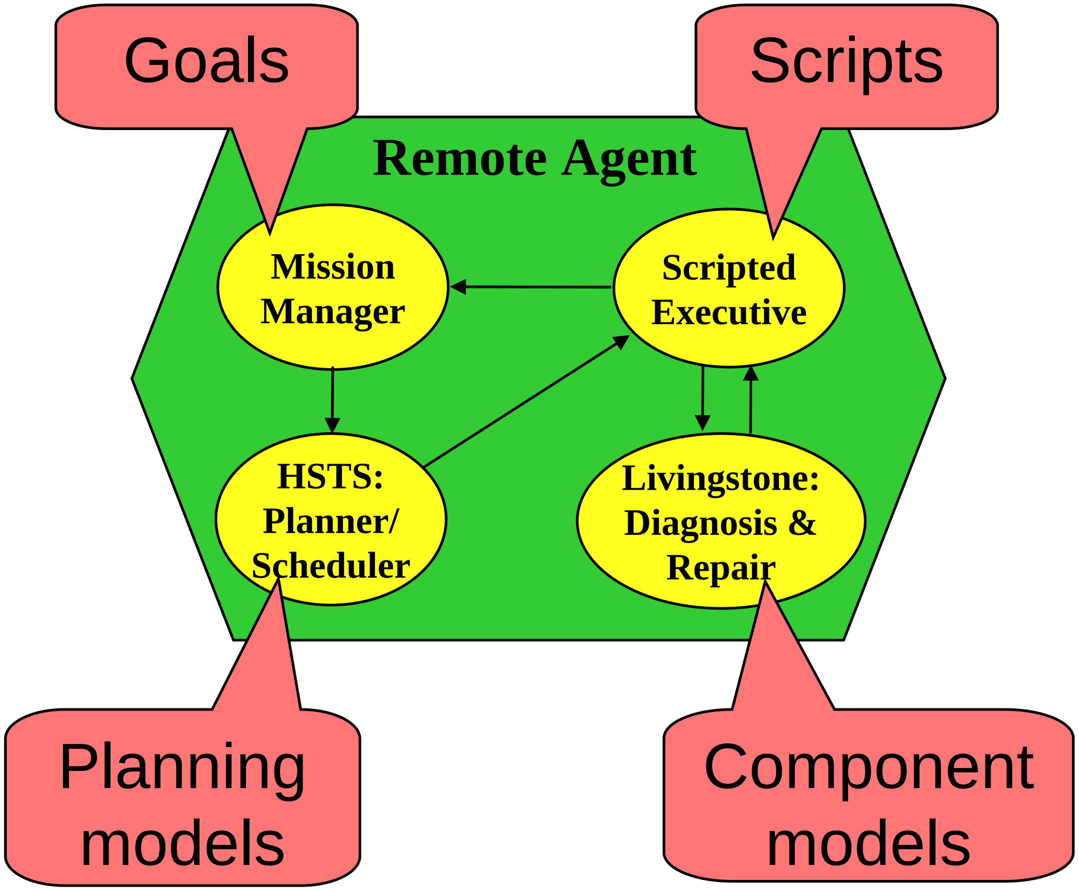
Challenge Questions

- How do we avoid the potential for divergence and knowledge duplication due to use of multiple knowledge representations?
- How can we facilitate transitioning the operational paradigm from “product flow” to “work flow”?
- How do we design for operability (i.e., integrate goal-based operations into the end-to-end mission lifecycle)?
- Can we adapt legacy tools to this new operations paradigm?
- How can we assure the reliability of goal-based planning & scheduling (V&V of goal-based planning & scheduling capabilities)?
- How do we overcome the “cultural” hurdles to acceptance of these new methods and tools?

