Temporal Planning in Space

based on:

“Application of Mapgen to MER,”
by Kanna Rajan

“Handling Time:
Constraint-based Interval Planning,”
by David E. Smith

Brian C. Williams and
Robert Morris (guest lect.)
16.412J/6.834J
March 2nd, 2005

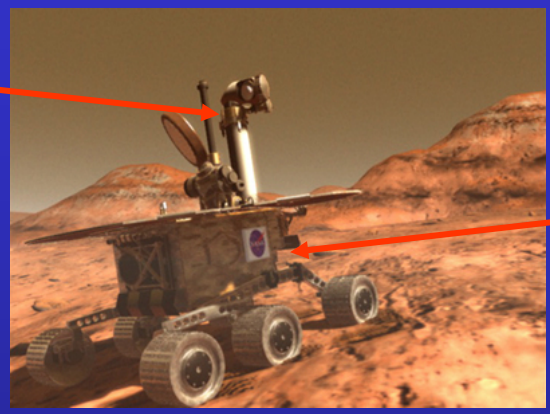
Outline

- Operational Planning for the Mars Exploration Rovers
- Review of Least Commitment Planning
- Constraint-based Interval Planning
- Temporal Constraint Networks
- Temporal Constraints with Preference

Based on slides by Dave Smith, NASA Ames

Mars Exploration Rovers – Jan. 2004 - ?

Mini-TES
Pancam
Navcam

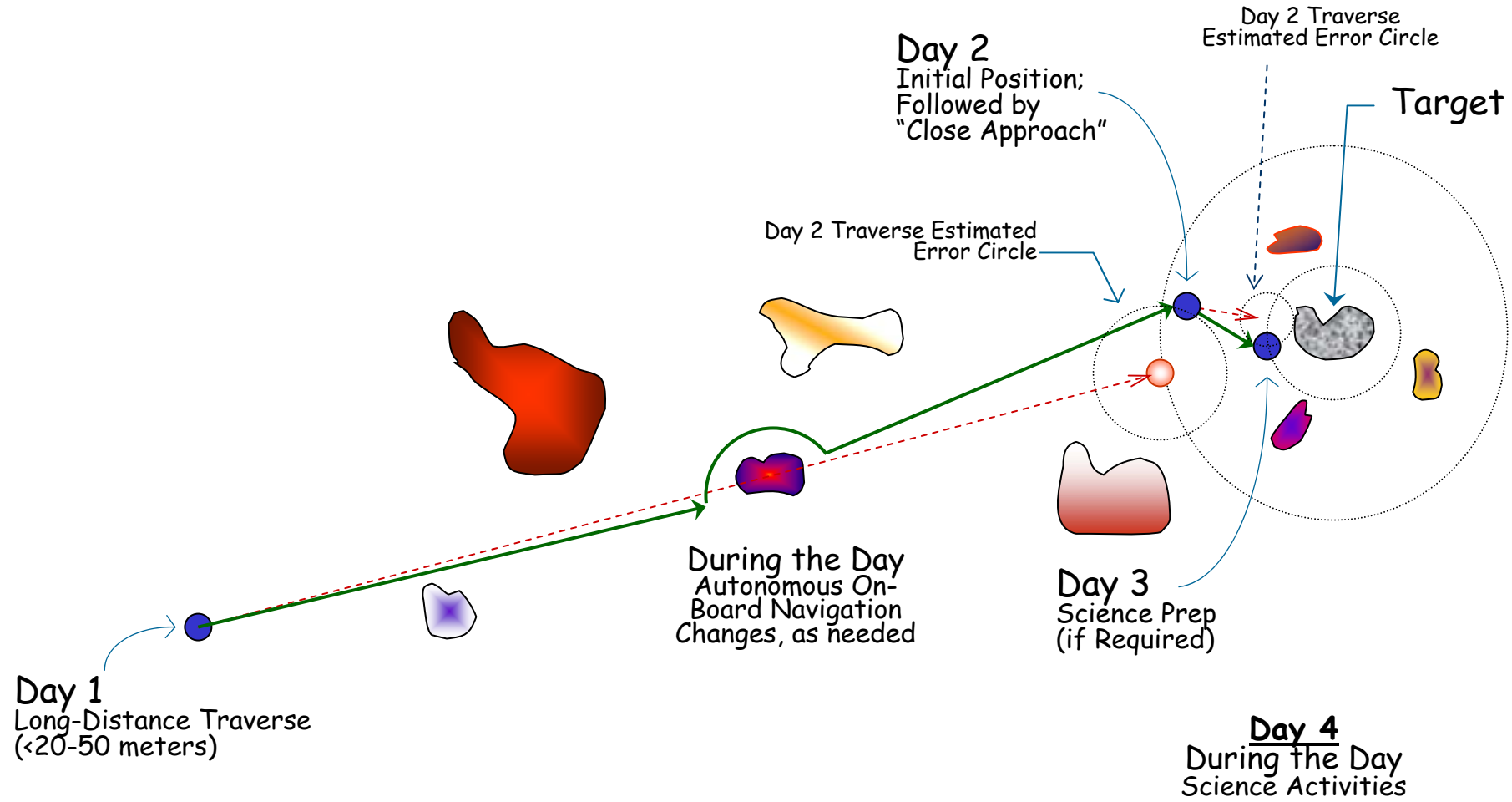


Mossbauer spectrometer
APXS
Rock Abrasion Tool
Microscopic Imager

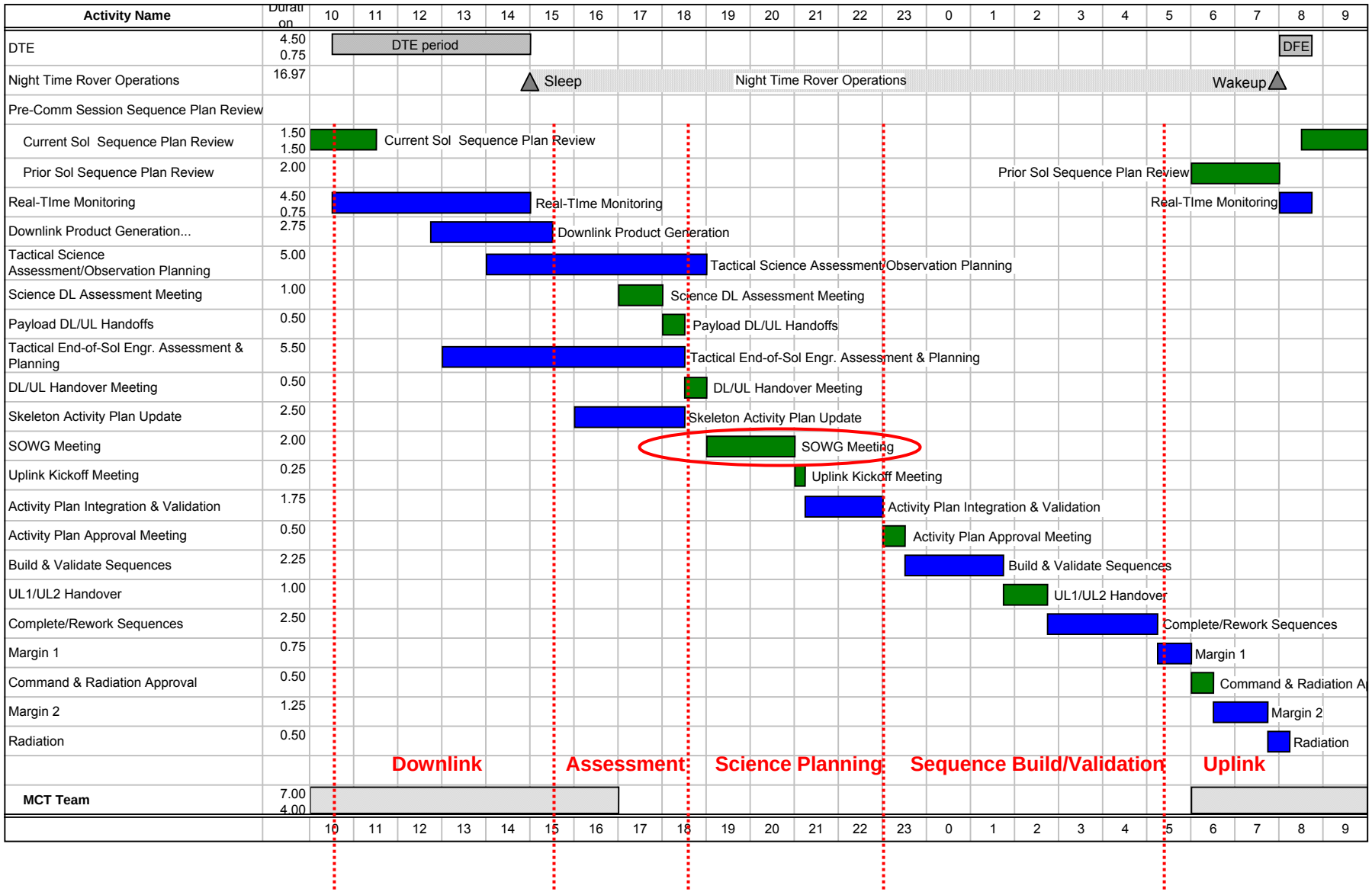
Mission Objectives:

