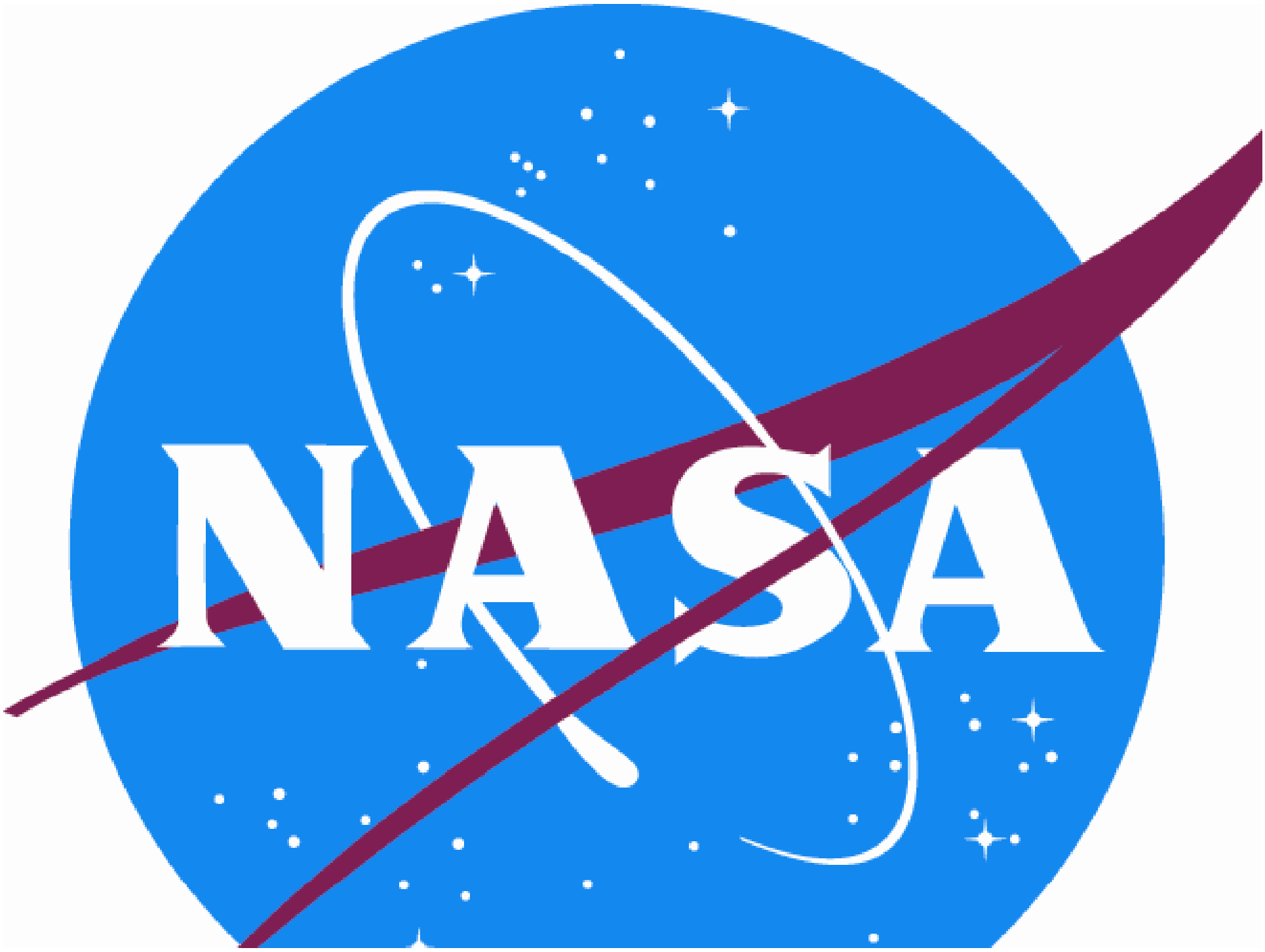
NASA

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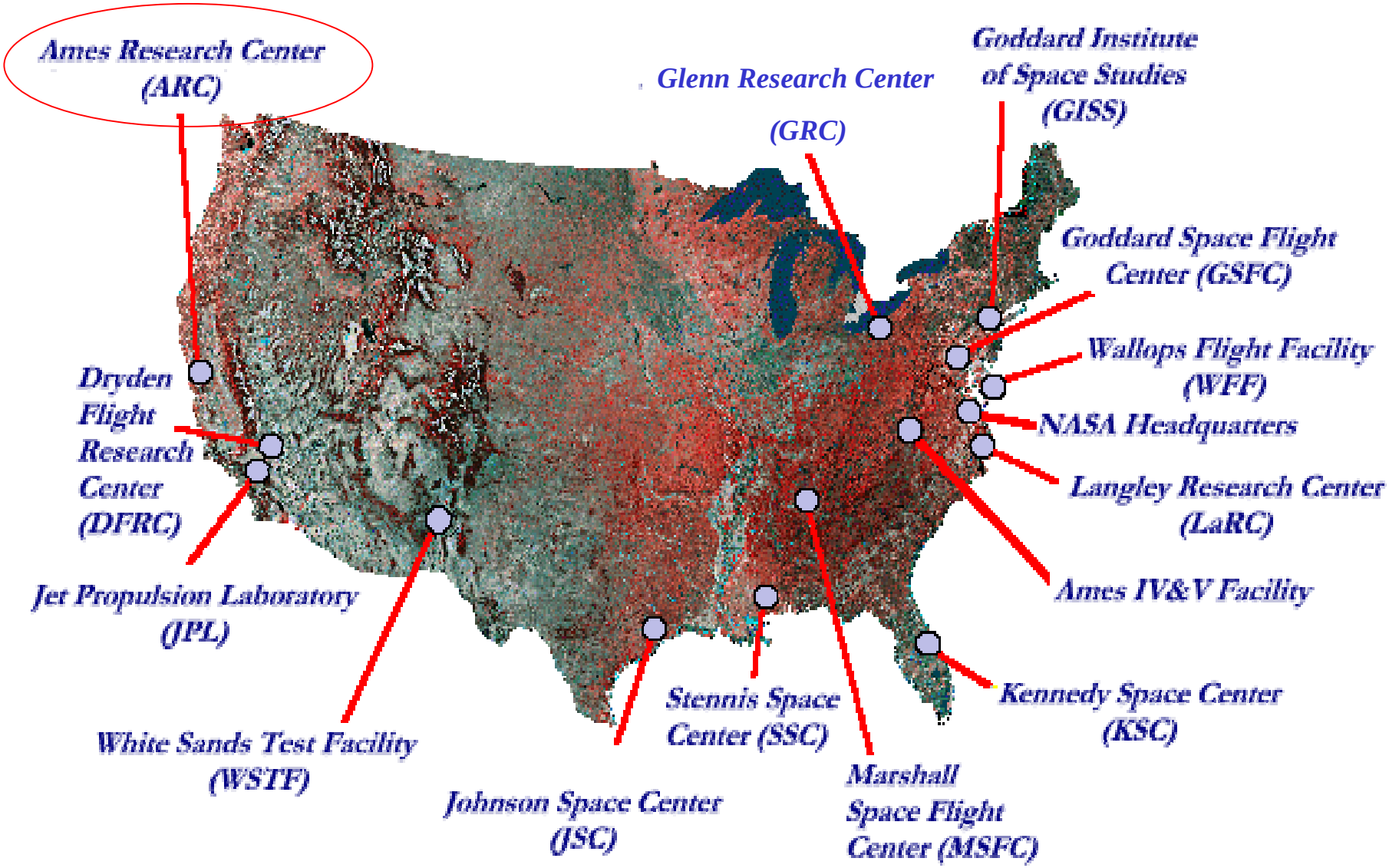
Where is NASA?



Outline

- Introduction
- What is MAPGEN?
- Lessons Learned from MER
- Wrap up and Conclusions

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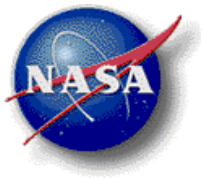
Outline



- Introduction
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National Aeronautics and Space Administration

Vision

Our mandate is:

- To improve life here,
- To extend life to there,
- To find life beyond

Mission

- To understand and protect our home planet
- To explore the Universe and search for life
- To inspire the next generation of explorers

…as only NASA can

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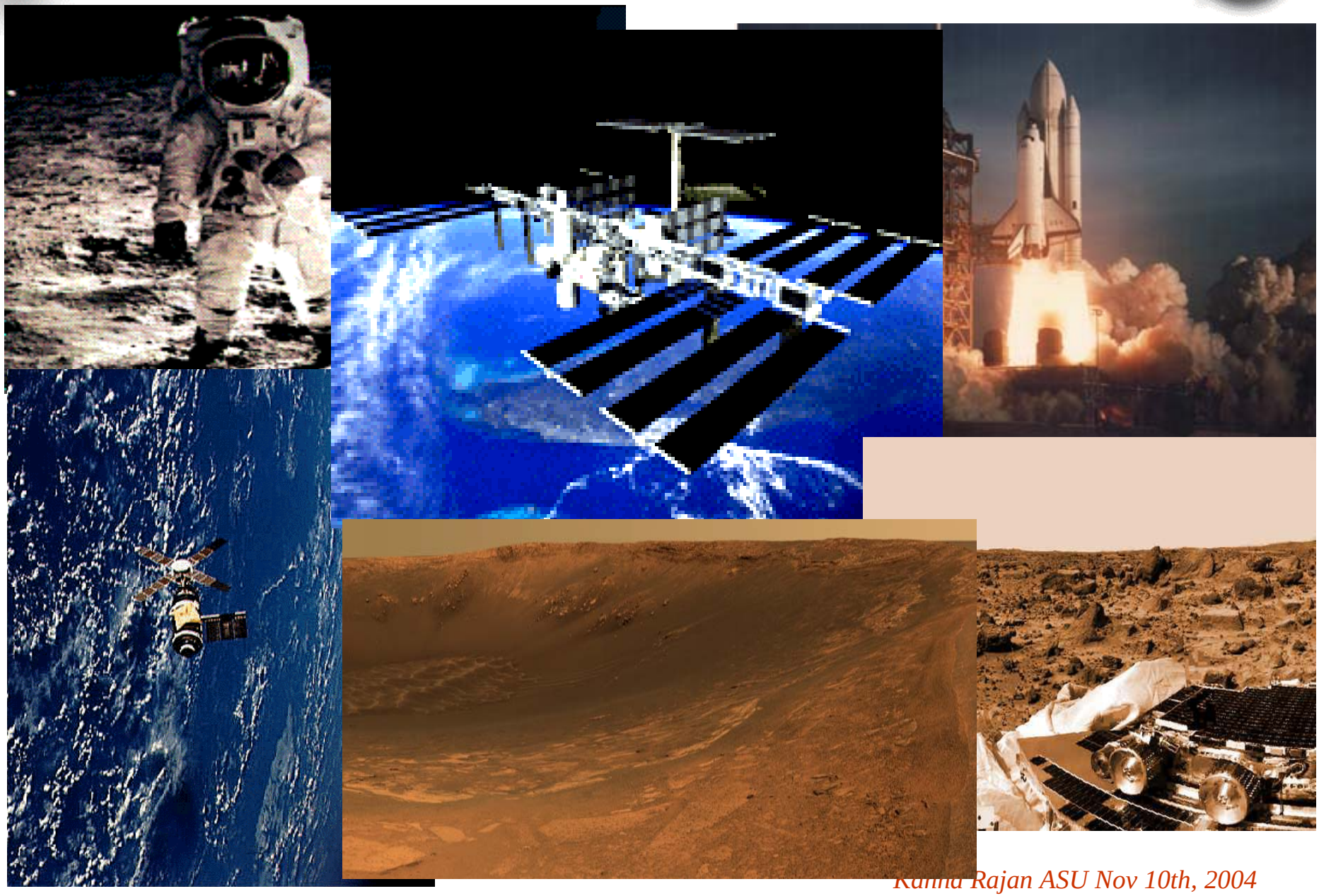
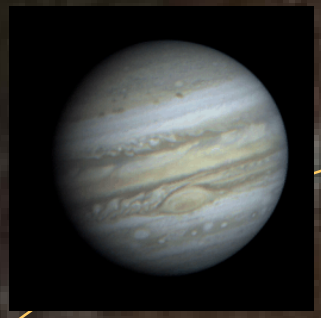
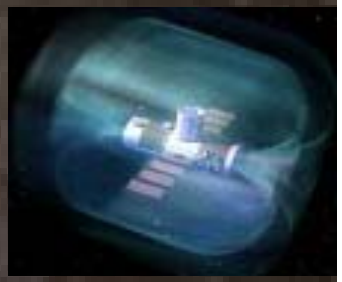
Where have we been?



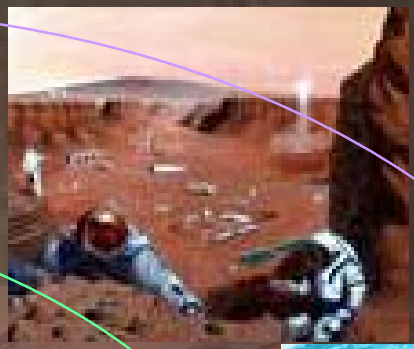
Stepping Stones



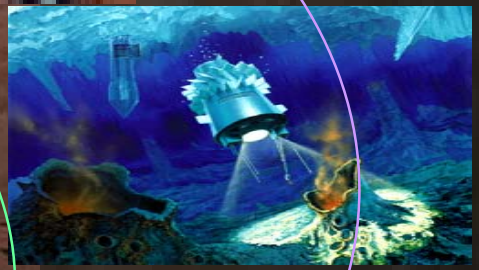


Go anywhere, anytime

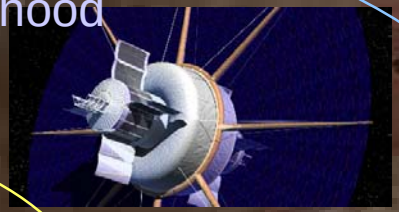
Sustainable Planetary Surfaces



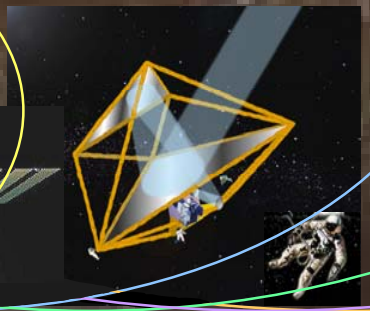
Accessible Planetary Surface



Earth's Neighborhood



Earth and LEO



Key Motivations for AI & Autonomy

- More Optimal use of Deep Space Network (DSN) coverage
- Robust sequences generated on-board
  - Anticipate faults and use software to reconfigure
  - Faster and more robust response to faults
  - Can close loops on-board (e.g., navigation)
- Doing serendipitous science
- Finding requisite skill-set in NASA's workforce

Another Key Motivation

- Human Control is Not Safe!
  - This situation occurred when humans, overriding the autonomous navigation system, went into a very rocky area with Mars Pathfinder in 1997
  - "Blind" moves and turns were used, compounded by noise on rate gyro.