Backup Slides

(Details on each Challenge Question)

Multiplicity of knowledge representations



- Different modules require distinct knowledge representation
  - benefit: ability to reason at different levels of abstraction
  - drawbacks: potential divergent models, knowledge duplication

Multiplicity of knowledge representations

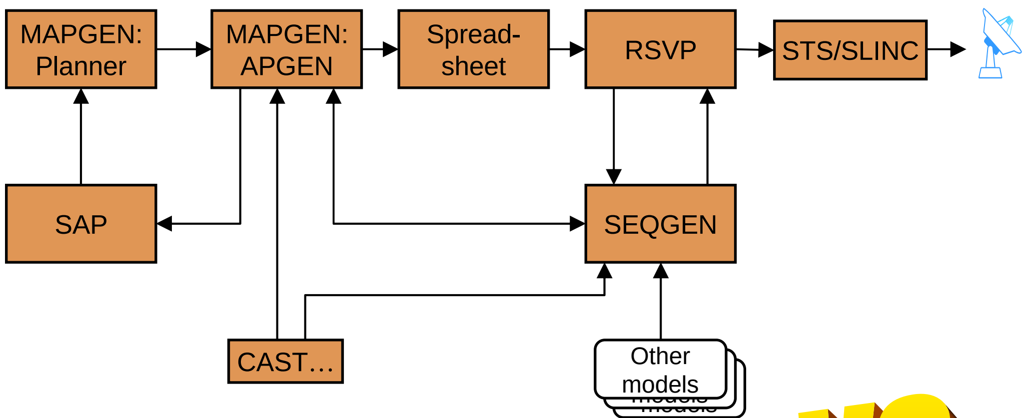
Barrier to wide deployment of autonomy s/w:

numerous tasks use variety of
modeling & programming languages

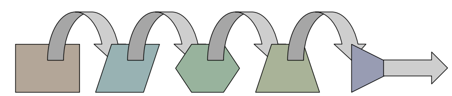
Our goal:

- ✓ head toward unified representation of spacecraft
- ✓ accommodate complexities of spacecraft domain
- ✓ maintain capacity for knowledge abstraction

Transitioning from “product flow” to “work flow”

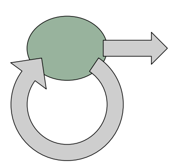


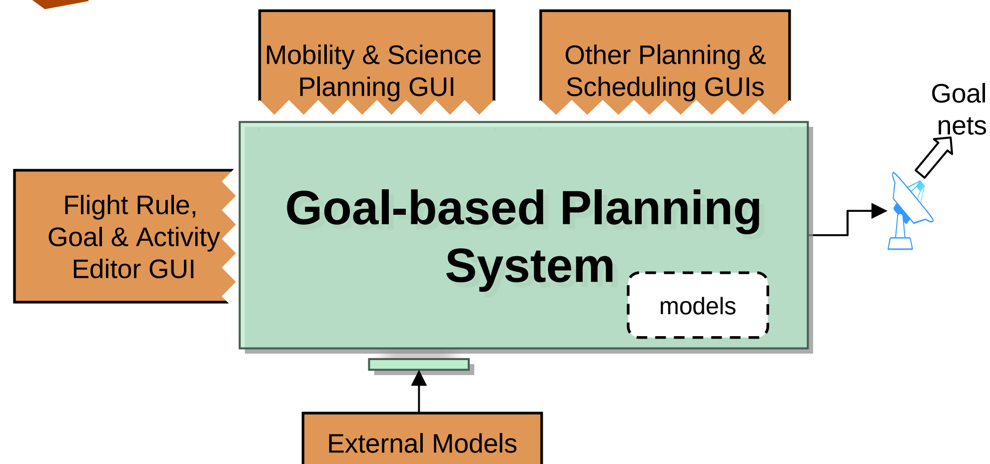
Product Flow



VS.

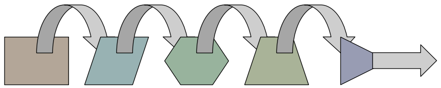
Work Flow



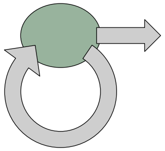


Transitioning from "product flow" to "work flow"

- Goal-based operations facilitates a shift in our approach:
  - From product flow