- Learn about ancient water and climate on Mars.
- For each rover, analyze a total of 6-12 targets
  - Targets = natural rocks, abraded rocks, and soil
- Drive 200-1000 meters per rover

Mars Exploration Rover Surface Operations Scenario



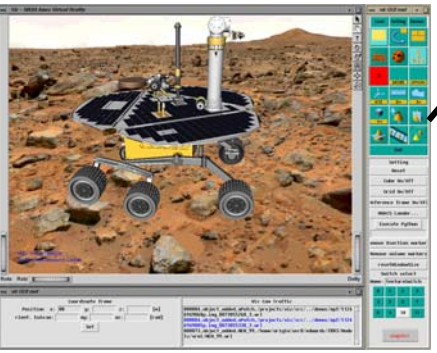
One day in the life of a Mars rover



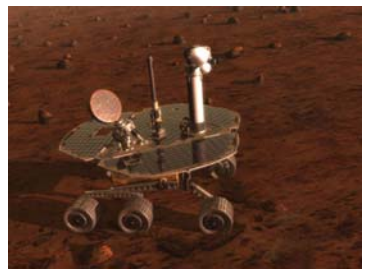
Courtesy: Jim Erickson

MAPGEN: Automated Science Planning for MER

Planning Lead: Kanna Rajan (ARC)



EUROPA Automated Planning System



Flight Rules

Engineering

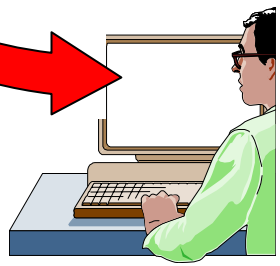
Resource Constraints

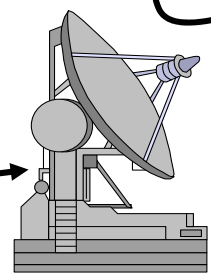
Science

Navigation

DSN/Telcom

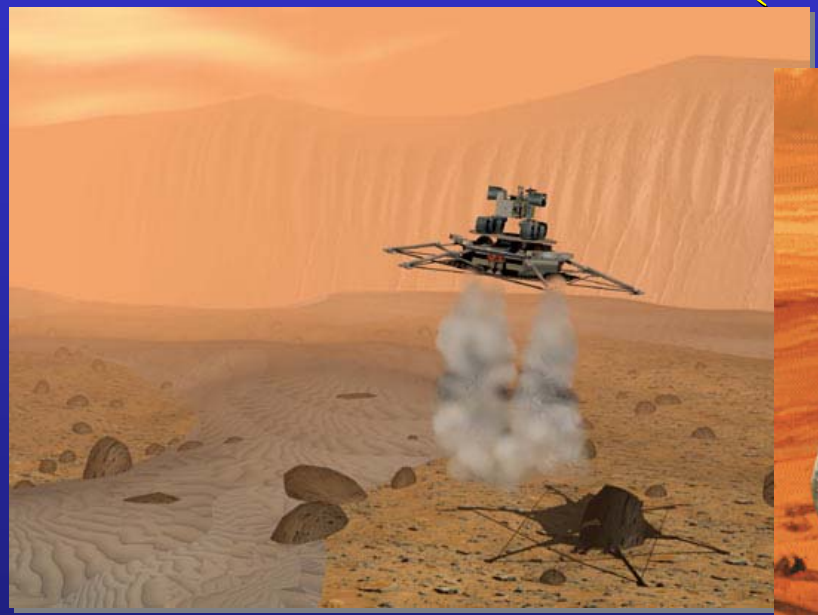
Sequence Build

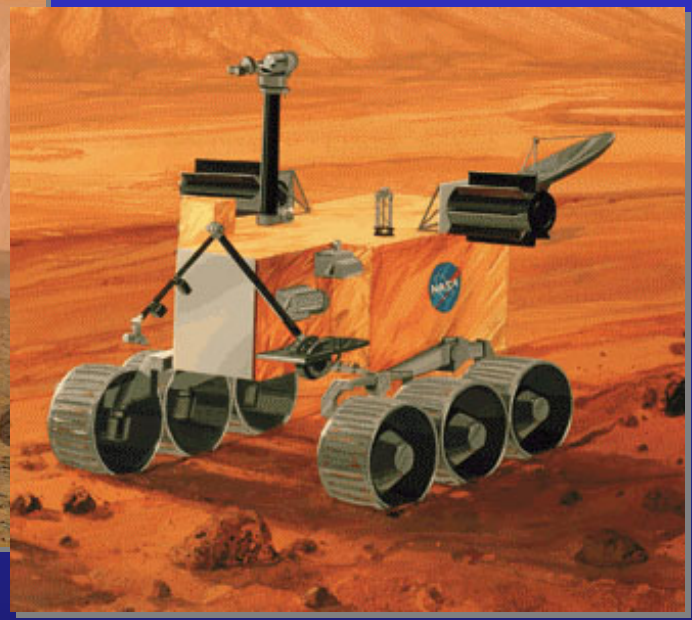




Science Team

Next Challenge: Mars Smart Lander (2009)





Mission Duration: 1000 days
Total Traverse: 3000-69000 meters
Meters/Day: 230-450
Science Mission: 7 instruments, sub-surface science package (drill, radar), in-situ sample "lab"

Technology Demonstration: (2005).

Course Challenge: 16.413 Fall 03

- What would it be like to operate MER if it was fully autonomous?

Potential inspiration for course projects:

- Demonstrate an autonomous MER mission in simulation, and in the MIT rover testbed.

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Based on slides by Dave Smith, NASA Ames

Planning

Find:

program of actions that achieves the objective

Planning

Find:

program of actions that achieves the objective

partially-ordered set

typically unconditional

goals

Paradigms

Classical planning

(STRIPS, operator-based, first-principles)

"generative"

Hierarchical Task Network planning

"practical" planning

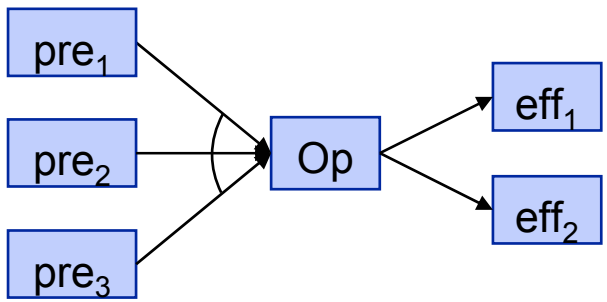
MDP & POMDP planning

planning under uncertainty

The Classical Representation

Initial Conditions: P_1 P_2 P_3 P_4

Operators:



Goals: $Goal_1$ $Goal_2$ $Goal_3$

Simple Spacecraft Problem

Observation-1
- **target**
- **instruments**

Observation-2

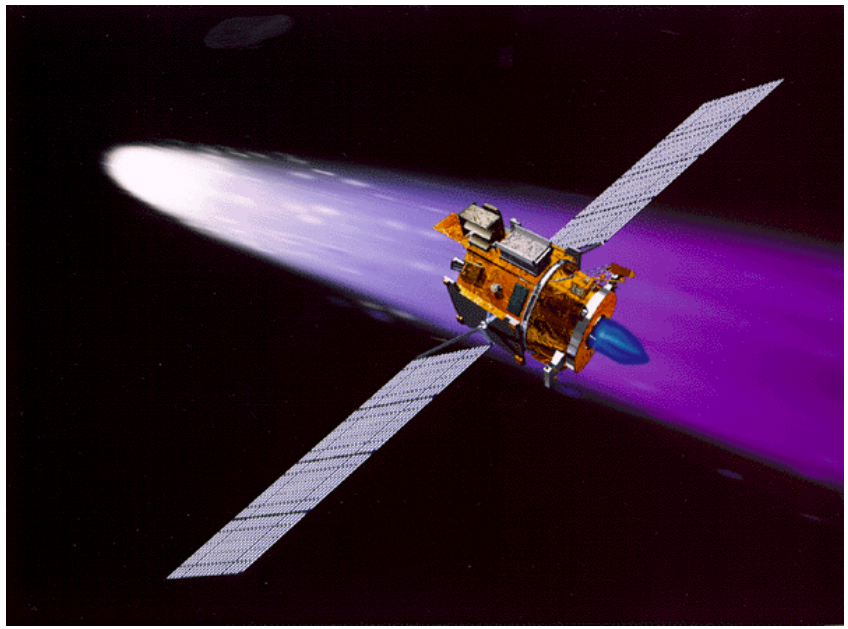
Observation-3

Observation-4

…

pointing

calibrated

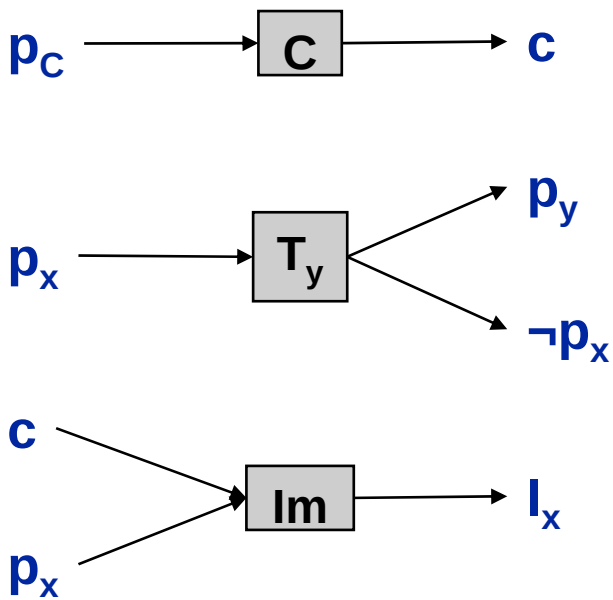


Example

Init

p_C

Actions



Goal

l_A

16.410/13: Solved using Graph-based Planners (Blum & Furst)