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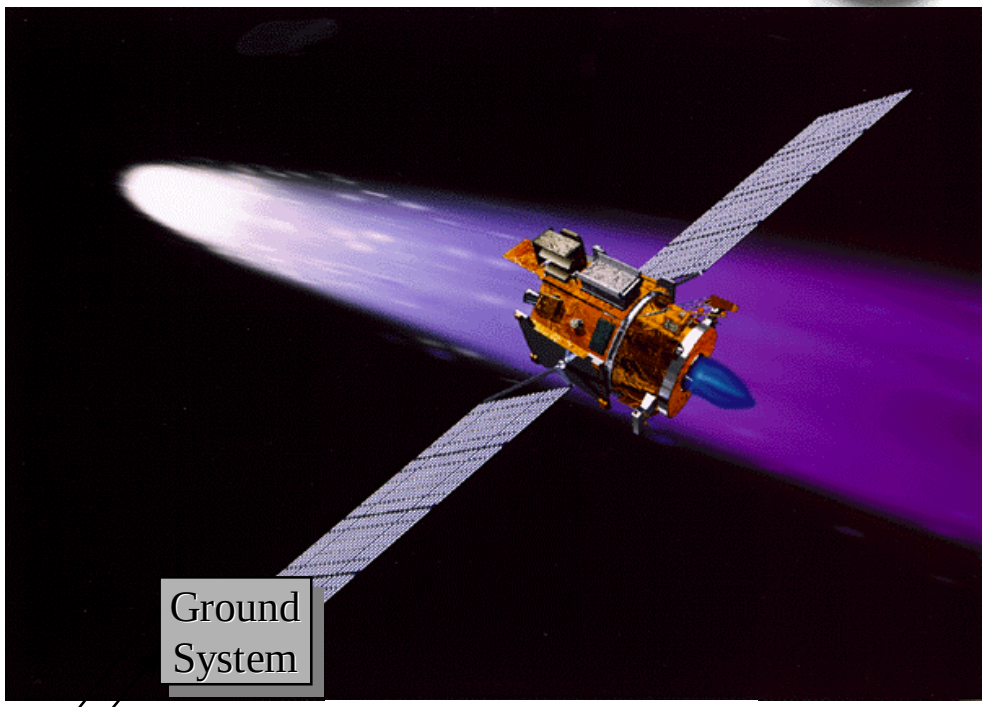
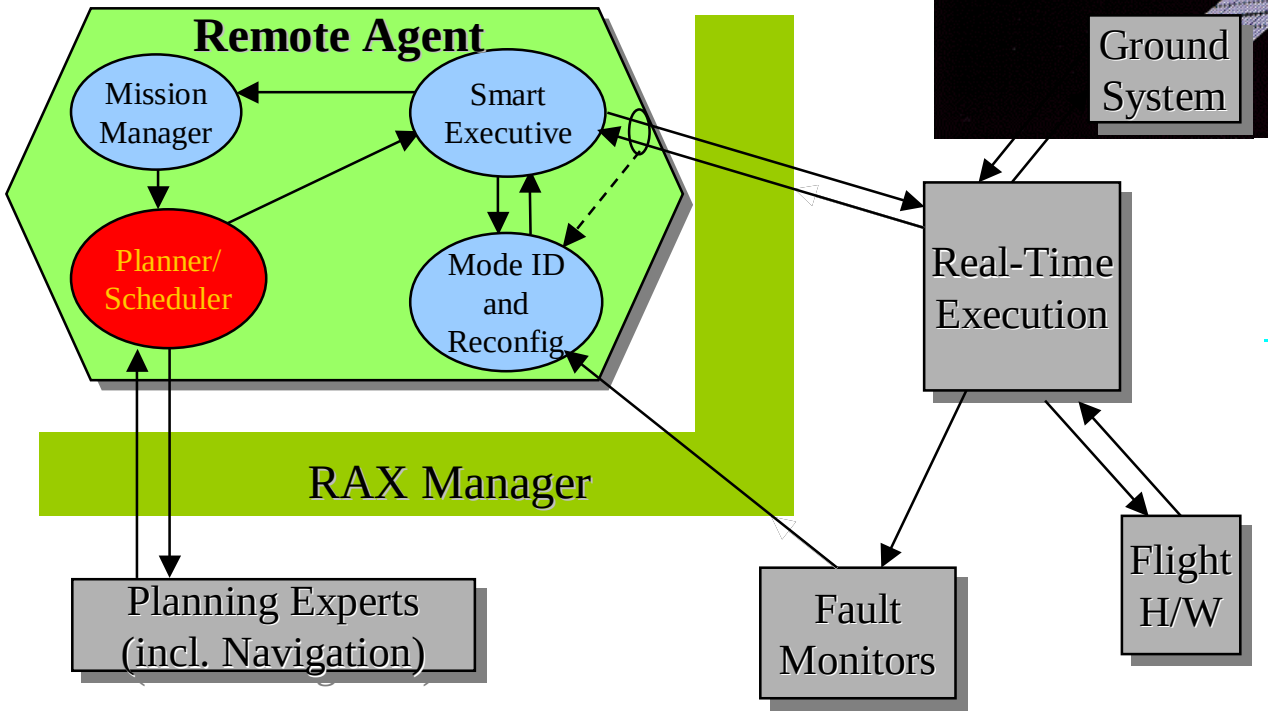
Remote Agent Experiment

- Remote Agent Experiment
  - May 17-21, 1999
  - 65 Million miles from Earth
  - During *Ballistic Cruise*
- Remote Agent on DS1 wins NASA's 1999 Software of the Year





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JPL

Carnegie Mellon

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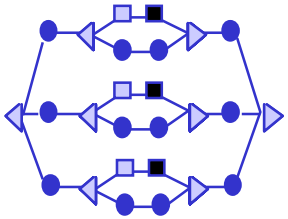
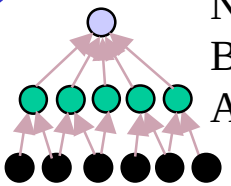
Feigenbaum, *et al.* s' DENDRAL

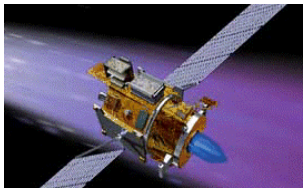
Hierarchical Planners (SIPE, O-PLAN)

Newell,Shaw, & Simon's GPS



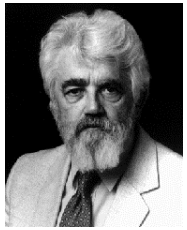


Neural Net Backprop Algorithm



NASA's Remote Agent (RAX)

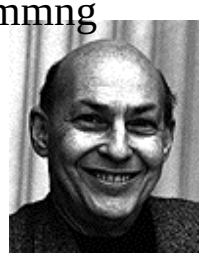
Turing's paper on machine intelligence



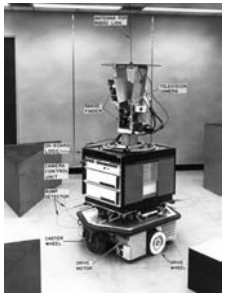
1950 1956 -58 '60s 1968 -74 1980's 1985-90 1997 1999

Dartmouth Conf. & McCarthy's Advice Taker

Heuristic Programmng at MIT



SRI's Shakey, STRIPS, A*



Lenat's CYC

CYCORP

Pearl's Belief Nets

Brooks's Behavior-Based Robots

IBM's Deep Blue

Courtesy: N. Nilsson AAAI-99

ajan ASU Nov 10th, 2004

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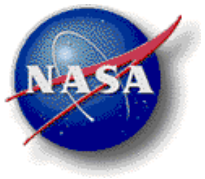
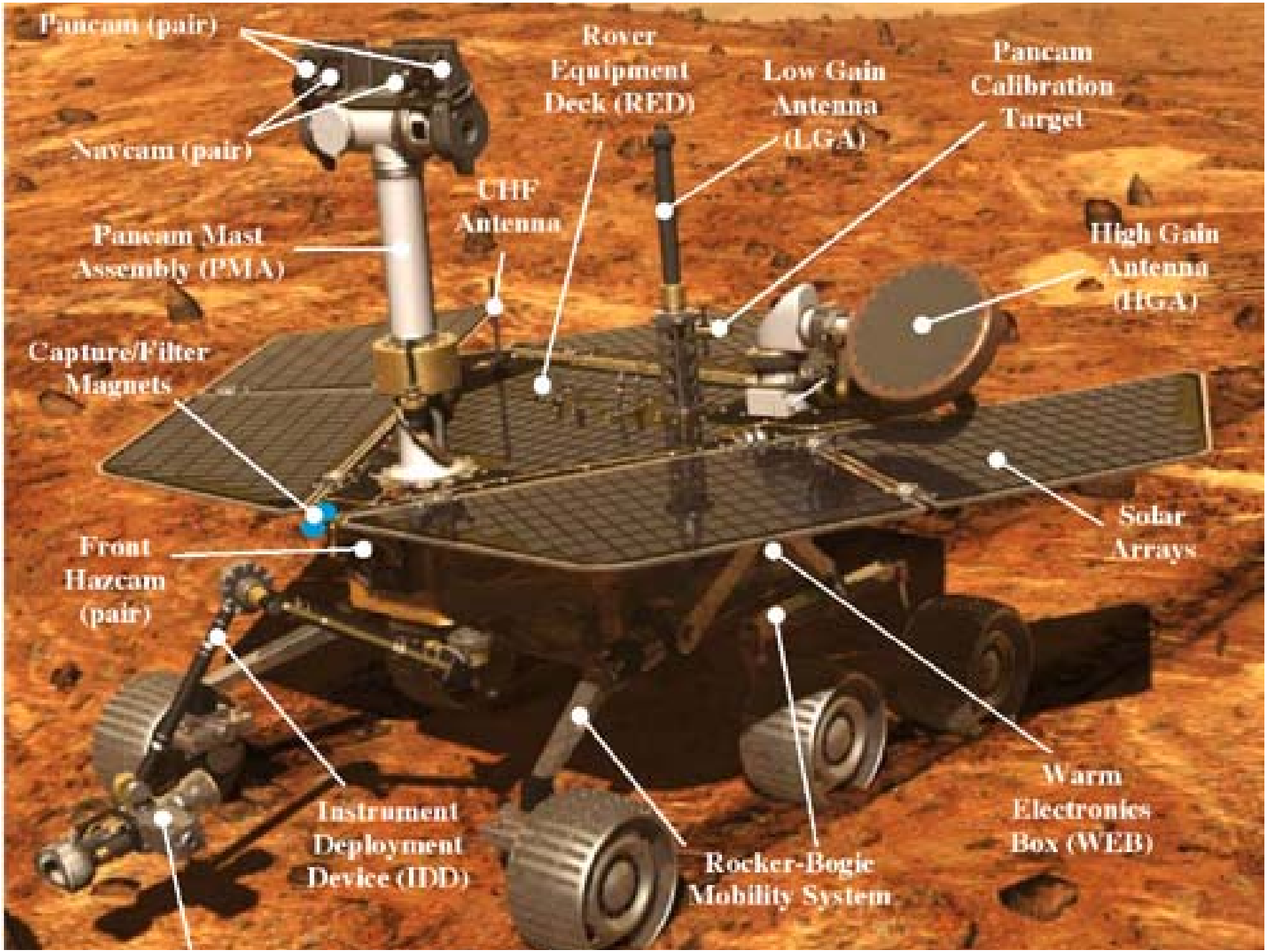
So what is *this talk about?*



- Lessons Learned from infusing a *ground-based* AI Planning/Scheduling system for the Mars Exploration Rovers Mission (MER)
  - Most complex science mission to date in the agency's history
  - Most awaited and examined due to previous Mars mission failures
- What did we learn from infusing a (perceived) high-risk tool set into the mission-critical uplink process
    - How to respond to critics about the utility of AI techniques and their applicability to solving real world problems


Pancam (pair)
Navcam (pair)
Rover Equipment Deck (RED)
Low Gain Antenna (LGA)
Pancam Calibration Target
UHF Antenna
Pancam Mast Assembly (PMA)
High Gain Antenna (HGA)
Capture/Filter Magnets
Solar Arrays
Front Hazcam (pair)
Instrument Deployment Device (IDD)
Rocker-Bogie Mobility System
Warm Electronics Box (WEB)

Outline

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A Brief History of Mission Planning

- DEVISER (Vere et.al) 1982/JPL
  - Mission: Voyager
  - Operational Mode: Uranus encounter (30 days prior)
  - Technology: Chronological backtracking search with simple pre/post conditions
    - Shortcomings: Very high level of abstraction (e.g “turn on scan platform”)
      - Only 100’s of activities in each generated plan
    - No heuristics
      - Programmed specific activities with specific CPU time slices
      - Took 40 CPU hours on a Symbolics LISP machine for plan generation
    - Actual plans with start times might *not* have been used to sequence spacecraft
  - Lesson Learned : Search not feasible in a real-time environment
- PLANIT-2 (Mittman, Eggemeyer et.al) 1999/JPL
  - Mission: Mars Pathfinder
  - Operational Mode: Lander operations commanding every other day
  - Technology:
    - Shortcoming: No search
    - Used an algebraic formulation for maintaining consistency
      - “complex excel spreadsheet”
    - 7 to 30 day plan horizon
      - 1000’s of activities for a multi-sol plan
  - Lesson Learned: Search is not needed in a mission-critical area