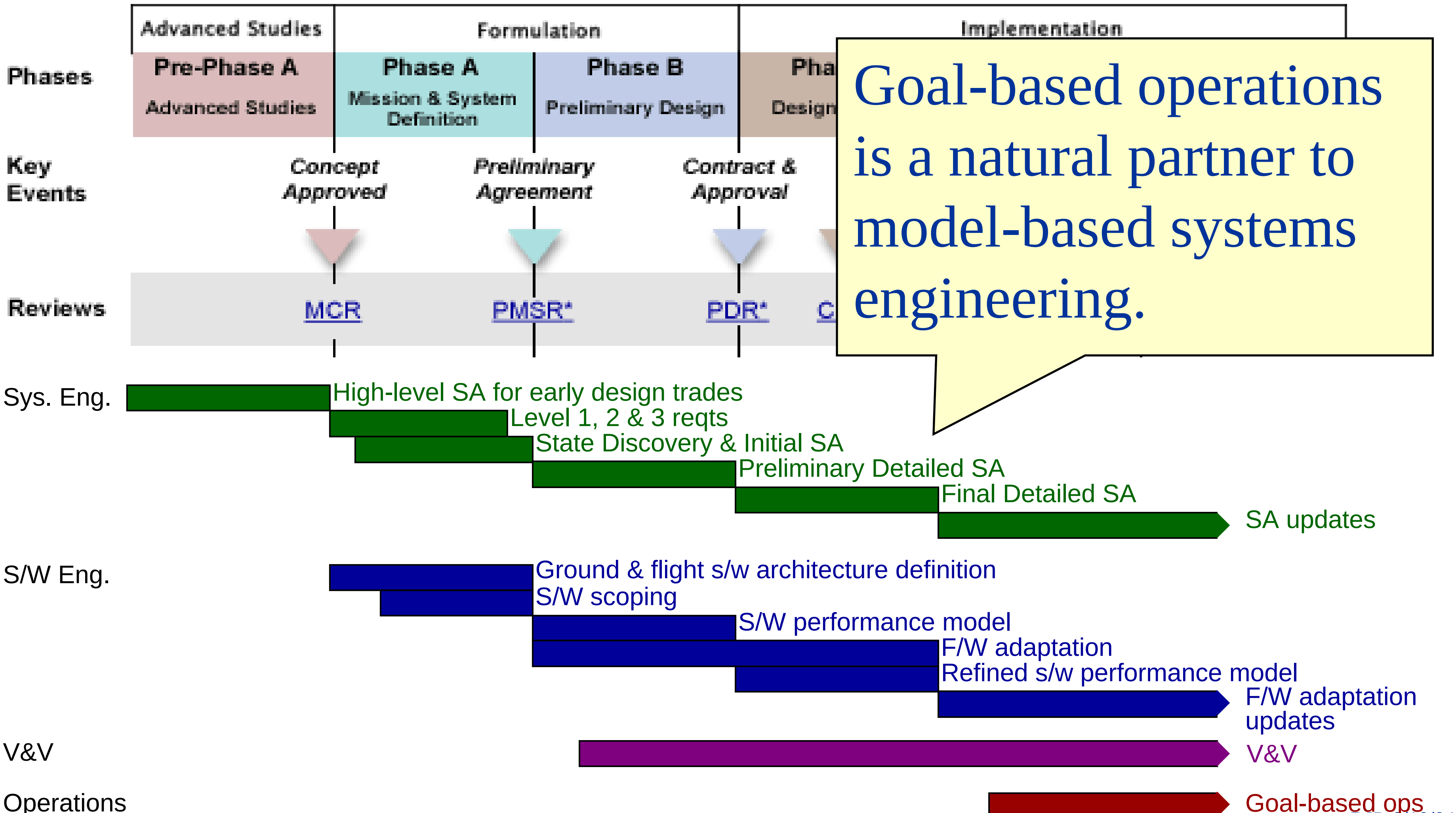


    - Development progressing from one tool to another through exchange of data files along a development path
    - Progress is measured by where activity is in the tool chain
    - Reverse flow to address problems is awkward, at best, and usually avoided
      - Fixes often made in place without benefit of earlier steps
  - To work flow



    - One uniform product set managed by a common tool going through successive stages of refinement
    - Progress is measured by level of completeness, validation, and approval
      - Manageable through a parallel workflow process
    - Reversing to address problems is straightforward