Some STRIPS Operators

TakeImage (?target, ?instr):
    Pre: Status(?instr, Calibrated), Pointing(?target)
    Eff: Image(?target)

Calibrate (?instrument):
    Pre: Status(?instr, On), Calibration-Target(?target), Pointing(?target)
    Eff: ¬Status(?inst, On), Status(?instr, Calibrated)

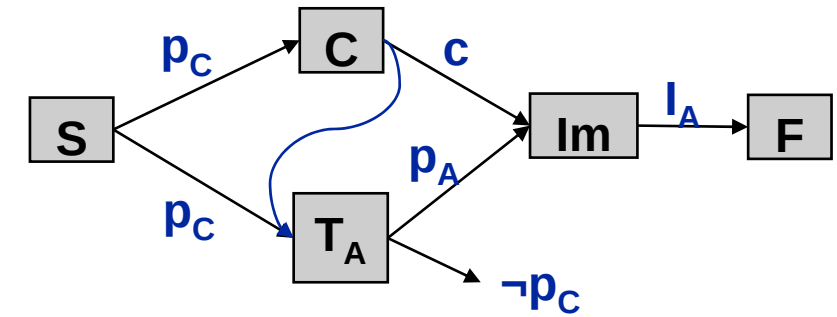
Turn (?target):
    Pre: Pointing(?direction), ?direction ≠ ?target
    Eff: ¬Pointing(?direction), Pointing(?target)

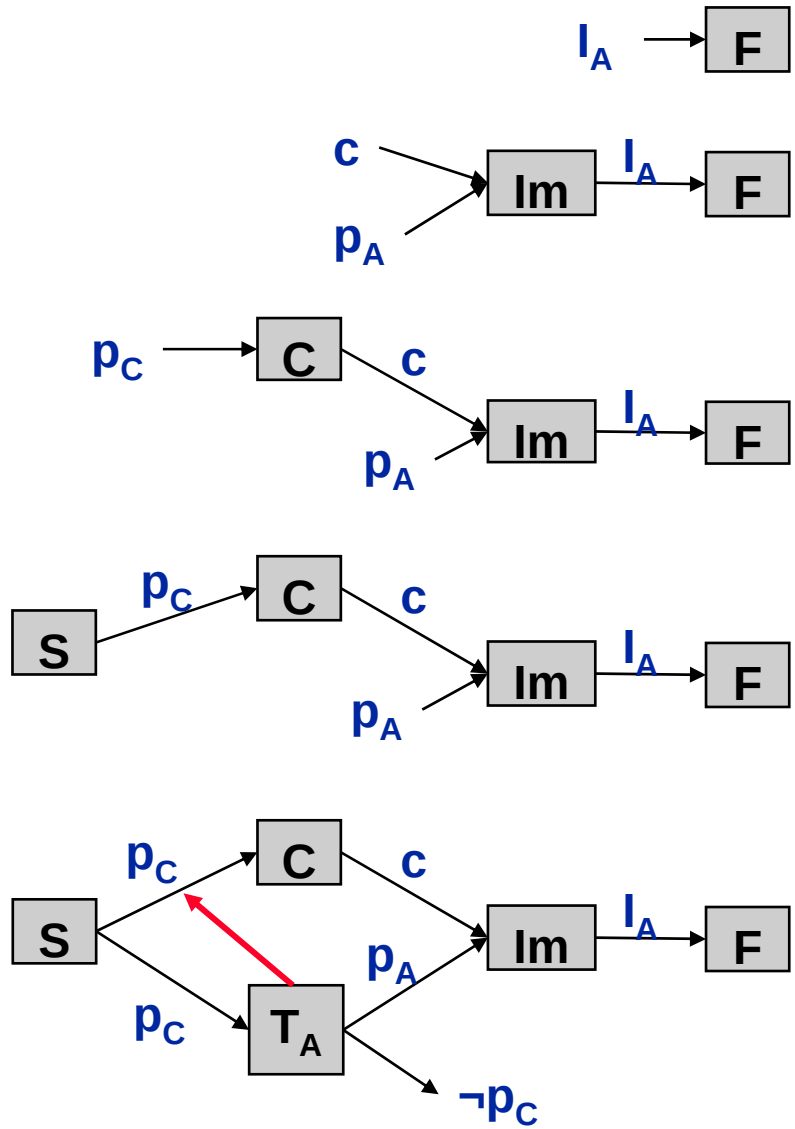
Based on slides by Dave Smith, NASA Ames

Partial Order Causal Link Planning

(SNLP, UCPOP)

1. Select an open condition
2. Choose an op that can achieve it
   - Link to an existing instance
   - Add a new instance
3. Resolve threats





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Based on slides by Dave Smith, NASA Ames

An Autonomous Science Explorer

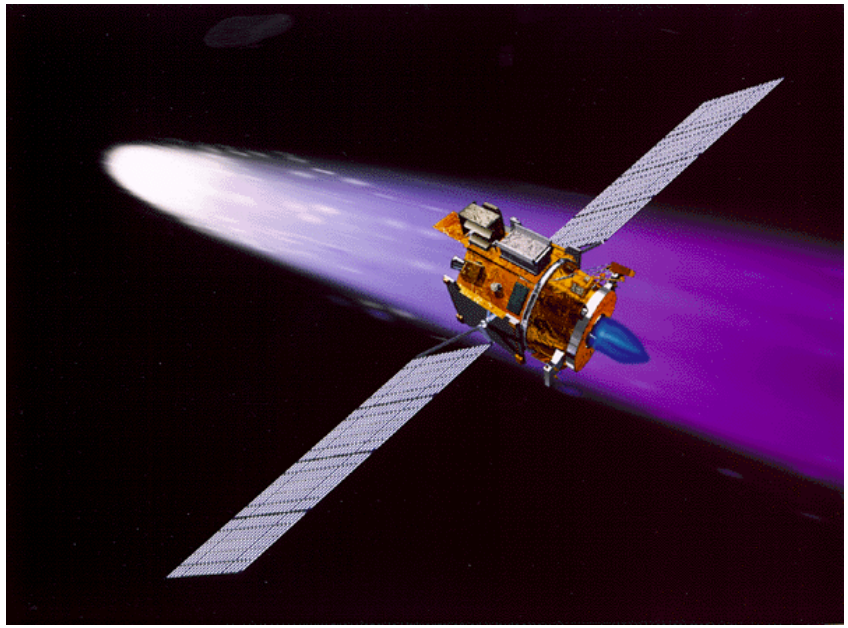
Observation-1
- **priority**
- **time window**
- **target**
- **instruments**
- **duration**

Observation-2

Observation-3

Observation-4

…



Objective:

maximize science return

Based on slides by Dave Smith, NASA Ames

Complications

linked

Observation-1
- priority
- time window
- target
- instruments
- duration

Observation-2

Observation-3

Observation-4

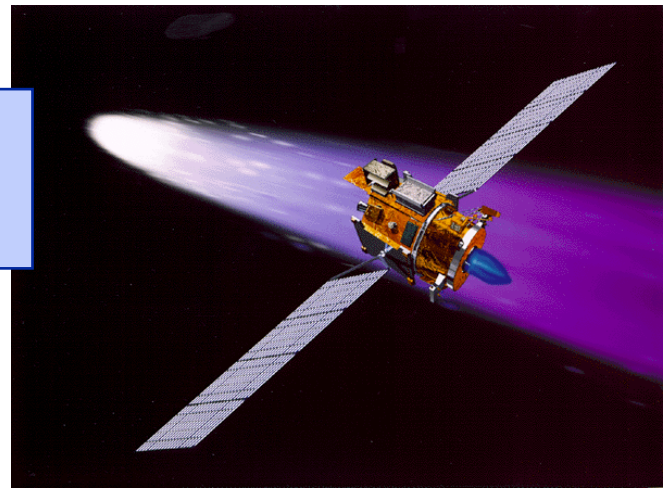
…

angle between targets

$\Rightarrow$ **turn duration**

calibration
- target1
- target2
- …

consumables:
- fuel
- power
- data storage
- cryogen



Objective:

maximize science return

Based on slides by Dave Smith, NASA Ames

Limitations of Classical Planning with Atomic Actions (aka STRIPS)