Courtesy: Sven Grenander & David Mittman/JPL

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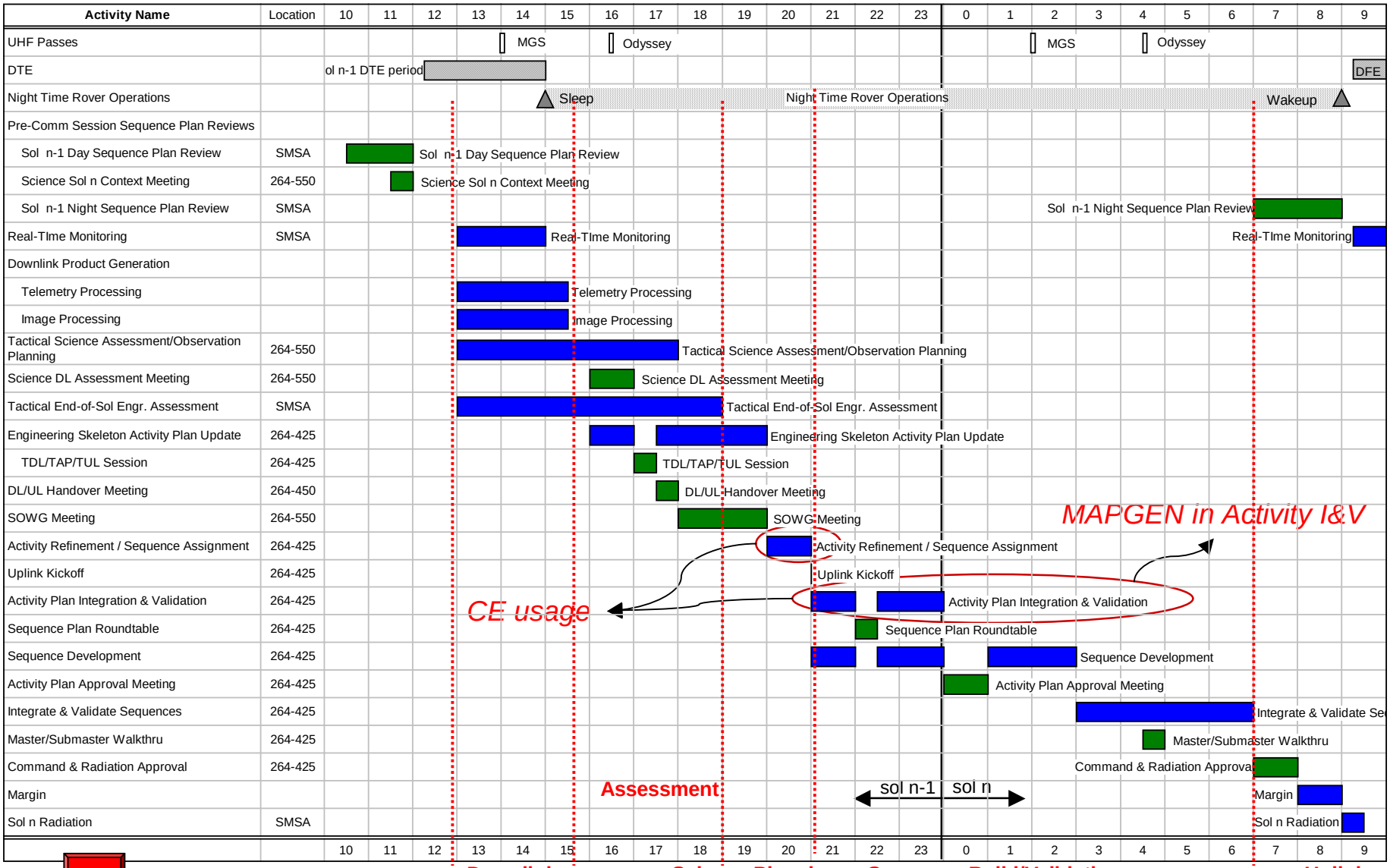
Tactical Timeline for MER Nominal Mission



Courtesy: Jim Erickson

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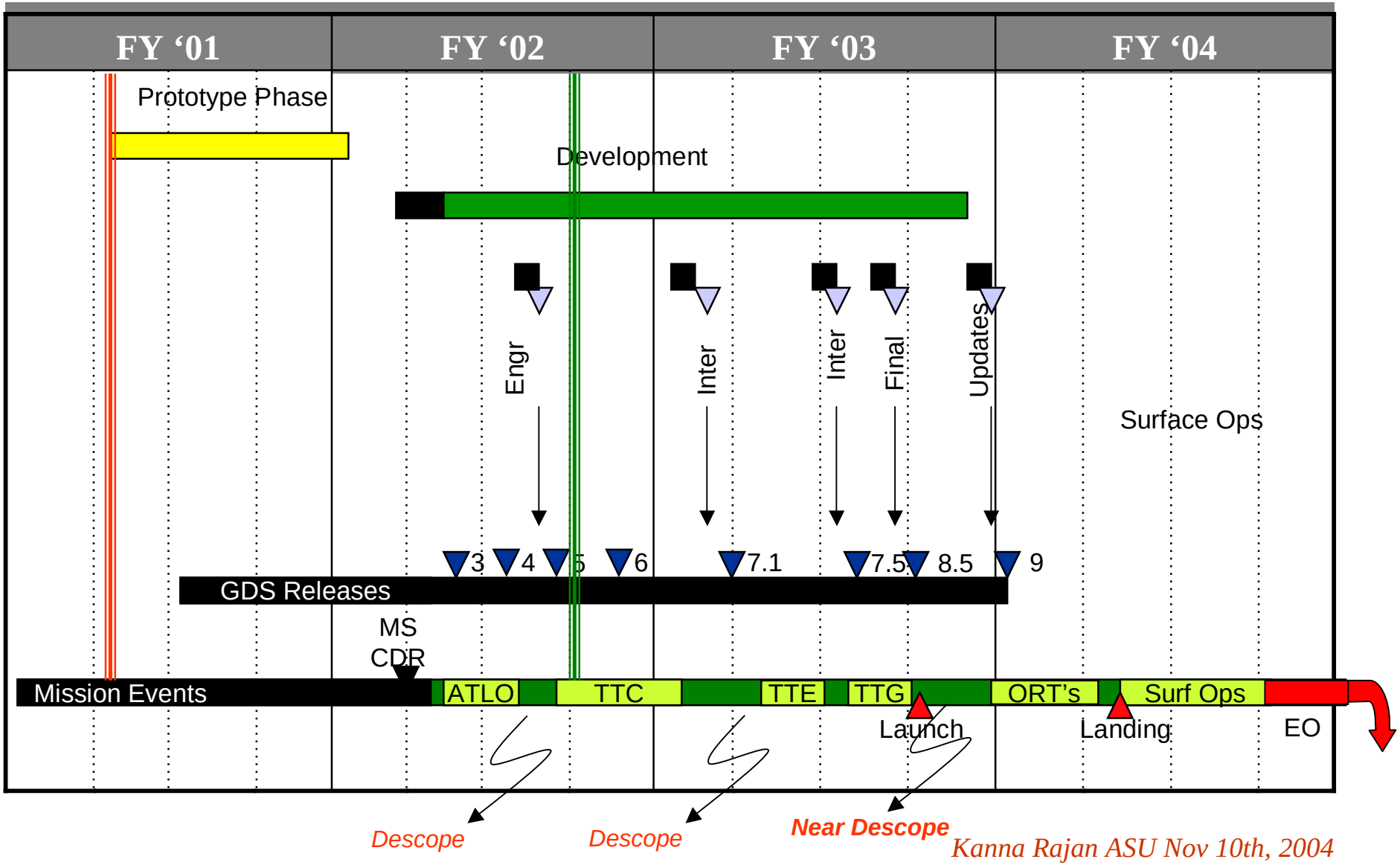
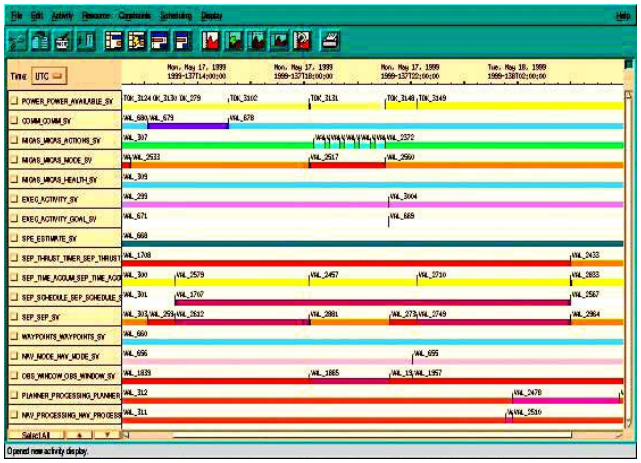
Where we've been on MER



What did we start off with?

- APGEN
  - JPL/TMOD Multi-mission Planning Tool
  - Manual plan construction and editing
  - Flags resource and activity temporal violations
  - Deals with activity hierarchies and abstractions
  - Constraint violations are flagged by SeqGen another multi-mission tool



What did we start off with?

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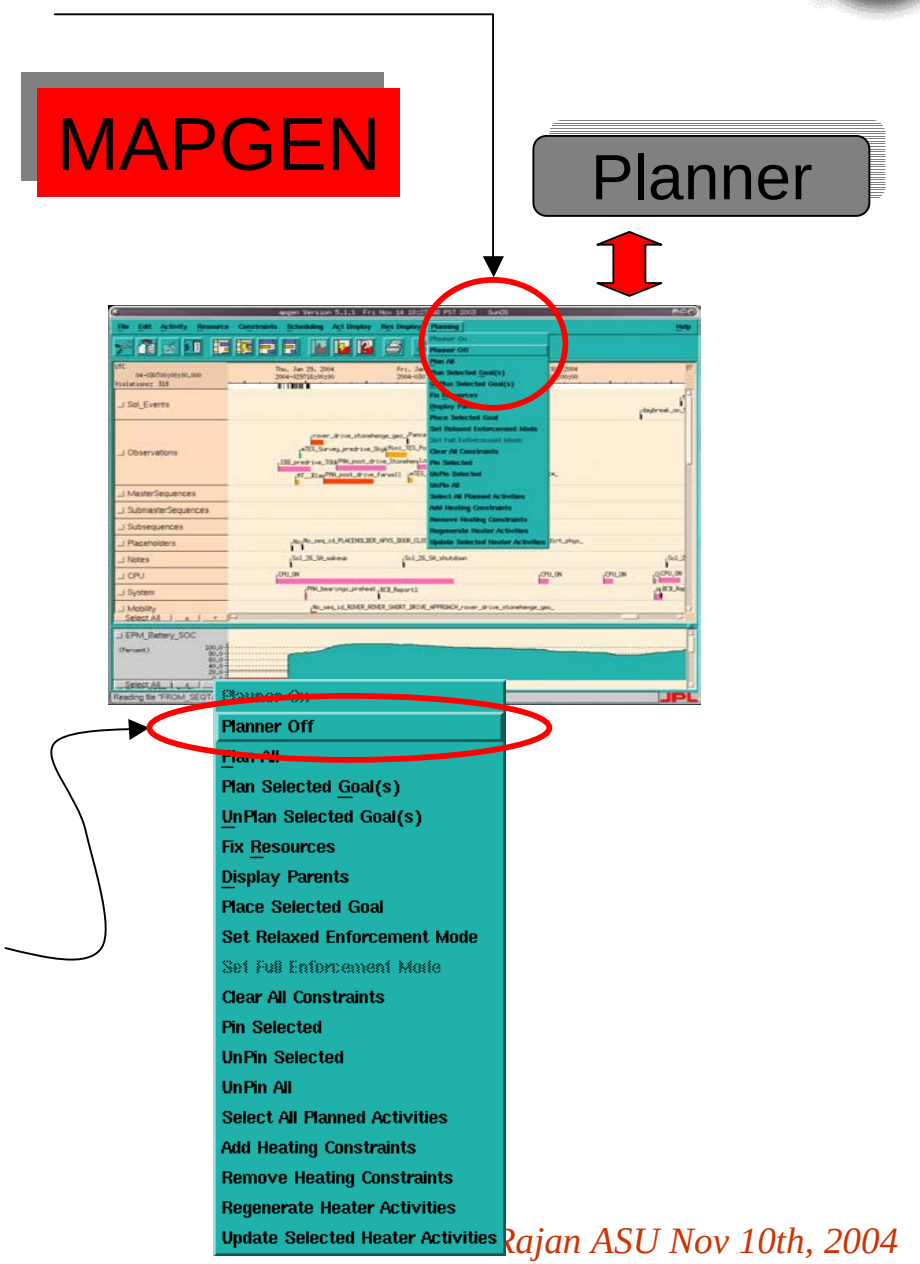
  - Manual plan construction and editing
  - Flags resource and activity temporal violations
  - Deals with activity hierarchies and abstractions
  - Constraint violations are flagged by SeqGen another multi-mission tool
- Added
  - EUROPA Constraint Based Planner
  - A new communications interface between APGEN & Planner
  - Menu items
    - Jim Erickson's ***Disable Planner*** menu item
    - Manual mode was base-lined for the mission



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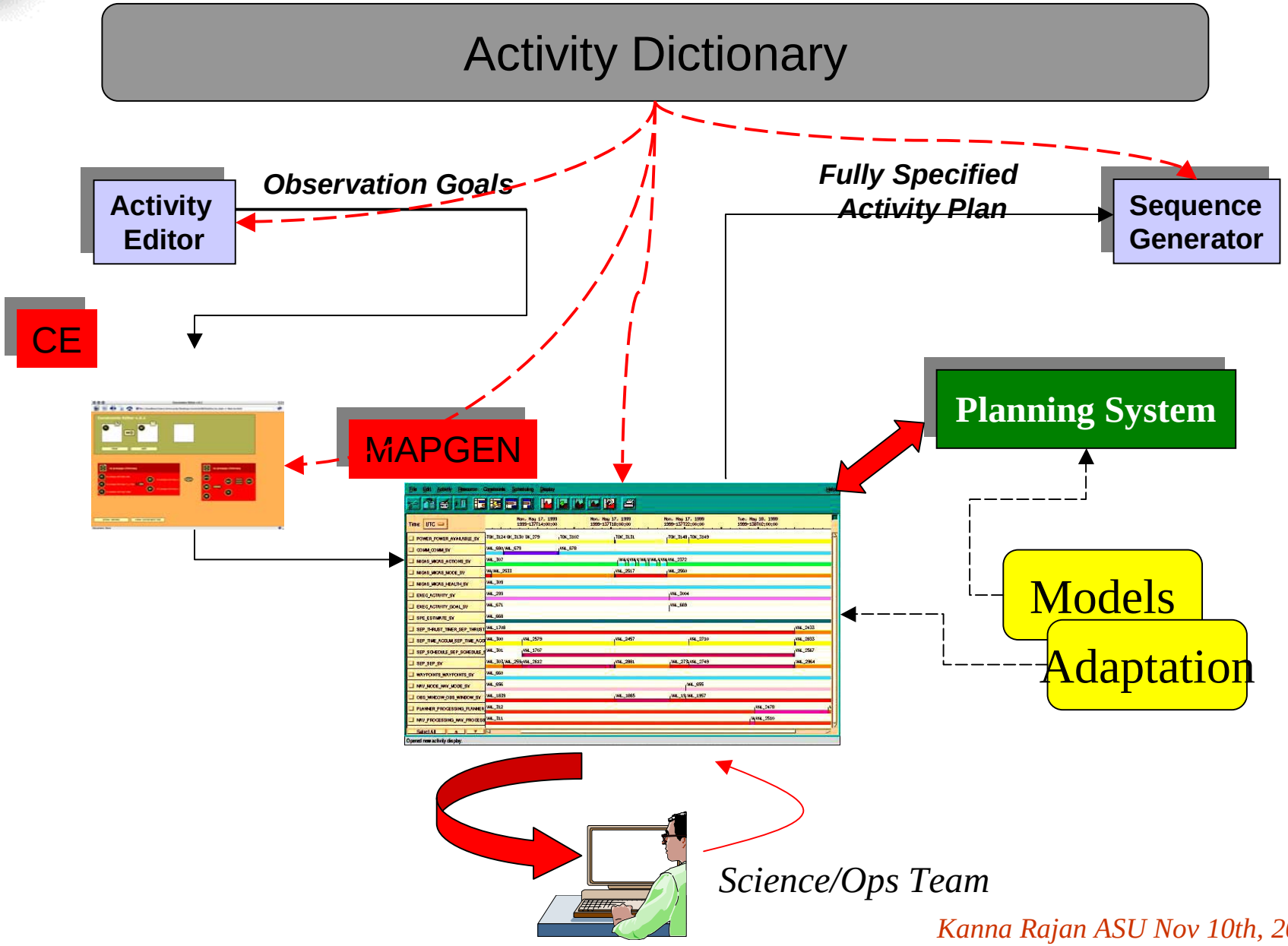
Process Block Diagram for MER