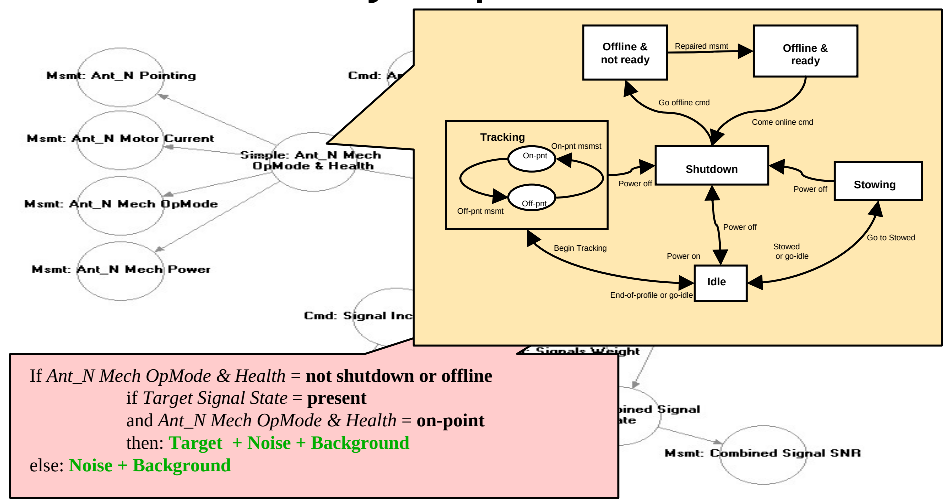
Integration of goal-based ops into the mission lifecycle



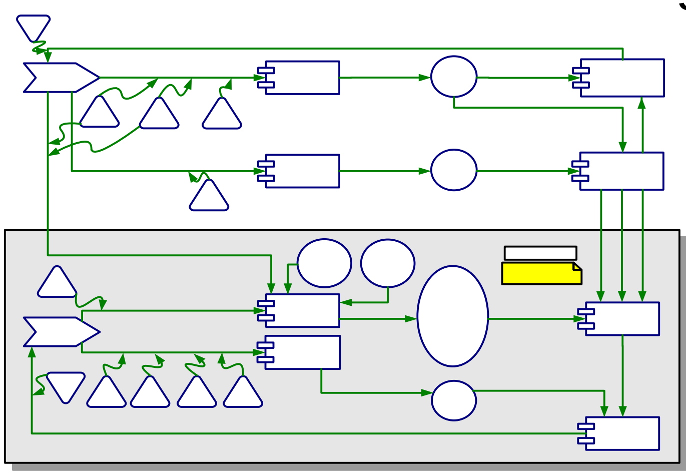
Integration of goal-based ops into the mission lifecycle