Instantaneous actions

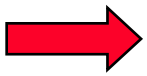
No temporal constraints

No concurrent actions

No continuous quantities

Based on slides by Dave Smith, NASA Ames

Needed Extensions



Time

Resources

Utility

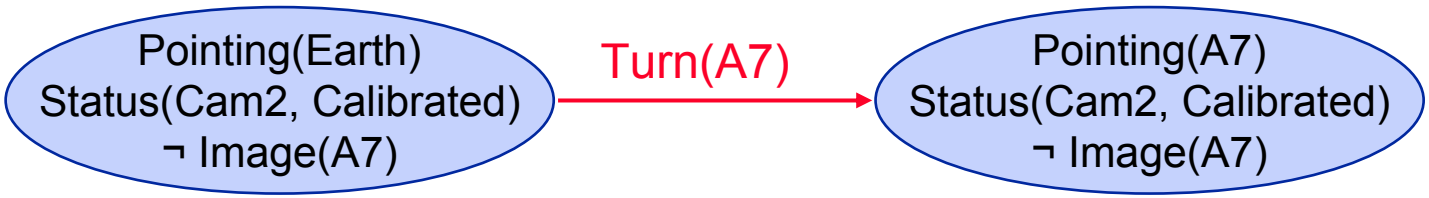
Uncertainty

Based on slides by Dave Smith, NASA Ames

World Description

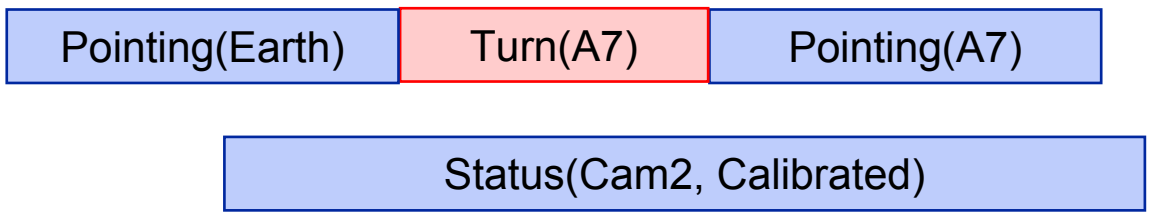
State-centric (Mc Carthy):

for each time describe propositions that are true



History-based (Hayes):

for each proposition describe times it is true



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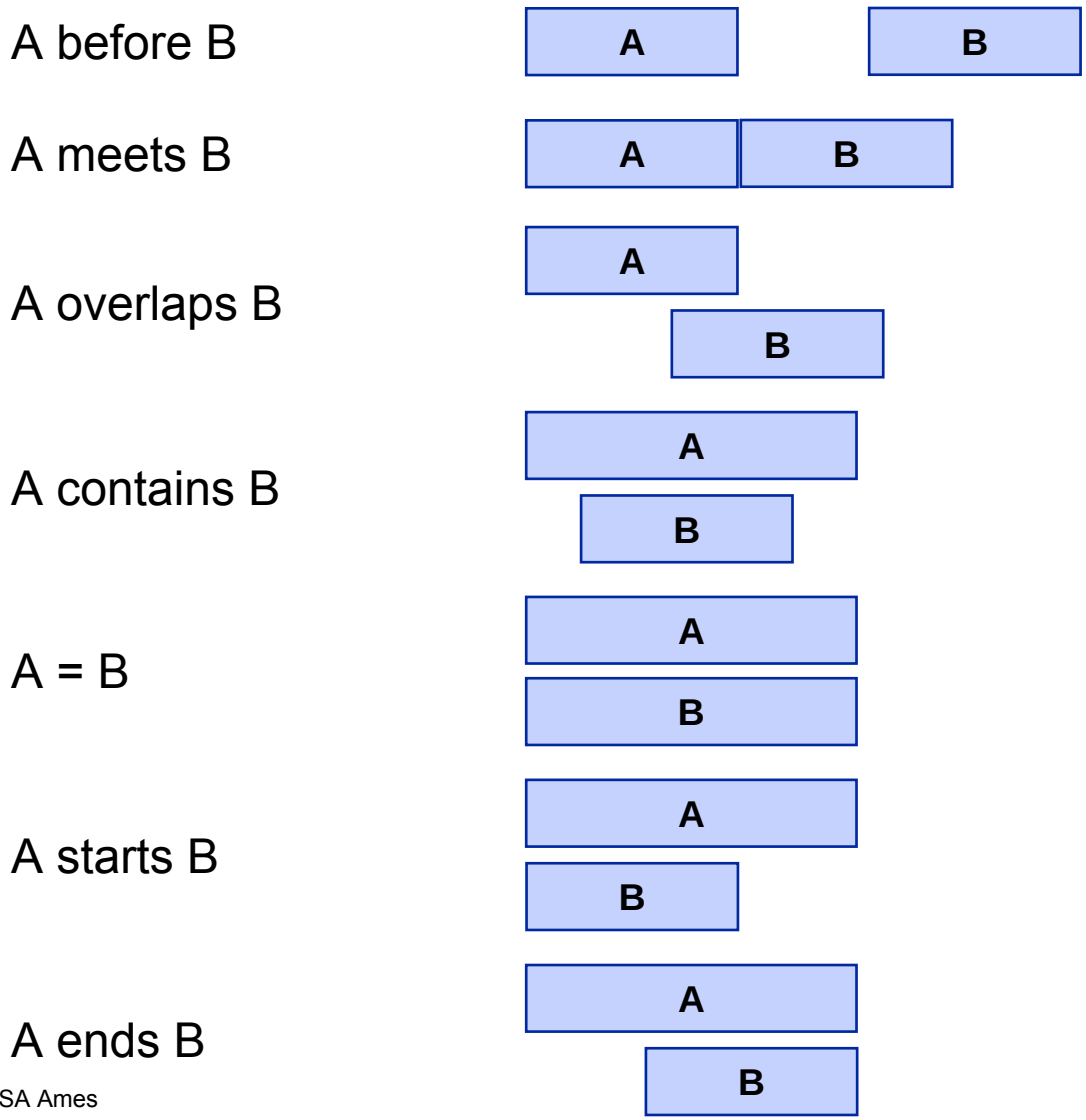
Representing Timing: Qualitative Temporal Relations [Allen AAAI83]



Based on slides by Dave Smith, NASA Ames

Representing Temporal Operators: TakeImage Schema

TakeImage (?target, ?instr):
Pre: Status(?instr, Calibrated), Pointing(?target)
Eff: Image(?target)

TakeImage (?target, ?instr)

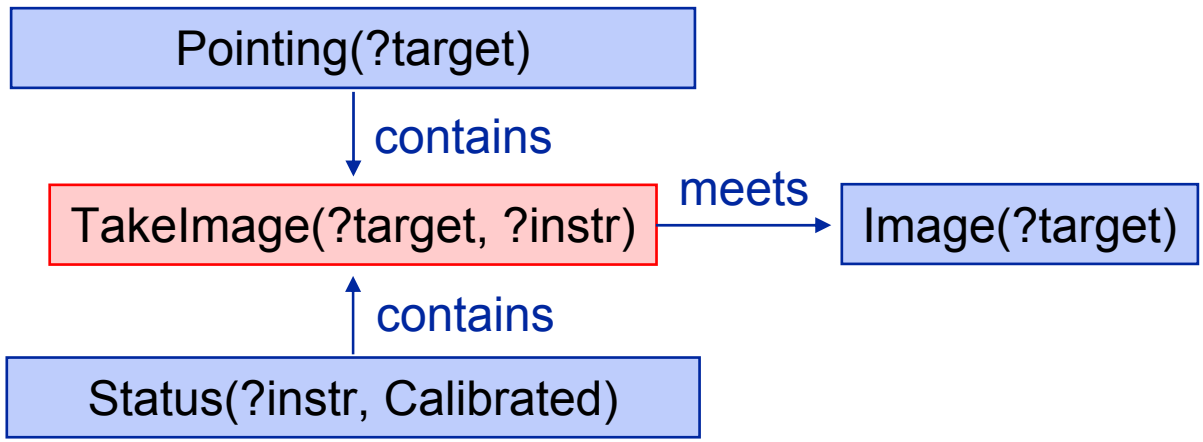
contained-by	Status(?instr, Calibrated)
contained-by	Pointing(?target)
meets	Image(?target)

Based on slides by Dave Smith, NASA Ames

Pictorially

TakeImage (?target, ?instr)

contained-by	Status(?instr, Calibrated)
contained-by	Pointing(?target)
meets	Image(?target)



Based on slides by Dave Smith, NASA Ames

TakeImage Schema Semantics

TakeImage (?target, ?instr)

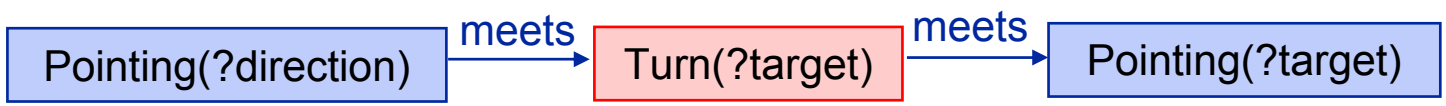
contained-by	Status(?instr, Calibrated)
contained-by	Pointing(?target)
meets	Image(?target)

$$\text{TakeImage}(?target, ?instr)_A$$
$$\Rightarrow \exists P \{\text{Status}(?instr, \text{Calibrated})_P \wedge \text{Contains}(P, A)\}$$
$$\wedge \exists Q \{\text{Pointing}(?target)_Q \wedge \text{Contains}(Q, A)\}$$
$$\wedge \exists R \{\text{Image}(?target)_R \wedge \text{Meets}(A, R)\}$$