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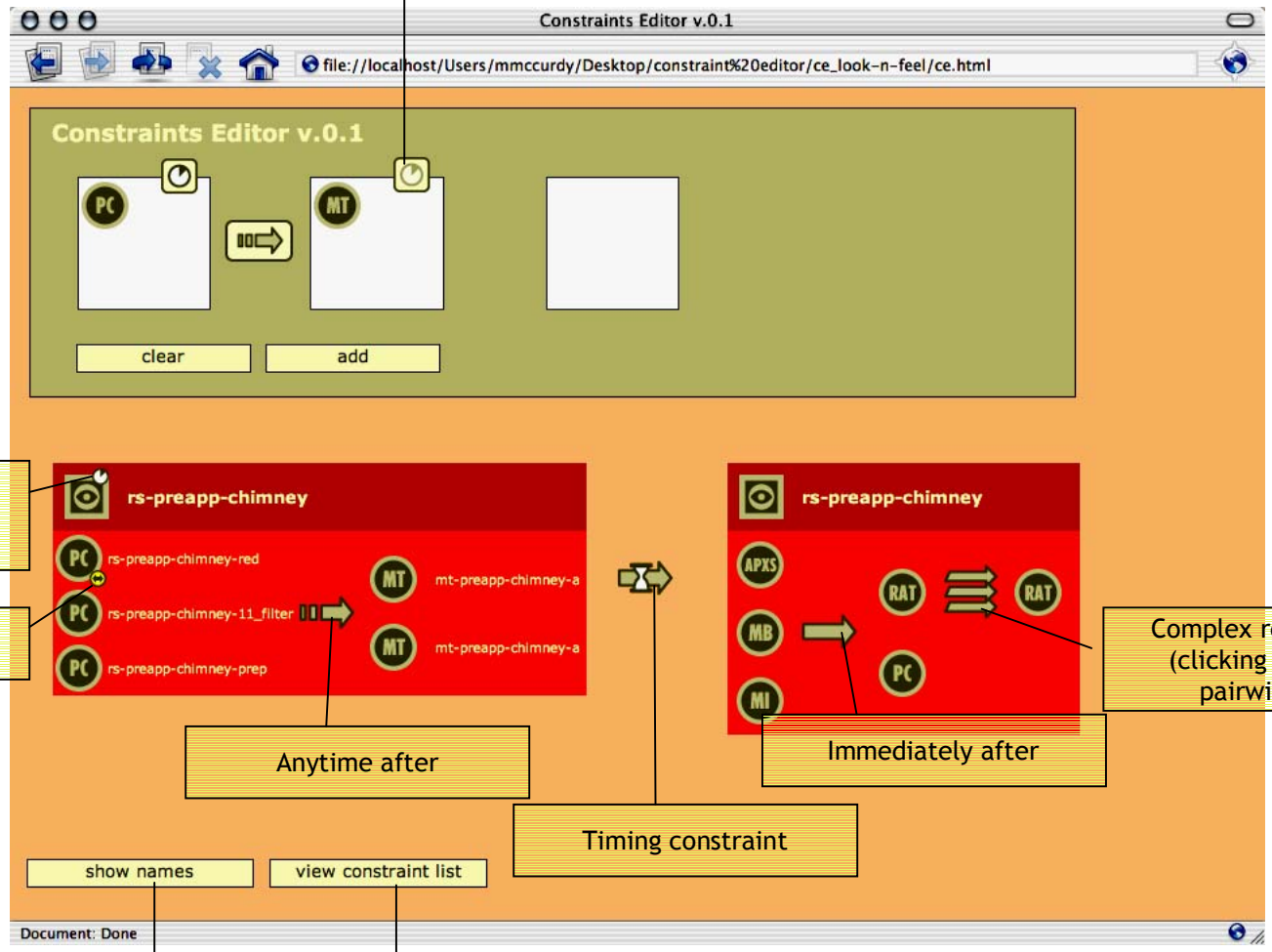
The Constraint Editor



grayed out until time-of-sol set for box

Time-of-sol set for observation/activity

Hidden constraint

Anytime after

Timing constraint

Immediately after

Complex relationship (clicking brings up pairwise list)

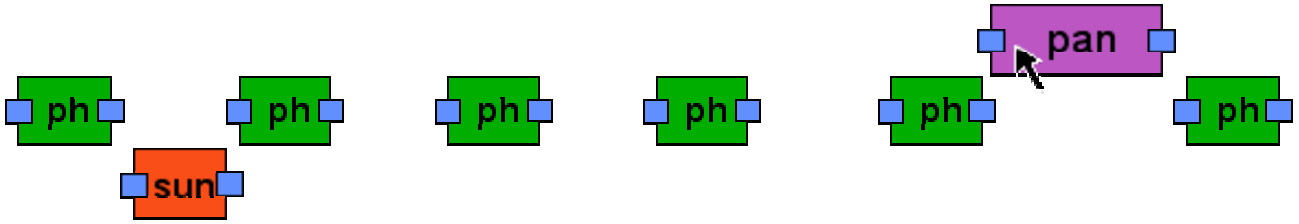
Toggles names as implemented previously. Button label changes to "hide names." (note: mockup shows one example of "names shown" and "names hidden.")

Shows complete list of pairwise constraints

Courtesy: Mike McCurdy, HCI team

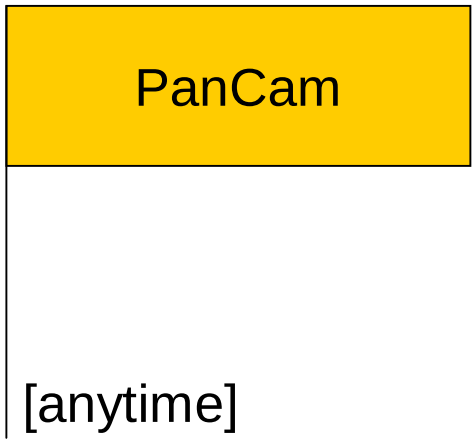
Temporal flexibility

- Time ranges
  - Activities in plan are not necessarily fixed in time
  - Planner keeps track of range for each activities
- Effects of constraints
  - Temporal restrictions (time of sol constraints) limit time range of activities
  - Temporal relations between activities limit time range on involved activities
  - Planner tracks impact of relations and restrictions on other activities



Courtesy: Ari K. Jónsson & Bob Kanefsky

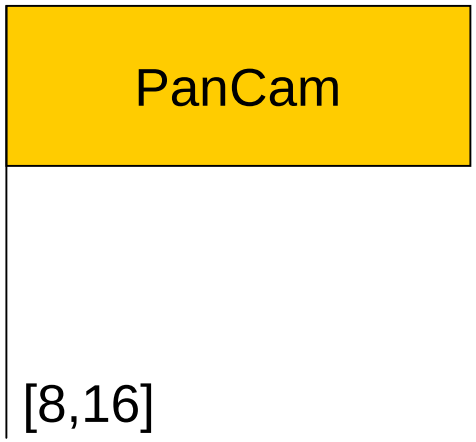
Example



Courtesy: Ari K. Jónsson

Example

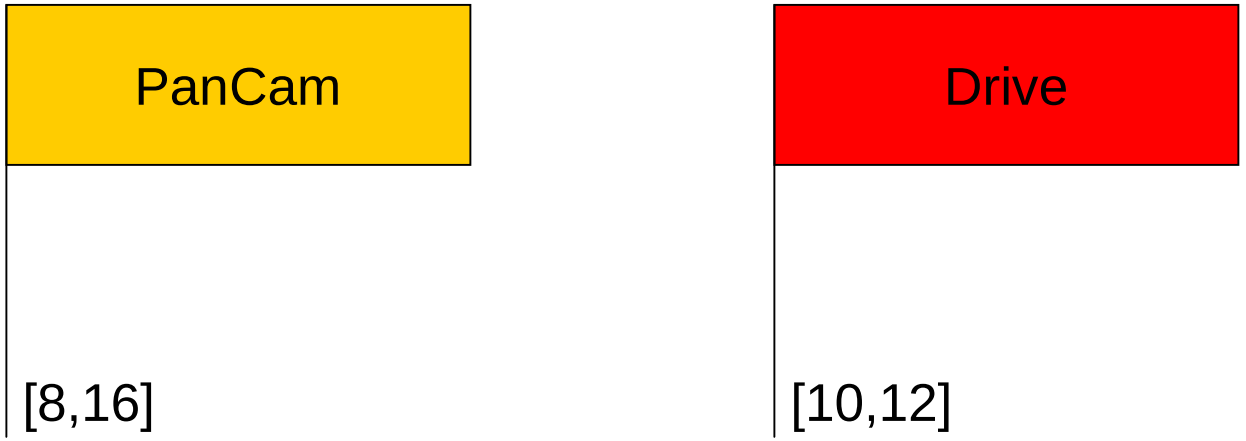
Add constraint: PanCam starts between 8 and 16



Courtesy: Ari K. Jónsson

Example

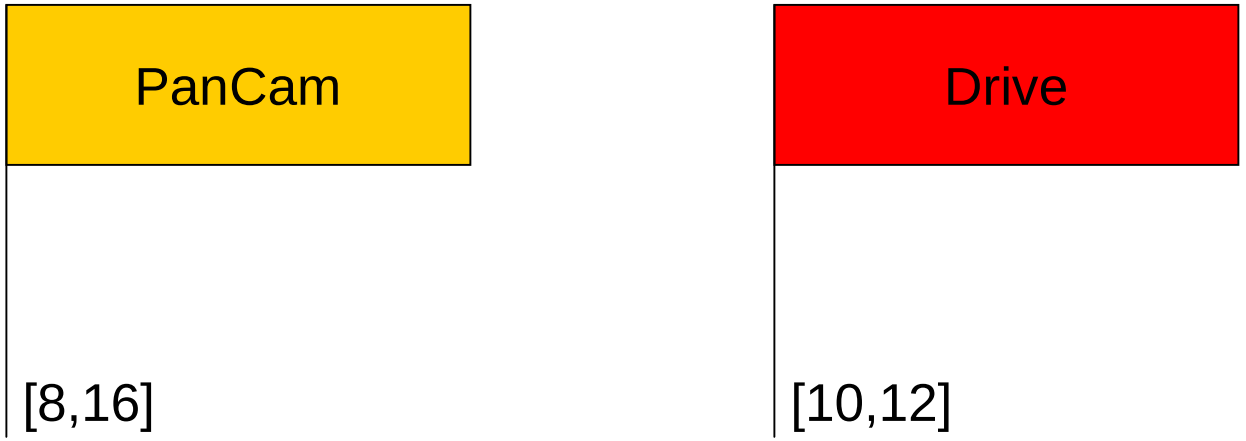
Constraint 1: PanCam starts between 8 and 16
Constraint 2: Drive starts between 10 and 12



Courtesy: Ari K. Jónsson

Example

Constraint 1: PanCam starts between 8 and 16
Constraint 2: Drive starts between 10 and 12
Add constraint: Start of PanCam after end of drive



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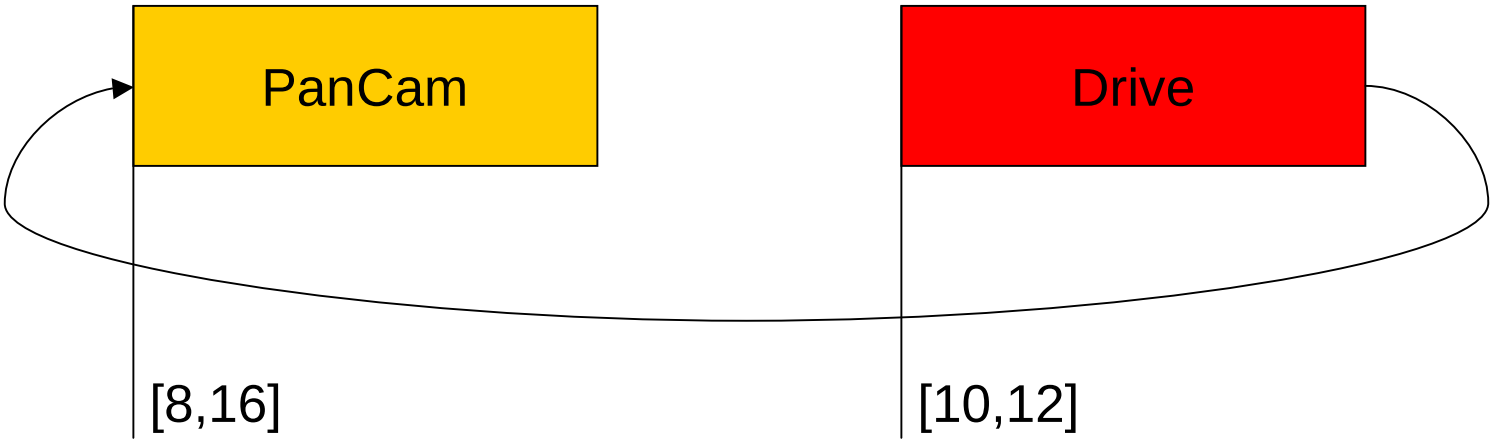
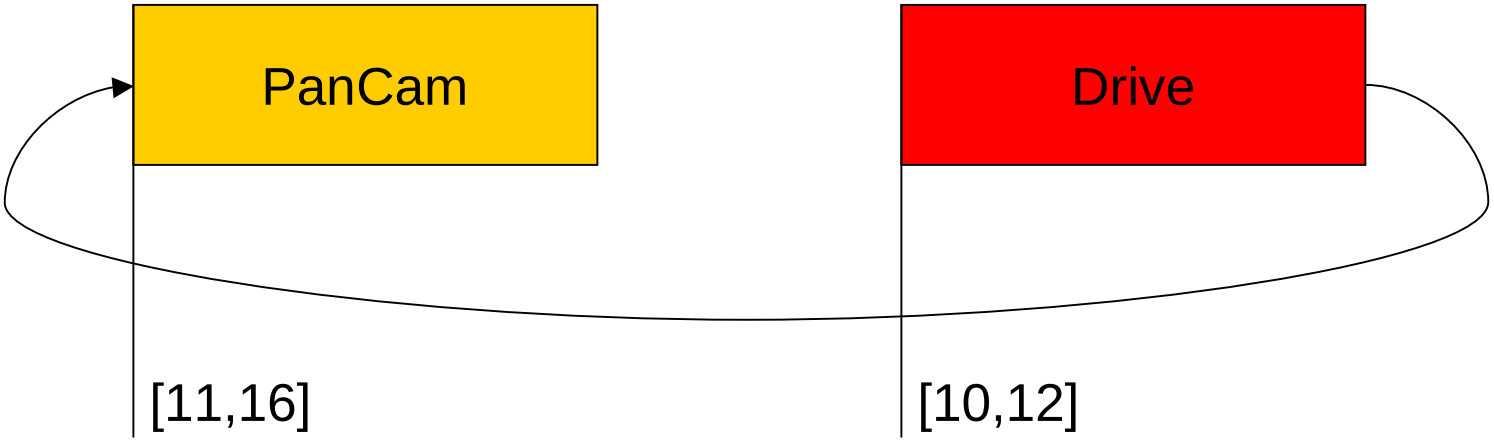