1. System to be controlled

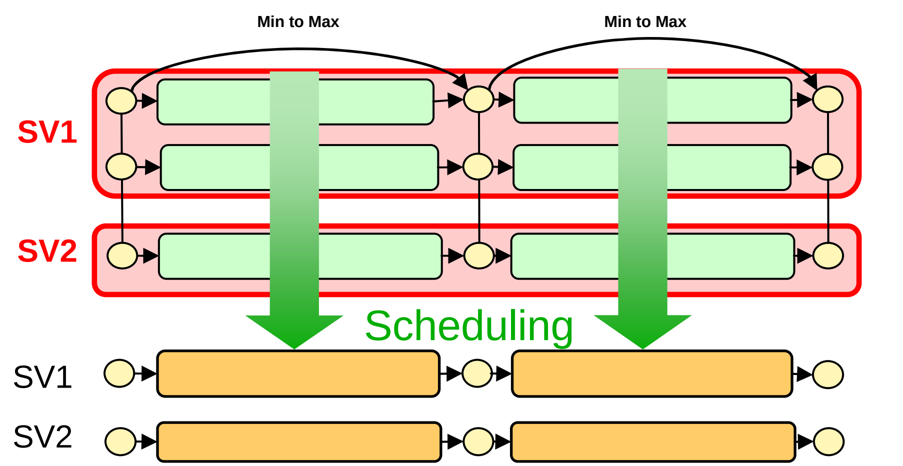
2. State Analysis produces model



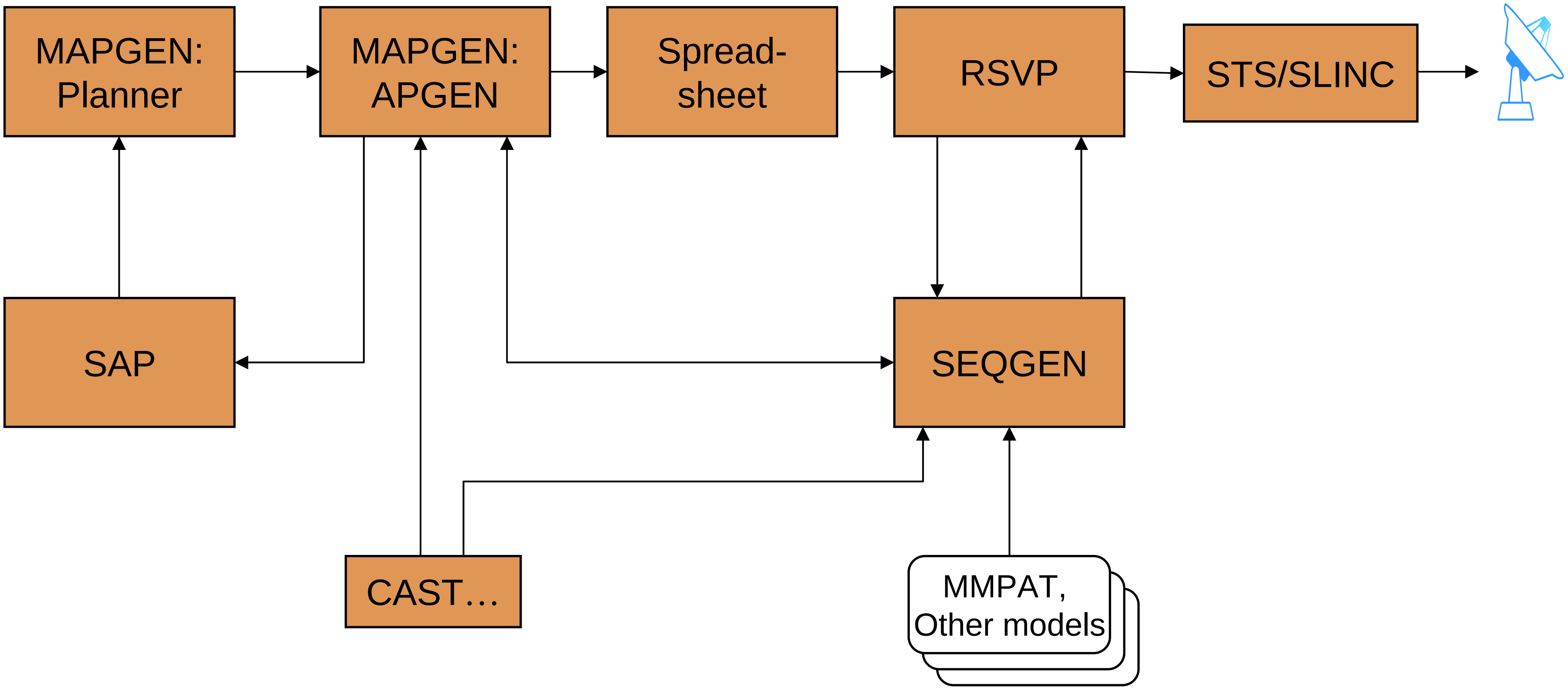
3. Model informs software design



4. Model informs operations



Adapting legacy tools



V&V of goal-based planning & scheduling tools

- Comprehensive V&V plan:
  - Engine & Model validation
  - High-fidelity mission testbeds
  - Auto-code generation where practical
  - Formal V&V methods where appropriate
- Where possible, initial flight validation on spacecraft with more aggressive risk posture
  - Technology validation missions (e.g., NMP)
  - Post-primary mission spacecraft assets
- Progressive capability phasing
- Ground-to-flight migration of capabilities
- Design for variable autonomy
- Extended deployments and in-situ stress testing

Cultural hurdles to acceptance

- Part of this is a “trust” issue, somewhat related to the previous challenge question
- This issue applies more broadly to any new technology, *especially* software technology
- “If it hasn’t flown before, I don’t want to fly it” - what incentives are there for Project Managers to embrace (or at least accept) new technology? This is an organizational issue…