Based on slides by Dave Smith, NASA Ames

Turn

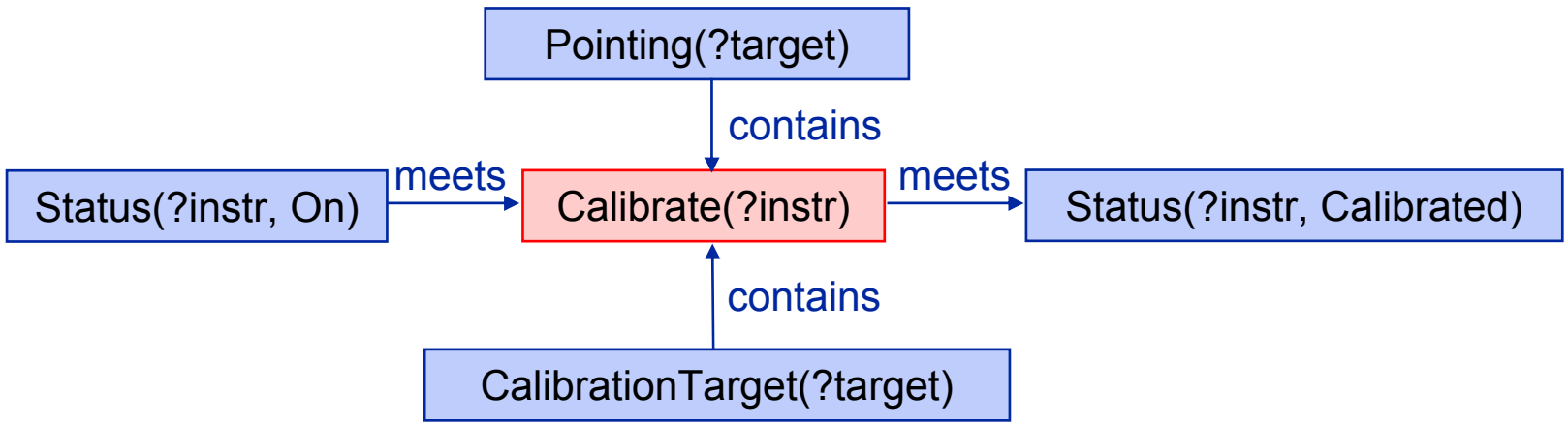
Turn (?target)	
met-by	Pointing(?direction)
meets	Pointing(?target)



Based on slides by Dave Smith, NASA Ames

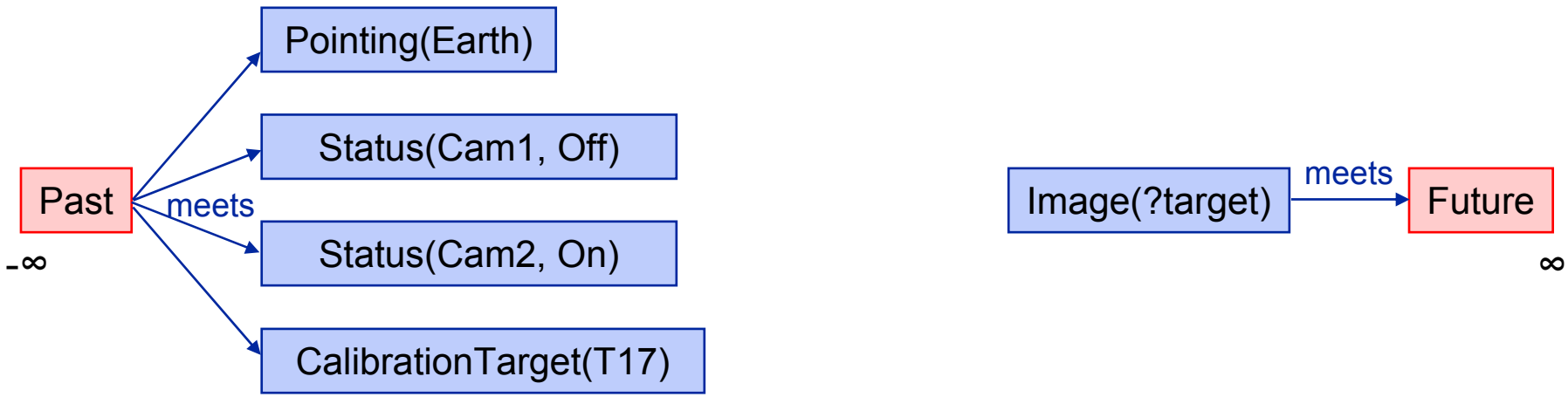
Calibrate

Calibrate (?instr)	
met-by	Status(?instr, On)
contained-by	CalibrationTarget(?target)
contained-by	Pointing(?target)
meets	Status(?instr, Calibrated)



Based on slides by Dave Smith, NASA Ames

A Temporal Planning Problem



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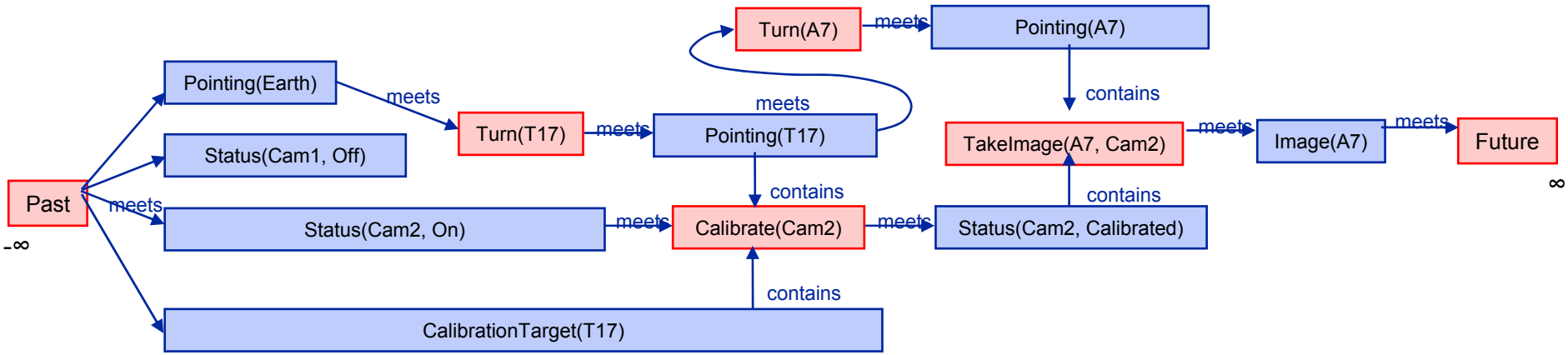
A Consistent Complete Temporal Plan



Based on slides by Dave Smith, NASA Ames

CBI Planning Algorithm

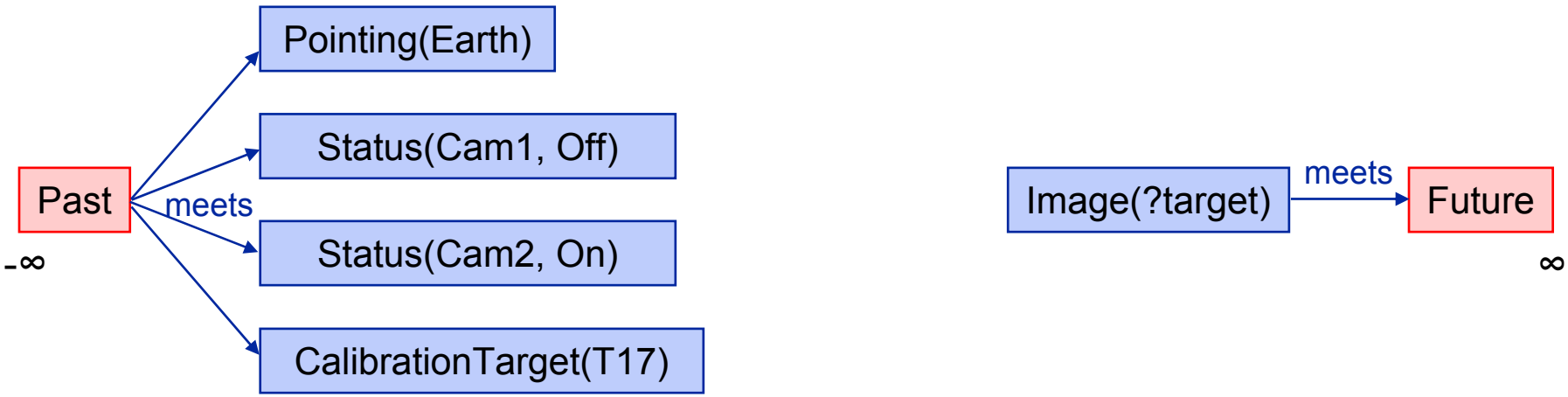
Choose:

- introduce an action & instantiate constraints
- coalesce propositions

Propagate constraints

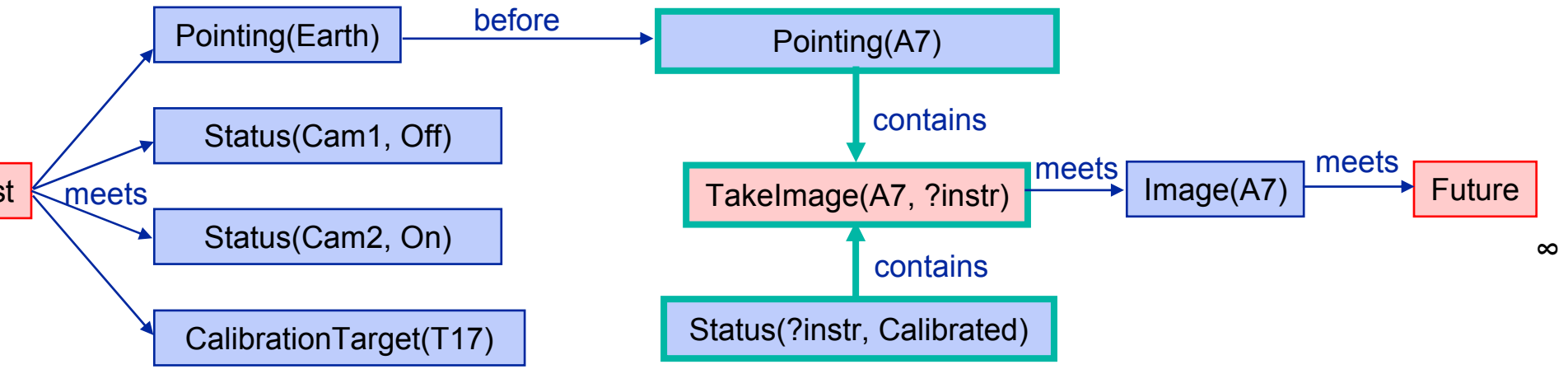
Based on slides by Dave Smith, NASA Ames

Initial Plan



Based on slides by Dave Smith, NASA Ames

Expansion 1



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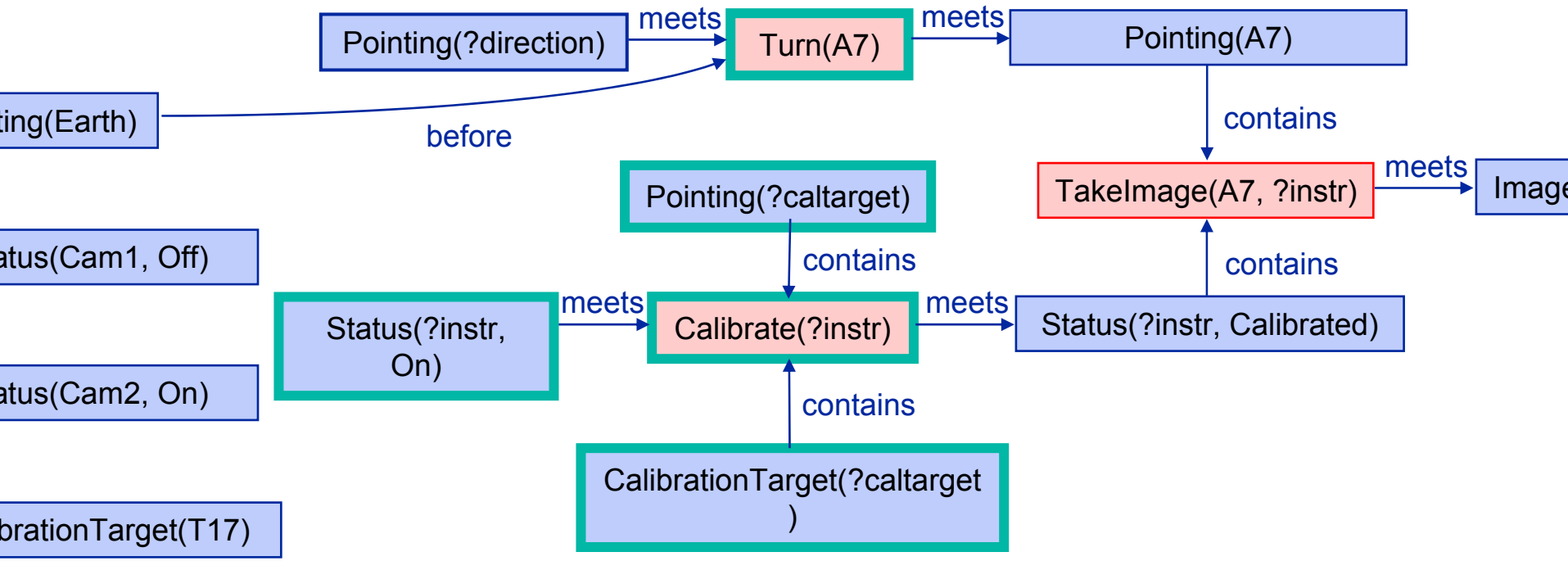
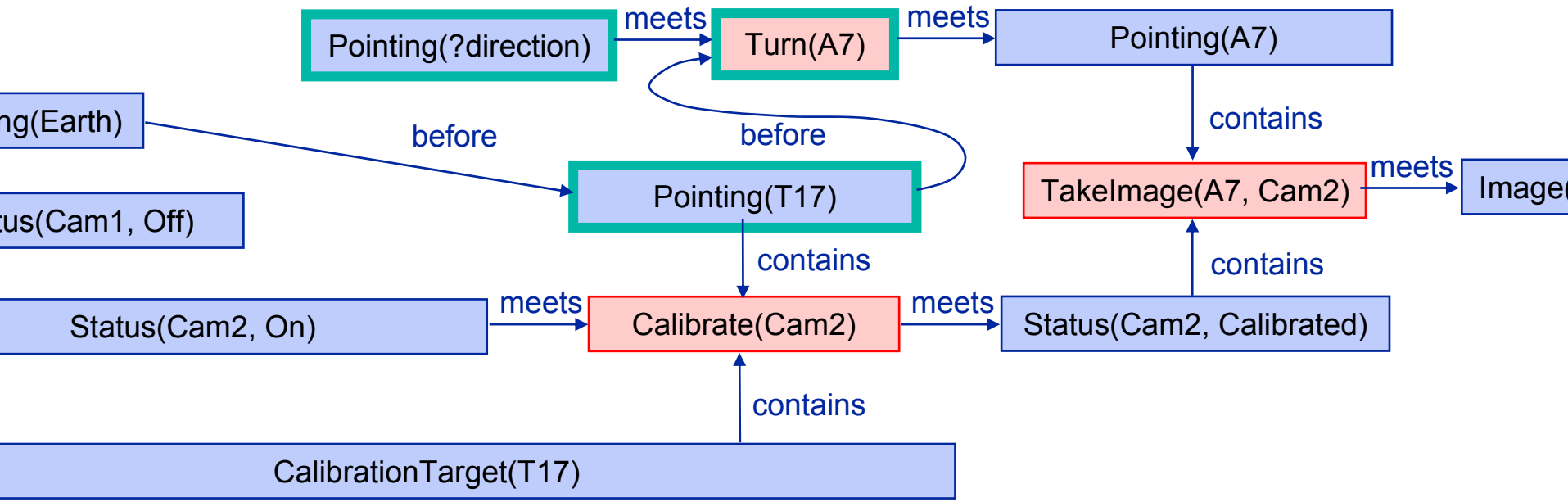
Expansion 2



Based on slides by Dave Smith, NASA Ames

Coalescing



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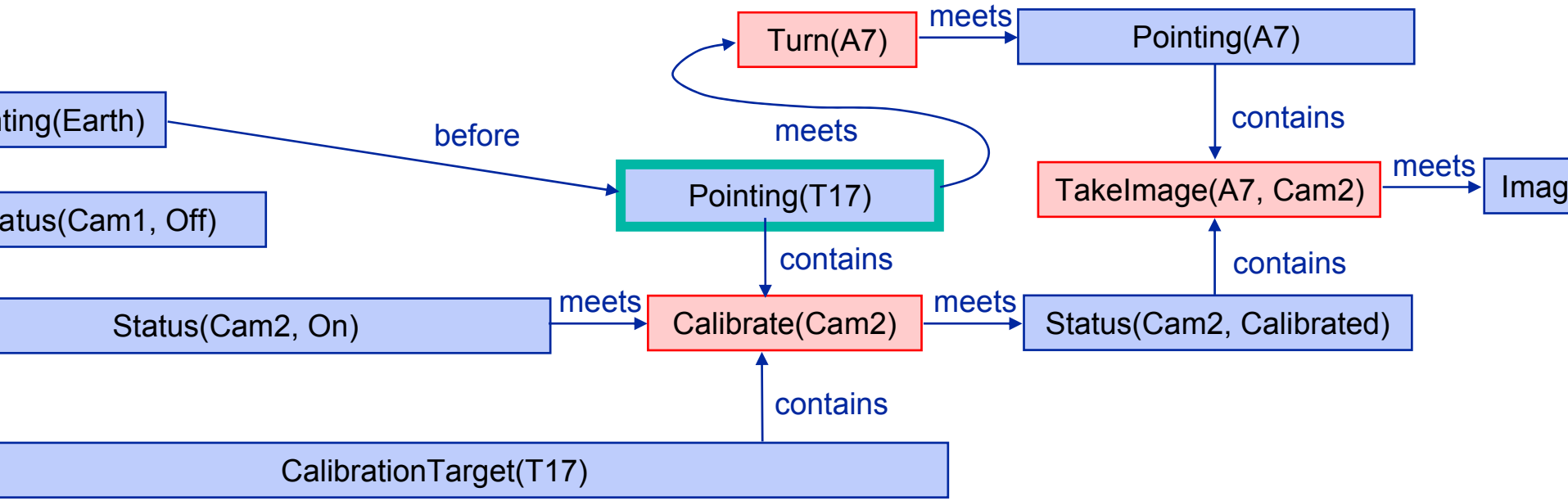
Coalescing