Courtesy: Ari K. Jónsson

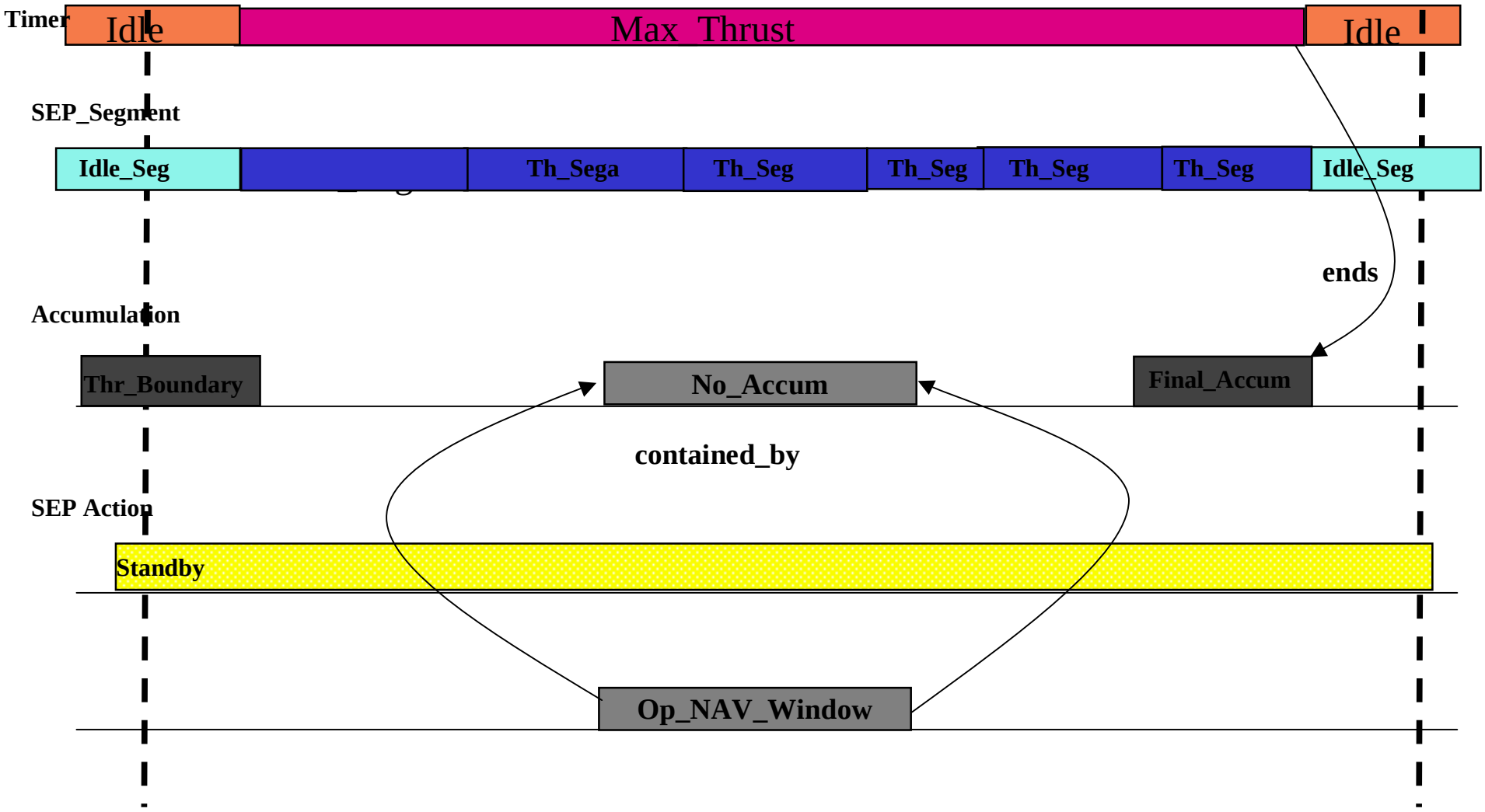
Example

Constraint 1: PanCam starts between 8 and 16
Constraint 2: Drive starts between 10 and 12
Add constraint: Start of PanCam after end of drive
Impact: Reduces time range for PanCam



Courtesy: Ari K. Jónsson

Plan Formulation DS1 Example



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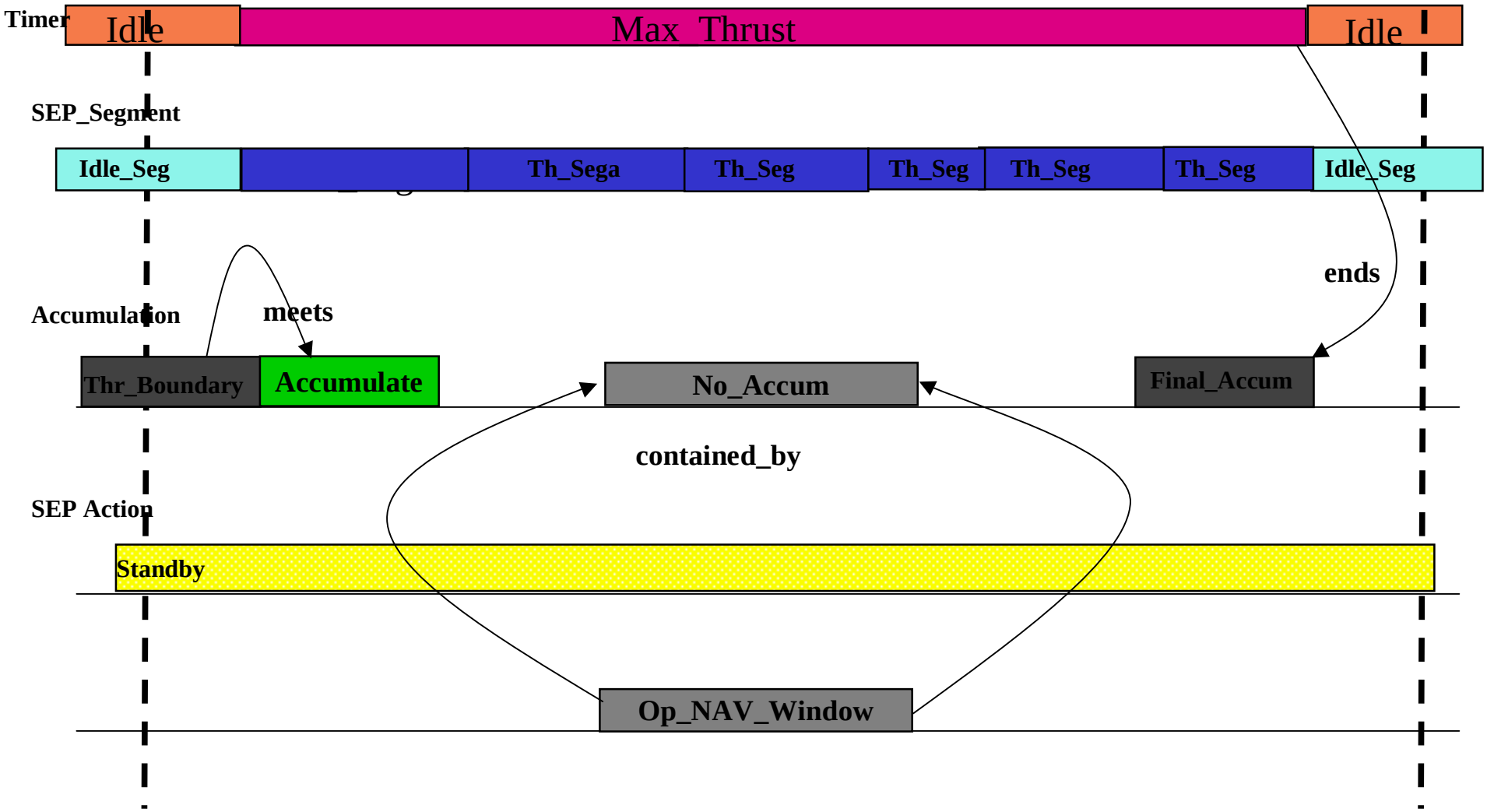
Plan Formulation DS1 Example



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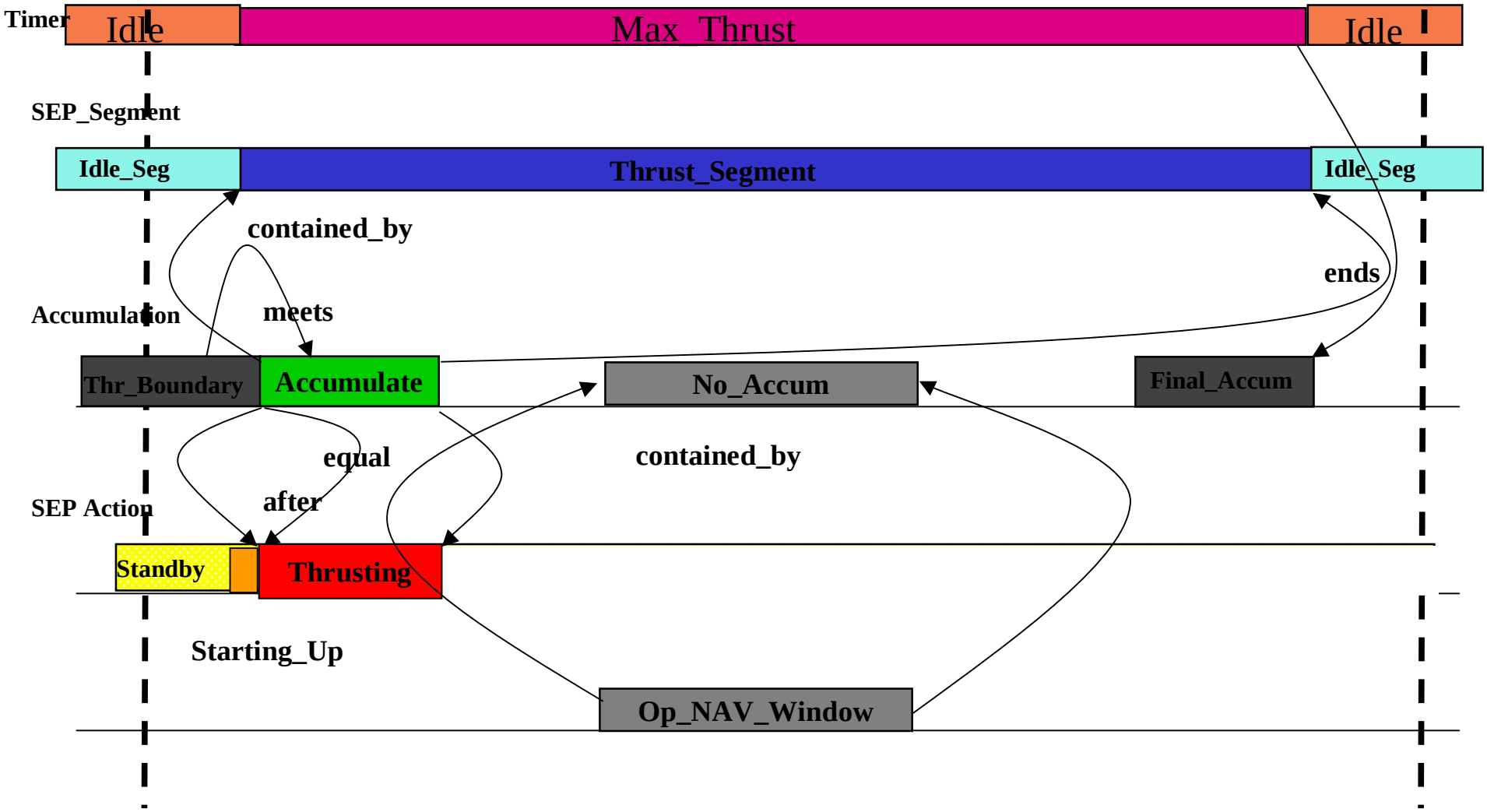
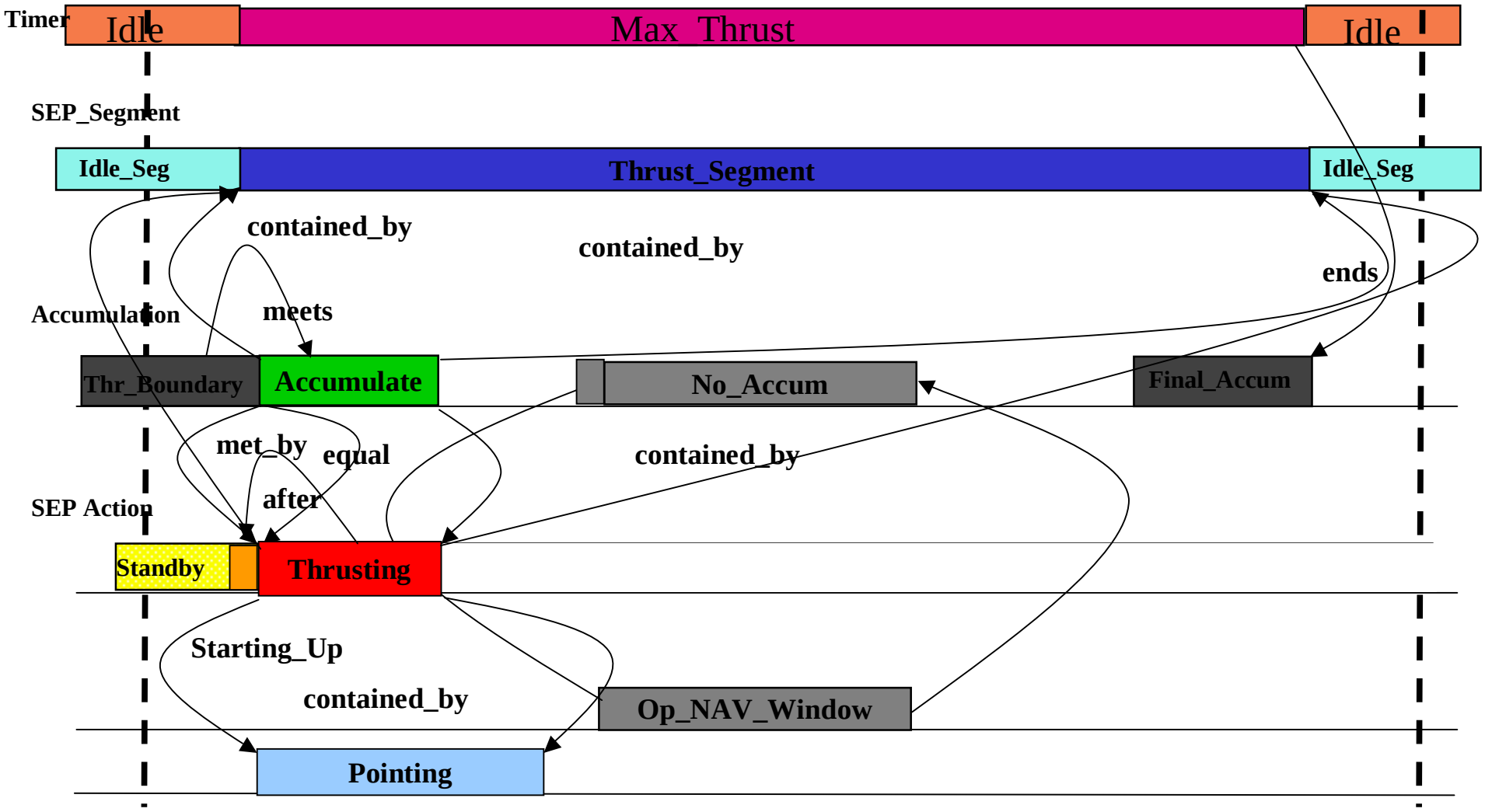