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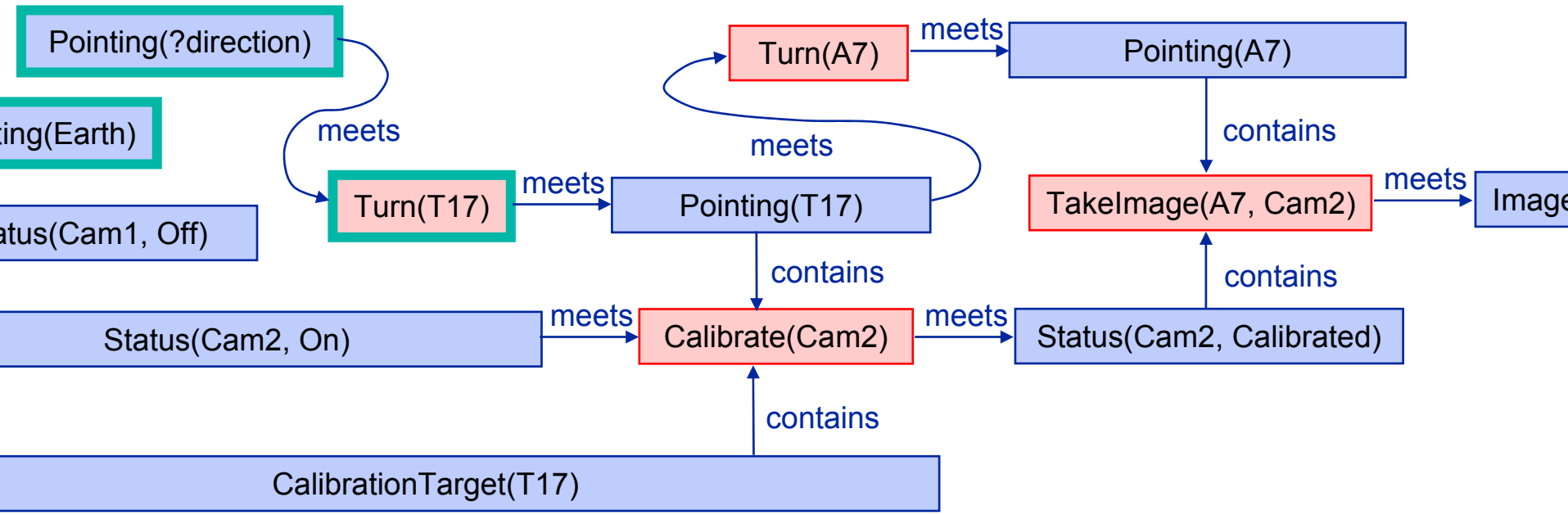
Expansion 3



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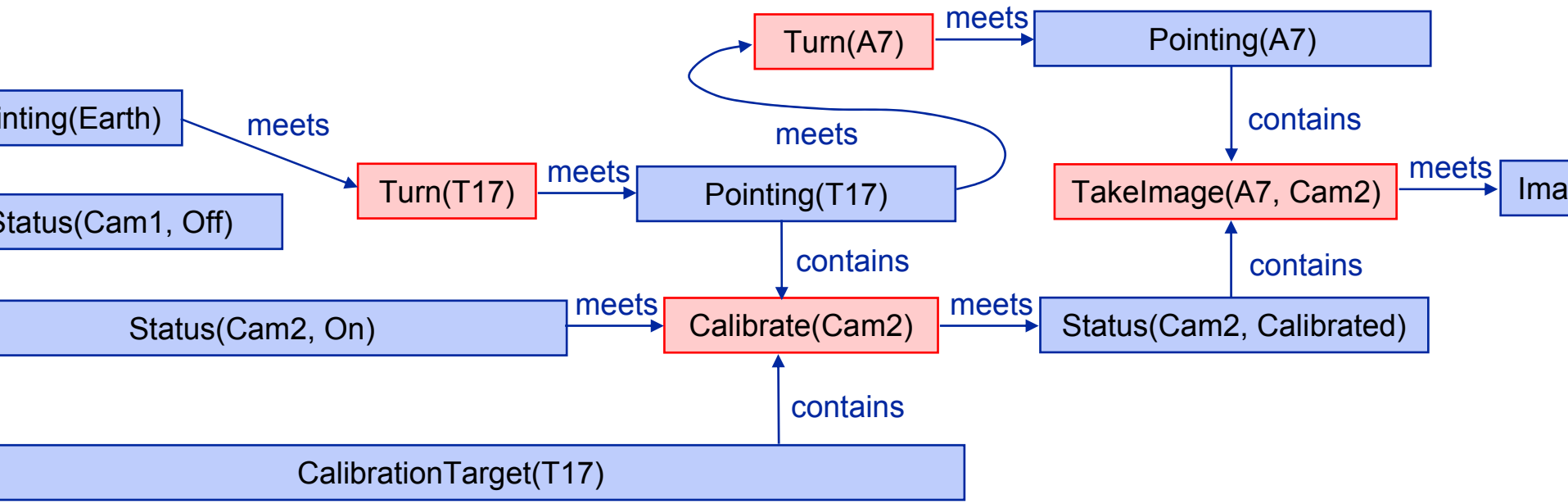
Coalescing



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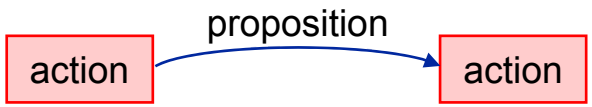
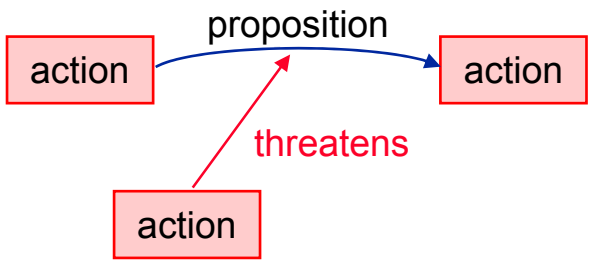
Relation to Causal Links & Threats

POCL

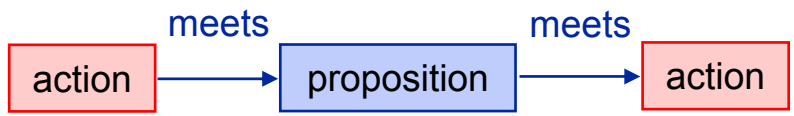
Causal links:

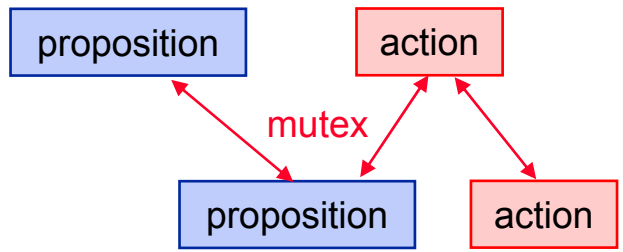


Threats:



CBI





Based on slides by Dave Smith, NASA Ames

Examples of CBI Planners

Zeno (Penberthy)	intervals, no CSP
Trains (Allen)	
Descartes (Joslin)	extreme least commitment
IxTeT (Ghallab)	functional rep.
HSTS (Muscettola)	functional rep., activities
EUROPA (Jonsson)	functional rep., activities

Based on slides by Dave Smith, NASA Ames

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- Operational Planning for the Mars Exploration Rovers
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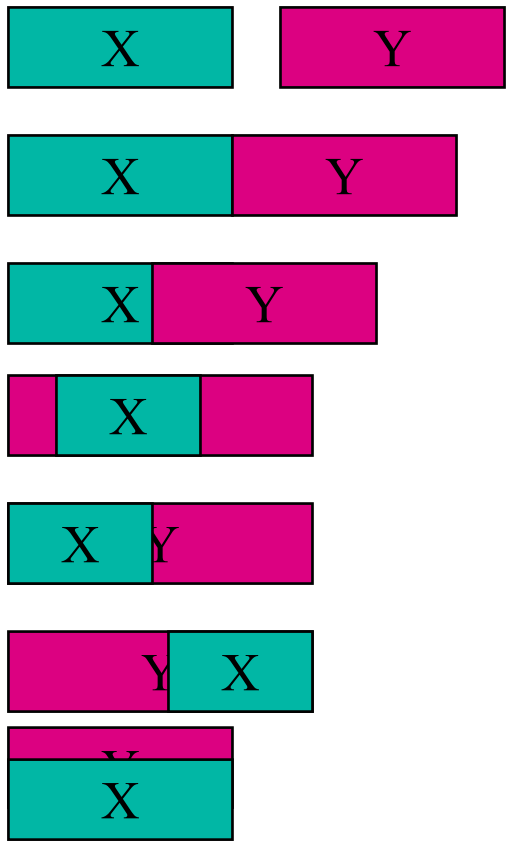
- Temporal Constraint Networks
- Model-based Program Execution
  as Graph-based Temporal Planning

Based on slides by Dave Smith, NASA Ames

Qualitative Temporal Constraints
(Allen 83)