Plan Formulation DS1 Example



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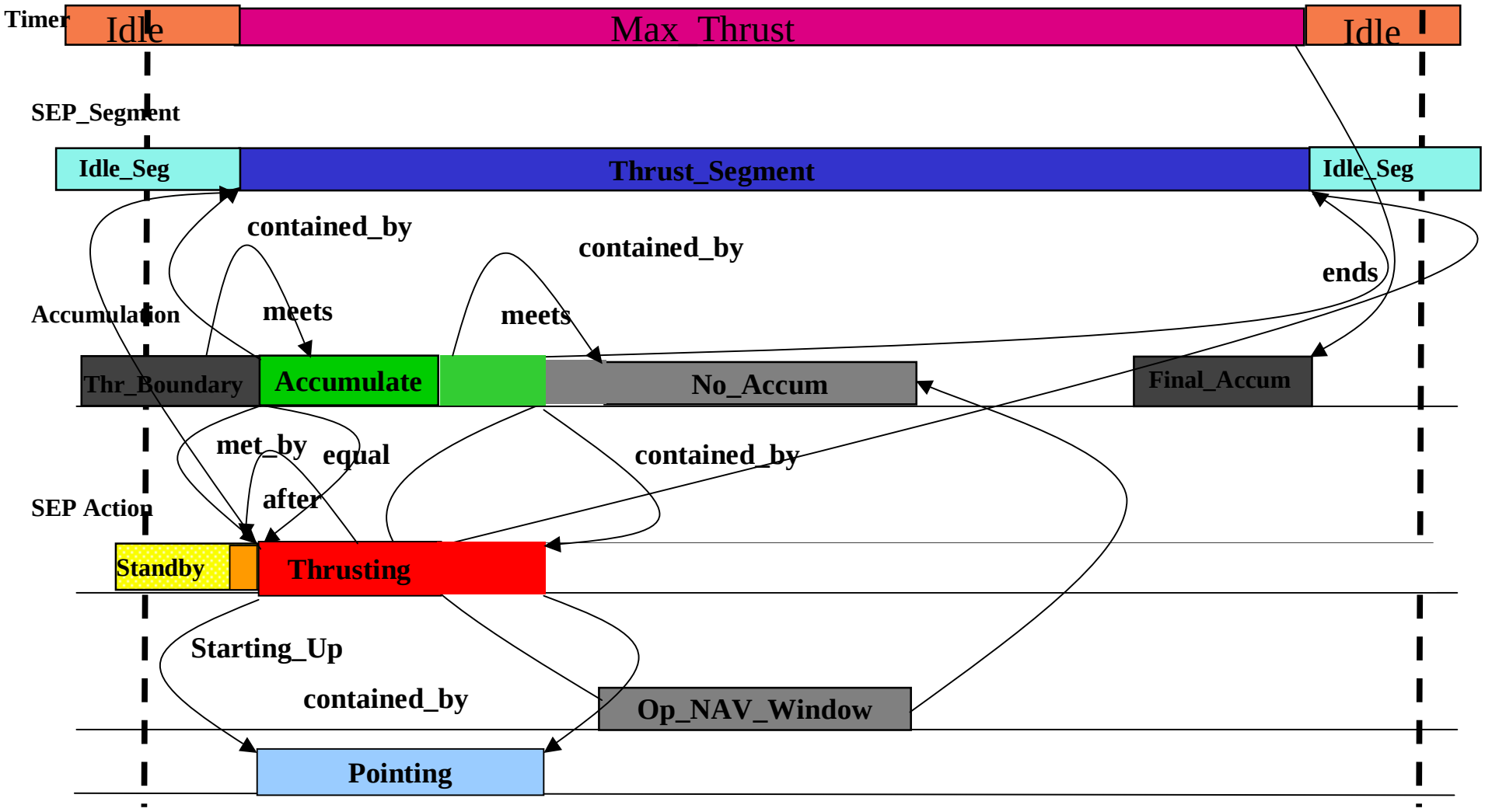

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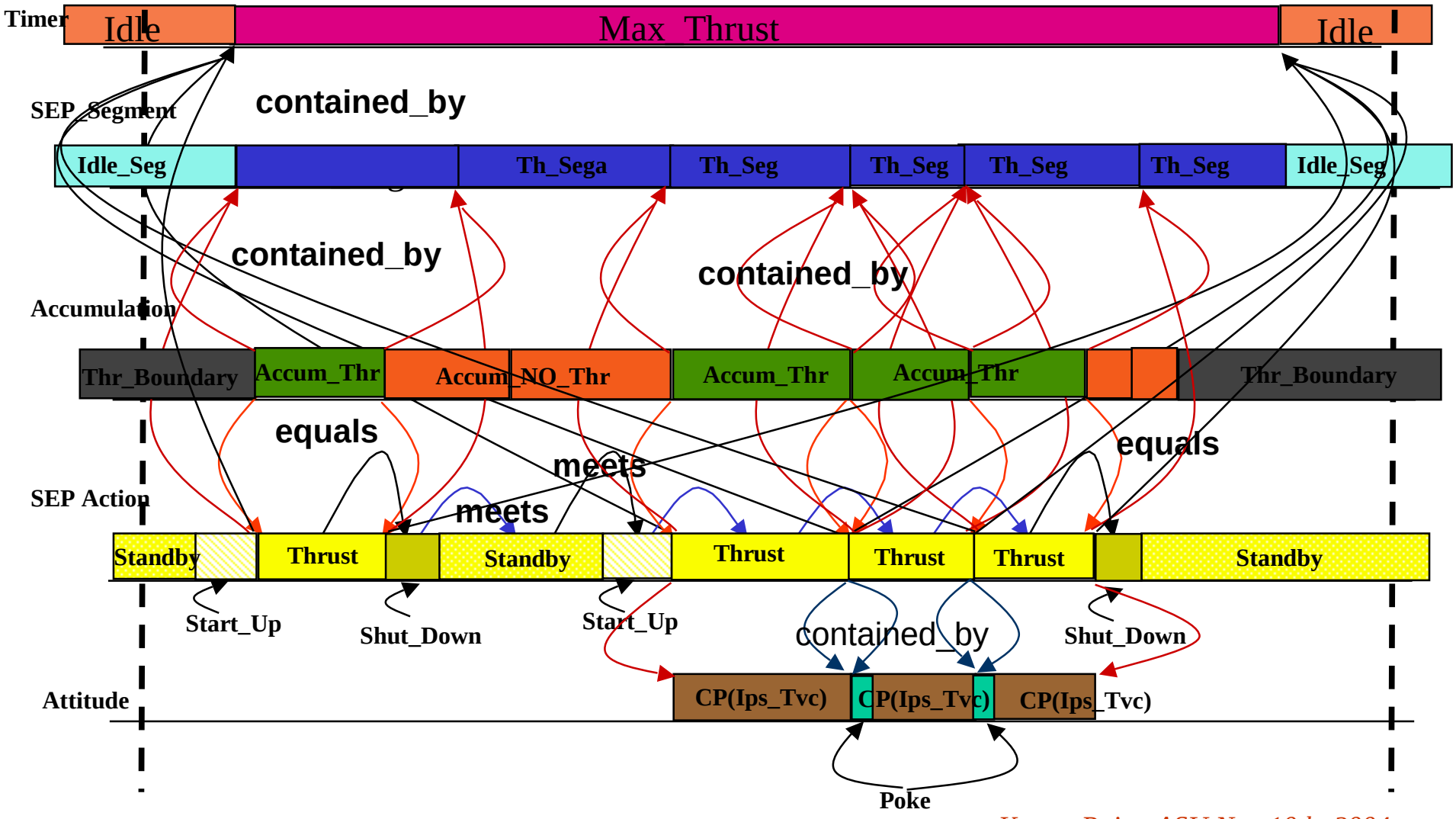
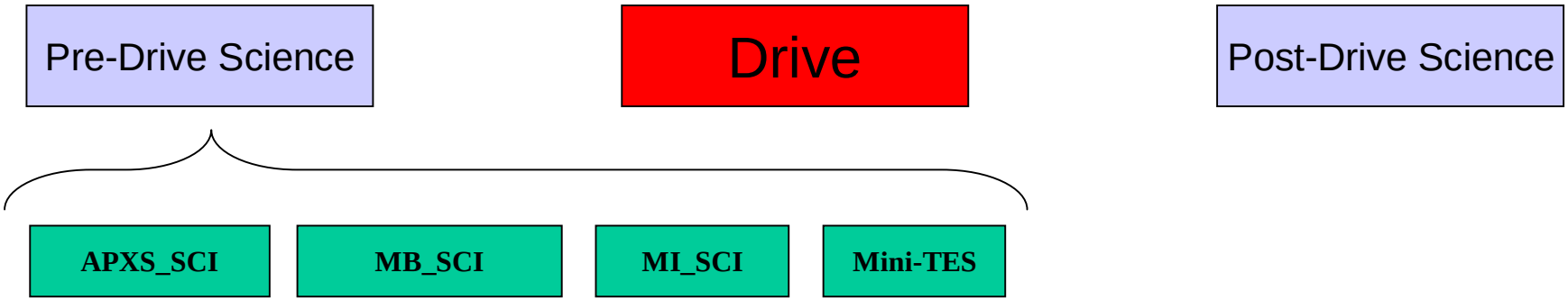
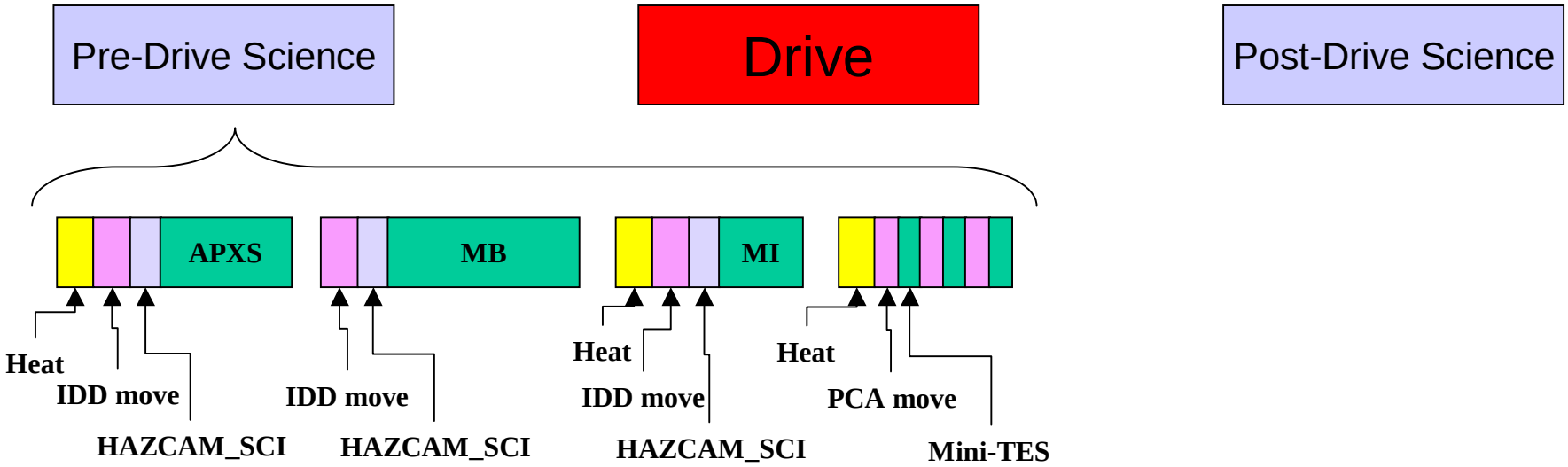


MAPGEN Example: Touch & Go Approach Sol



MAPGEN Example: Touch & Go Approach Sol



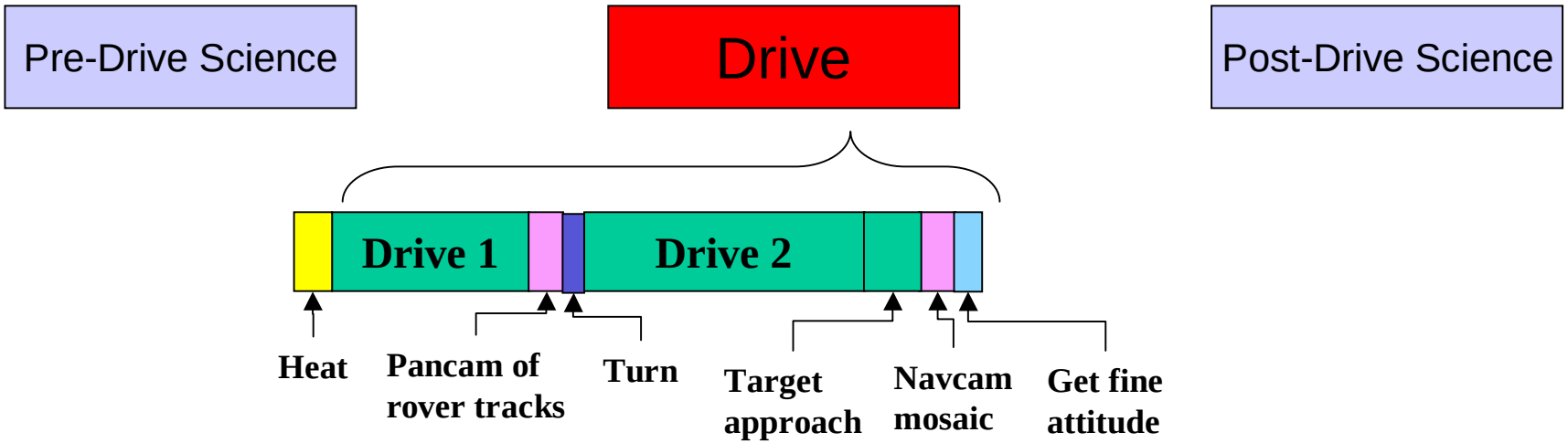
Science Constraints

- APXS duration 30 minutes
- Start APXS before 9:00
- MB duration 1 hour
- MB must follow APXS
- Start MB before 11:00
- MI must follow APXS and MB
- Mini-TES three different rocks in near field
- Prefer Mini-TES after noon
- All of the above to precede drive

Flight Rules

- Cannot move IDD during APXS, MB, or Mini-TES
- Cannot overlap APXS, MB, or MI
- Cannot use UHF antenna during MB
- Heating times a function of time of day

MAPGEN Example: Touch & Go Approach Sol



Science Constraints

- 2-color (left, right, red filter), 2x2 PC of rover tracks
- PC of rover tracks after 2:30pm (or as late as possible)
- PC of rover tracks should be after first drive but before turn at waypoint
- Navcam mosaic of 5 images facing target
- Navcam mosaic must complete before DTE pass
- PC of cal target within 15 minutes of any other image

Flight Rules

- Cannot drive during APXS, MB, or Mini-TES
- Pancam, navcam, and get fine attitude cannot overlap
- Heating times a function of time of day

MAPGEN Example: Touch & Go Approach Sol

Pre-Drive Science | Drive | Post-Drive Science

- Post-drive similar
- One DTE com pass in the afternoon (time varies)
  - Activities creating critical data must complete before pass
  - Various exclusions during the pass
  - Several additional UHF passes (with constraints)
- Other science targets are inserted, for example:
  - Mini-TES spots at 10º, 20º, 30º from horizon starting as early in the morning as possible and repeating every hour as possible
- Planer must respect resource constraints, for example:
  - Power (incremental and final state of charge)
  - Data buffers and critical data

Planner runs in about one minute for plan generation on a Solaris Blade 2000

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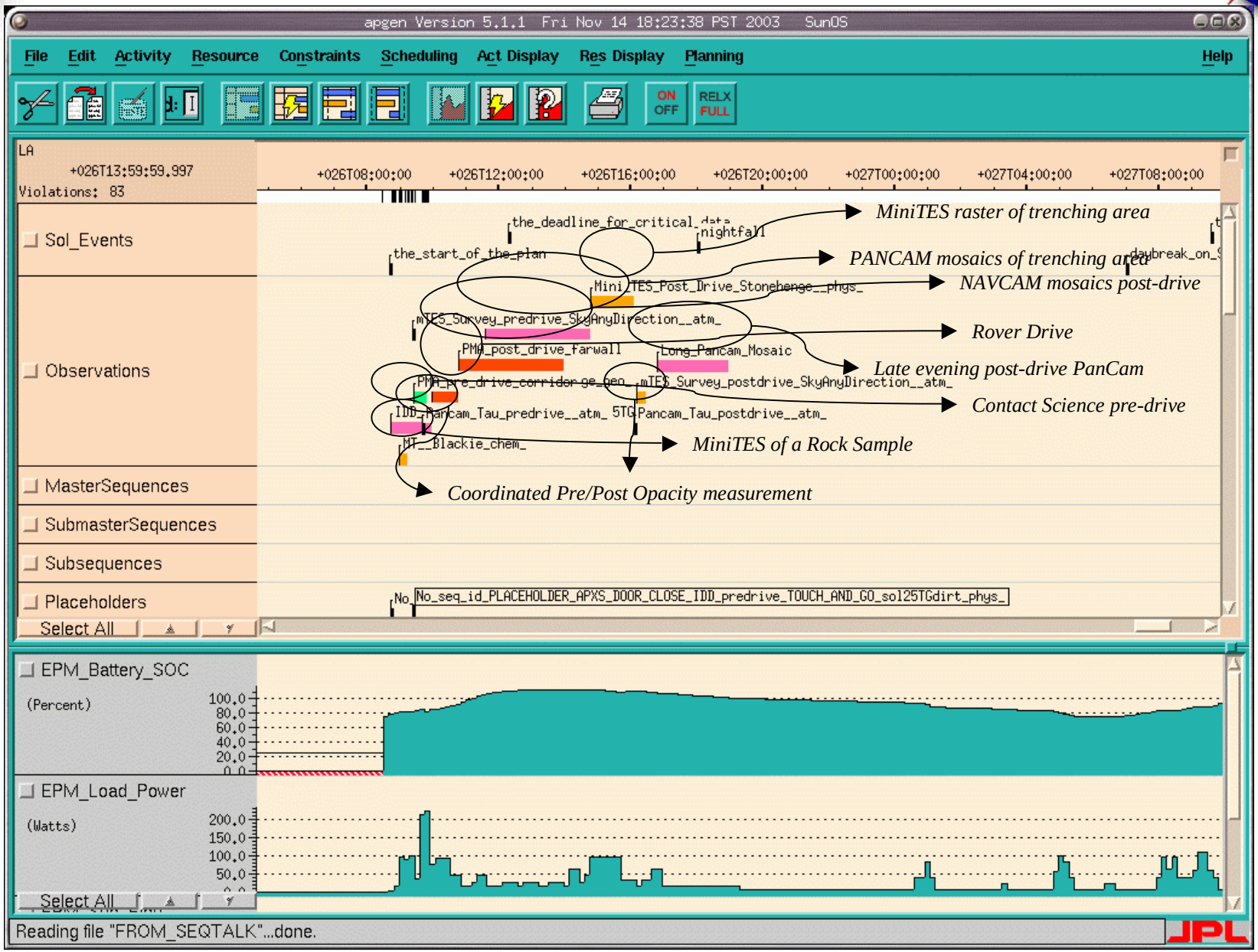
MAPGEN Plan Visualization



So what's the big deal?

1. As technologists we learned how to work with people!
   - Not just customers but also people who might have an integral role to play in systems deployment
2. The process of infusion showed how far the AI community is from solving real-world *mission-critical* problems
   - The technology itself was *less* important
   - Rather what the problem (and how) it was brought to bear was critical

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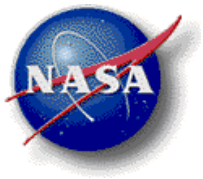
Outline



- Introduction
- What is MAPGEN?
- Lessons Learned from MER
- Wrap up and Conclusions

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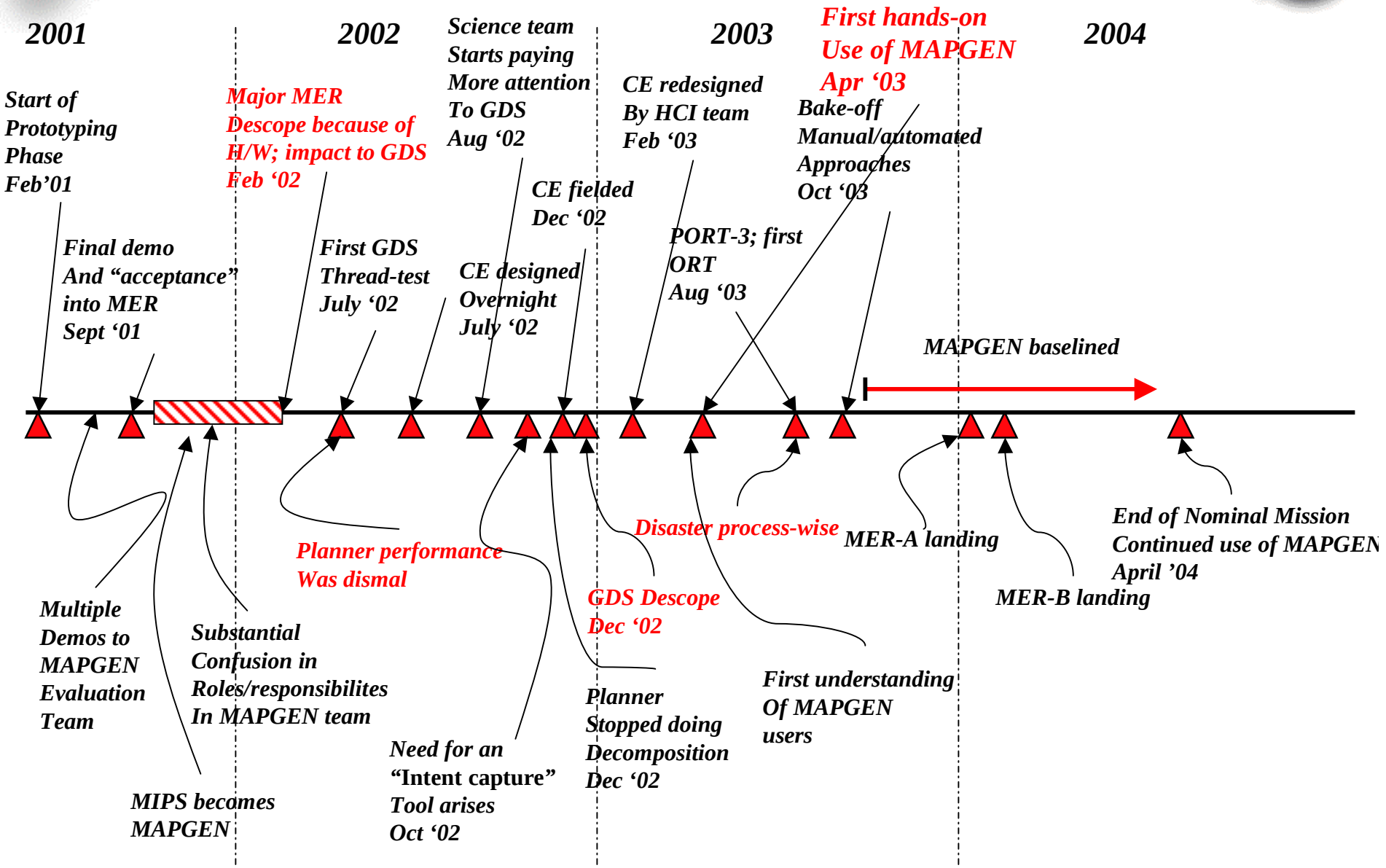
Deployment at a Glance

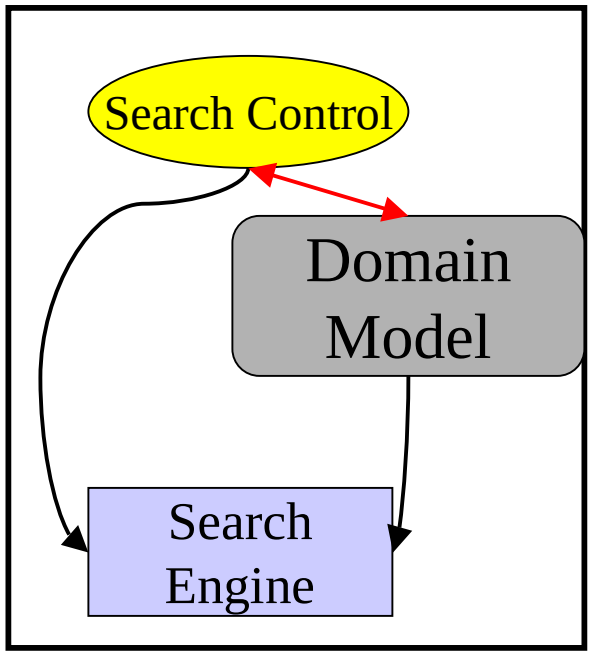


Generic Lessons (re)Learned

1. Advocacy from within the customers organization is crucial
   - Customer training and buy-in is not a luxury
2. Often the problems we'd like to solve (as AI researchers) are not considered important, others are
3. Requirements are either non-existent or evolving during the development phase
   - Software engineering texts about writing to well written requirements is all baloney!
4. Testing of software in the environment of its use must be like Italian elections
   - Early and often!

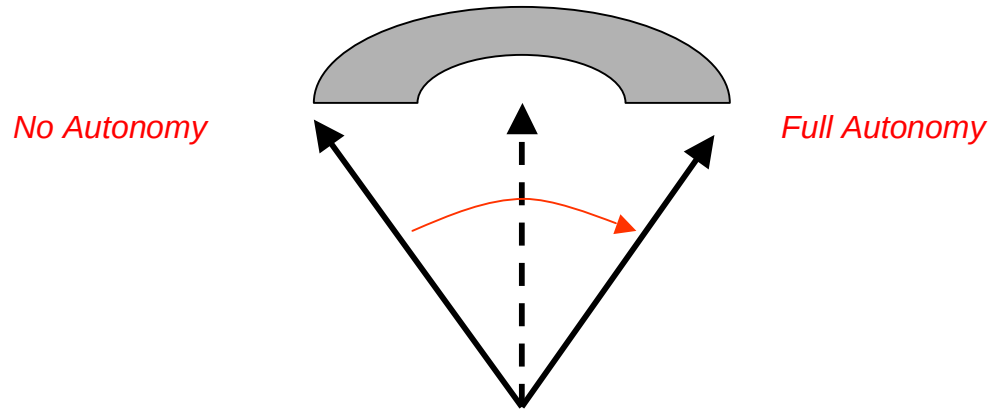
AI relevant Lessons Learned - 1

- Evolving requirements and the spiral development process calls for model based approaches
  - Core code base/engines need to be stable
  - Configuration or model files are easier to change than
  - Use general solutions as often as possible
  - Performance is important, but not by that much
    - Hardware is often fast enough to hide the (lack of) efficiency of implementation



AI relevant Lessons Learned - 2

- All or nothing approach = nothing
  - Adjustable autonomy is not just a buzz word
  - Incremental use of automated search (for example) should come after user(s) have a feel for the system using even primitive techniques



AI relevant Lessons Learned - 3

- Causal explanation: What is the system doing and why
  - Adds to the warm-fuzzy feeling of the end user
  - Useful for debugging complex domain models (even search engines)
- Preference (or soft) constraints
  - Rules are meant to be broken, even in a mission-critical environment
  - Doing so with human cognizance and systematically are important

AI relevant Lessons Learned - 4

- Often the need for validation & verification will follow the expression “AI” in the real world
  - Don’t be fooled by it. There is as little/much V&V for conventional software as there is for AI based systems
  - However V&V is still among the most crucial issues of deploying systems:
    - *You as a developer have to have as much (or more) confidence* that your system is built right and for the right requirements as the customer expects!

AI relevant Lessons Learned - 5

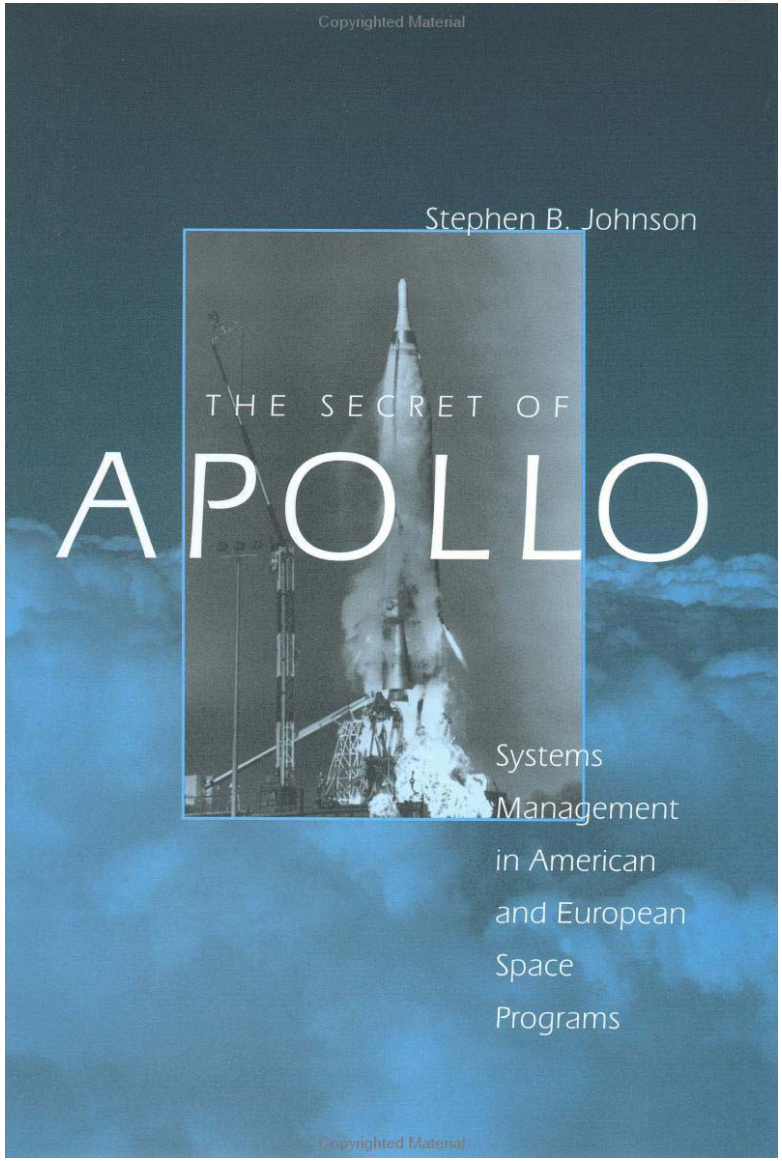
- Often the critical issue is better (not necessarily optimal) use of resources in problem solving
  - E.g "*Given the limited resources onboard the rover, how much more science can we get per Sol?*"
  - Optimality in problem solving is not necessarily an important *practical* consideration
  - Another reason why Scheduling techniques have had more success
  - AI techniques do need to deal with time and resources (renewable and expendable)

AI relevant Lessons Learned - 6

- As a community we need to pay more attention to the less sexy parts of the process:
  - Knowledge Acquisition and Engineering
  - Standardized domain modeling representations
    - For V&V, visualization
  - Information delivery

AI relevant Lessons Learned - 7

- For mission-critical software, systems engineering is something we as a community need to learn about
  - Involves a discipline of development
  - Systems engineering
    - Connecting the pieces in the software puzzle
    - Ensuring s/w is not developed in isolation to its operating environment



A word about Ethnographic studies

- Human Centered Computing applied ethnographic methods for three years during the design phase of the MER mission
  - in-situ observations during field tests and readiness tests
  - analysis of design documents and video tapes of trainings
  - participation in meetings and tele-cons
  - worked with JPL and Ames users and developers

- Contributions to MER included:
  - Development of an ontology for science activity planning.
  - Prioritization Scheme for decision making
  - Software recommendations
  - Design of the Mission Support Area
  - Processes and procedures for science planning and uplink process
  - Communications and work flow recommendations

Courtesy: Roxana Wales

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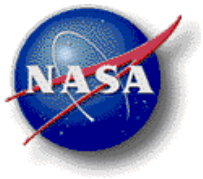

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What all did we do for MER?

- Increased Science Return
  - According to Steve Squyres, MER PI, *at least* a 20% increase over a manual approach
- Reduced Workload on TAP's
  - Encoding complex flight/mission rules
  - Captured scientific intent in the plan
  - Allowed TAP's to to do *what-if-analysis*
- Helped in Uplink design
  - Working with principal mission designers & TAP's
- Part of the Operations Team (supported by MER funding)
  - John Bresina as TAP
  - Bob Kanefsky as Uplink problem trouble-shooter
- Current Status:
  - Continued and consistent use in Extended Ops

MAPGEN in Surface Operations

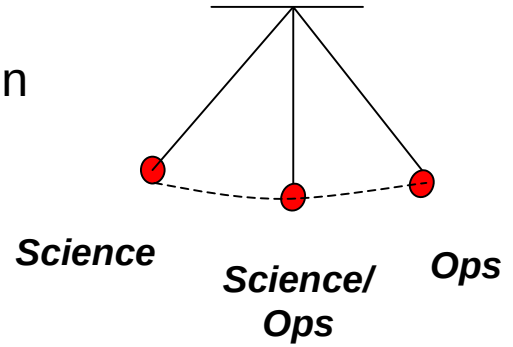
- MAPGEN: First AI based System to control a spacecraft on the surface of another planet on January 15th 2004

- Spirit:
  - Nominal science operations from Sol 15 to 18
    - All planned activities from 16/17 executed on board
  - Return to nominal science operations within 2-3 days
- Opportunity:
  - Informal use begins Sol 4/5
    - Commanded activities executed on board nominally
  - Nominal science operations tomorrow (Feb 6th)
- Dual rover support use of MAPGEN in full swing

- Conservative Return on Investment (ROI) to NASA: 20% to 30% additional science returned per Sol, over a manual approach for plan synthesis

Key MAPGEN Challenges

1. MER project's Ground Data System (GDS) was late in formulating a decisive plan of the uplink process
   - Navigate the challenges of process (re)(re)(re)design
   - Finding the "customer" to find the requirements
   - Shifting requirements



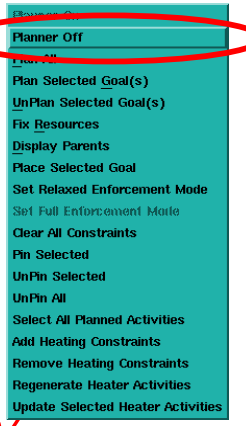
2. Convincing Operations personnel that plans produced would be
   - Quantitatively and qualitatively "better" plans
   - Plans during surface ops would be relatively complex enough for automation to help and cope with
   - Flight and mission rules encoded were being enforced in generated plans
     - Issue of Verification & Validation of search algorithm and models
   - Fundamental issue of a question of "trust"
3. Convincing management that AI can deliver a quantifiable ROI
4. Aggressive schedule with little time for training
5. Integrating a flexible time planner representation with a fixed time point visual representation.

Key AI Challenges

1. AI has a perception of replacing humans, rather than aiding them
   - Complexity of human tasks is rising nearing the limit of human cognitive skills
   - Human imagination far outpaces skill or ability
2. AI and "non-determinism" somehow seem to be linked in people's minds
3. Verification & Validation of AI and Autonomous systems *is critical*
4. AI needs hard problems to solve, not easy ones
   - Finding interesting problems that require a comparable human effort to solve will not cut it

Key MER Successes

1. MAPGEN Base-lined for dual rover ops Oct 2003!
   - Currently supporting Spirit and Opportunity surface ops
   - MAPGEN generated plans have been repeatedly executed on board both rovers
   - MAPGEN team members are considered part of MER Ops



2. Consistent use of MAPGEN since Spirit landing
   - Planner has not been turned off in actual Operations

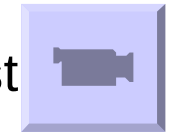
3. Impacted Science operations
   - MAPGEN increased the quantity of science upwards of 20% over a similar manual approach
   - MER Science community thinks in terms of constraints

"MAPGEN is doing exactly what we want it to do and more!" - Steve Squyres Sol 17/Spirit

Conclusion & Lessons Learned

- AI has a significant role to play in Mission Critical applications
- Technology Infusion is hard (but doable)
  - Advocacy is a crucial part & parcel of this enterprise
  - On site presence is a definite plus especially during the process design phase
  - Involve stake holders from the beginning (even if you're not sure who they are)
  - *Ethnographic* studies of work practice is important!
- Impact to mission customers must be tangible and quantifiable
  - Significant reduction in workload for TAP's
  - Quantitatively (and qualitatively) better activity plans

    TAP's:: "*Can't do the job without it*"
  - Never turned off the planner in nominal surface operations for MER!
- AI has pushed the state of the practice in mission planning, just a little further



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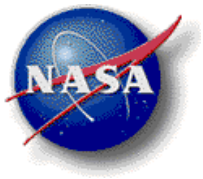
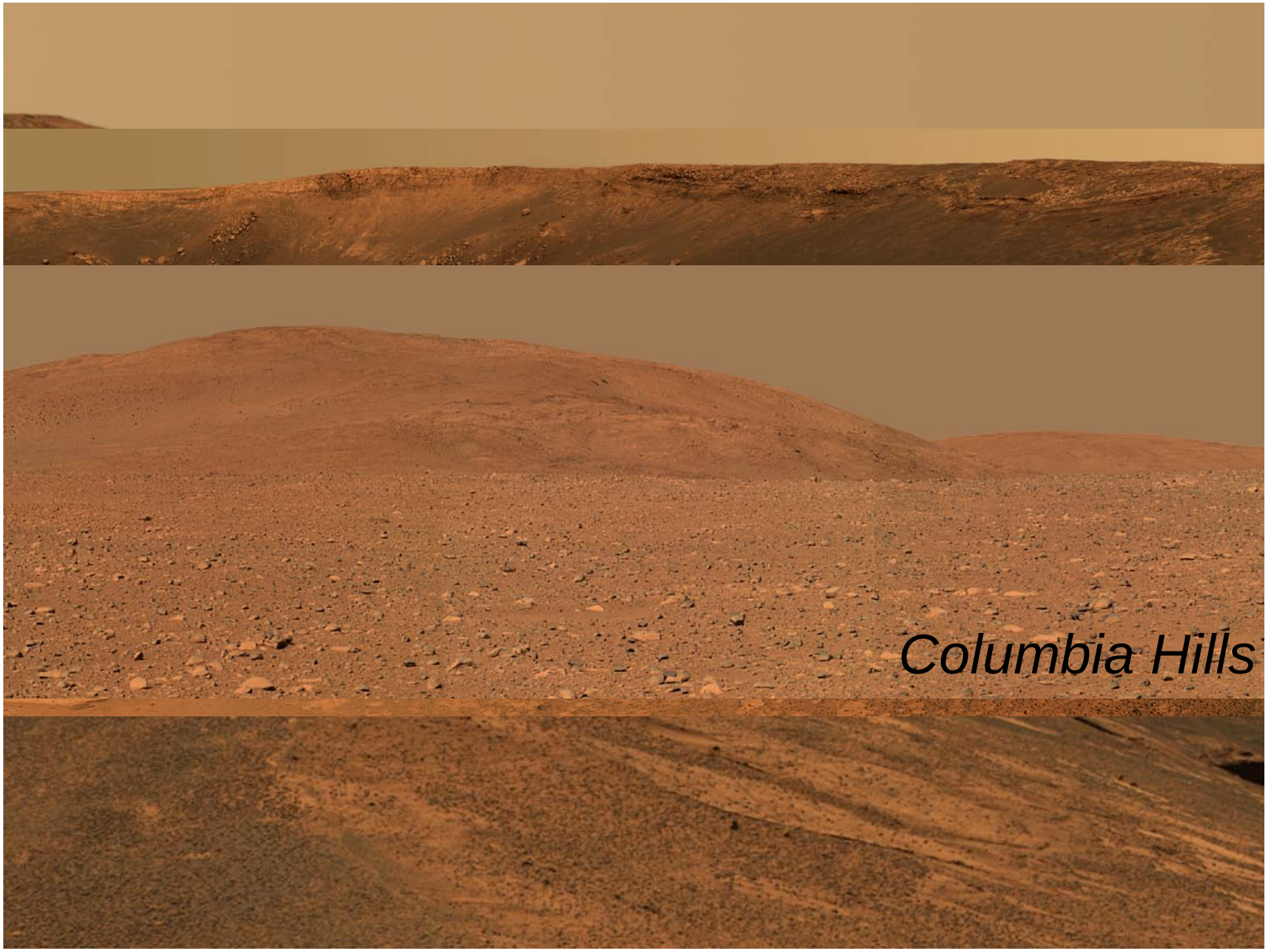
How did we do it for MER?



Mitch Ai-Chang	*ARC*	
John Bresina	*ARC*	
Len Charest	*JPL*	
Brian Chafin	*JPL*	
Adam Chase	*JPL*	
Mark Floyd	*JPL*	
Ari Jonsson	*ARC*	
Jennifer Hsu	*ARC*	
Bob Kanefsky	*ARC*	
Adans Ko	*JPL*	
Pierre Maldague	*JPL*	
Paul Morris	*ARC*	
Kanna Rajan	*ARC*	*PI and Project Lead*
Richard Springer	*JPL*	
Jeffrey Yglesias	*ARC*	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View of Earth from Mars from Spirit

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