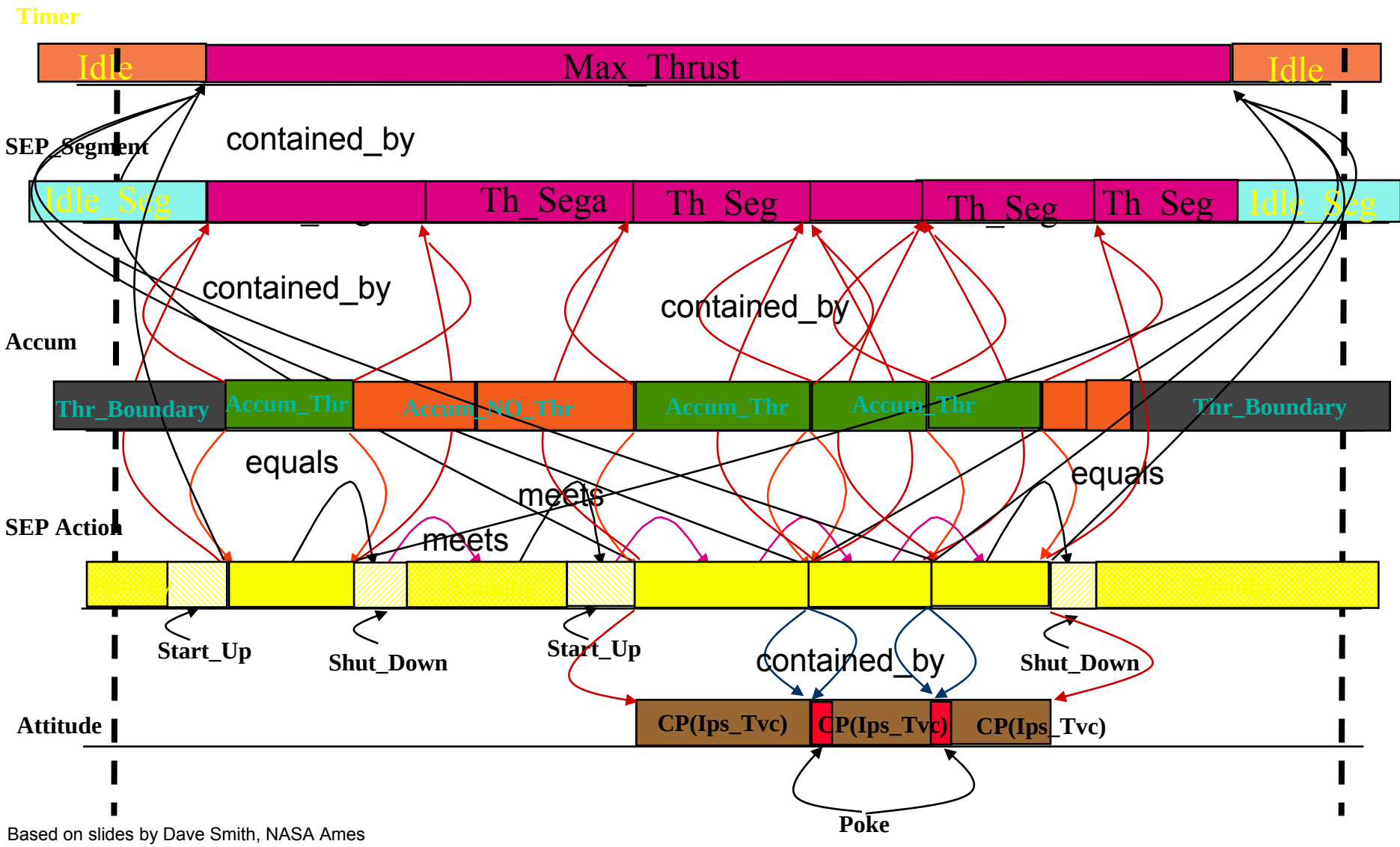
- x before y
- x meets y
- x overlaps y
- x during y
- x starts y
- x finishes y
- x equals y



- y after x
- y met-by x
- y overlapped-by x
- y contains x
- y started-by x
- y finished-by x
- y equals x

Based on slides by Dave Smith, NASA Ames

Example: Deep Space One Remote Agent Experiment



Based on slides by Dave Smith, NASA Ames

Qualitative Temporal Constraints Maybe Expressed as Inequalities

(Vilain, Kautz 86)

- x before y $X^+ < Y^-$
- x meets y $X^+ = Y^-$
- x overlaps y $(Y^- < X^+) \;\&\; (X^- < Y^+)$
- x during y $(Y^- < X^-) \;\&\; (X^+ < Y^+)$
- x starts y $(X^- = Y^-) \;\&\; (X^+ < Y^+)$
- x finishes y $(X^- < Y^-) \;\&\; (X^+ = Y^+)$
- x equals y $(X^- = Y^-) \;\&\; (X^+ = Y^+)$

Inequalities may be expressed as binary interval relations:

$X^+ - Y^- < [-\text{inf}, 0]$

Based on slides by Dave Smith, NASA Ames

Metric Constraints

- Going to the store takes at least 10 minutes and at most 30 minutes.
  → $10 \leq [T^{+}(\text{store}) - T^{-}(\text{store})] \leq 30$

- Bread should be eaten within a day of baking.
  → $0 \leq [T^{+}(\text{baking}) - T^{-}(\text{eating})] \leq 1 \text{ day}$

- Inequalities, $X^{+} < Y^{-}$, may be expressed as binary interval relations:
  → $-\inf < [X^{+} - Y^{-}] < 0$

Based on slides by Dave Smith, NASA Ames

Metric Time: Quantitative Temporal Constraint Networks

(Dechter, Meiri, Pearl 91)

- A set of time points X_i at which events occur.
- Unary constraints

$$(a_0 \leq X_i \leq b_0) \text{ or } (a_1 \leq X_i \leq b_1) \text{ or } \ldots$$

- Binary constraints

$$(a_0 \leq X_j - X_i \leq b_0) \text{ or } (a_1 \leq X_j - X_i \leq b_1) \text{ or } \ldots$$

Based on slides by Dave Smith, NASA Ames

Temporal Constraint Satisfaction Problem (TCSP)

$$< X_i, T_i , T_{ij} >$$

- X_i continuous variables
- T_i , T_{ij} interval constraints

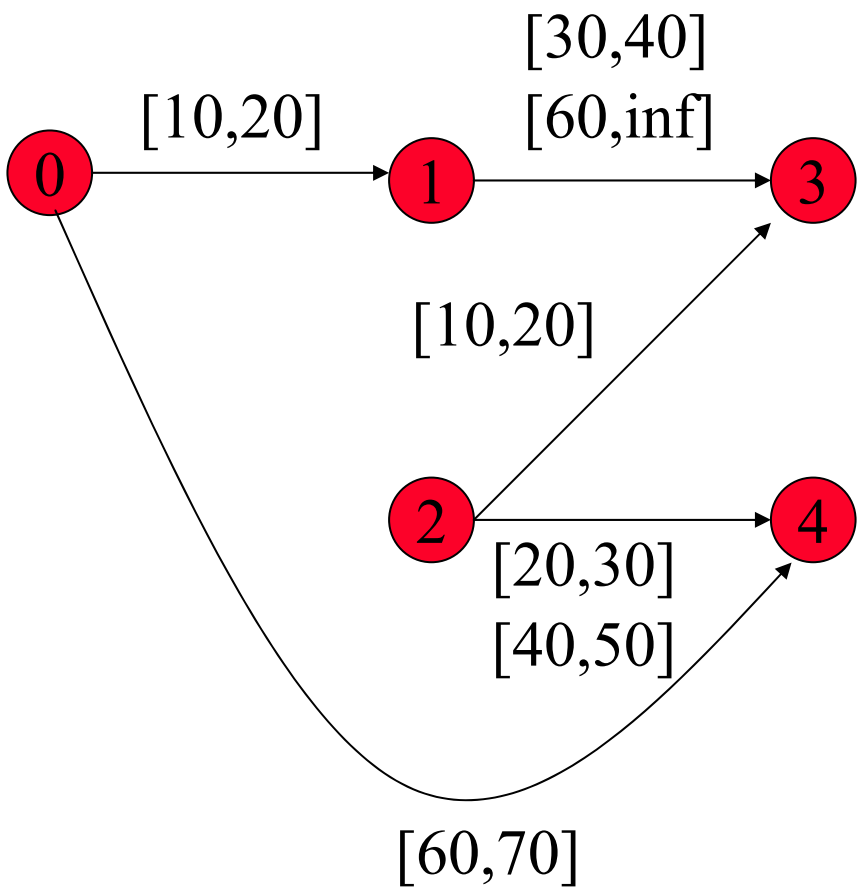
  $\{I_1, \ldots, I_n\}$ where $I_i = [a_i, b_i]$

  - $T_i = (a_i \leq X_i \leq b_i)$ or . . . or $(a_i \leq X_i \leq b_i)$
  - $T_{ij} = (a_1 \leq X_i - X_j \leq b_1)$ or ... or $(a_n \leq X_i - X_j \leq b_n)$

[Dechter, Meiri, Pearl, aij89]

Based on slides by Dave Smith, NASA Ames

TCSP Are Visualized Using Directed Constraint Graphs



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Simple Temporal Networks
(Dechter, Meiri, Pearl 91)

Simple Temporal Networks:

- A set of time points X_i at which events occur.
- Unary constraints

  $(a_0 \leq X_i \leq b_0)$ ~~or $(a_1 \leq X_i \leq b_1)$ or . . .~~
- Binary constraints

  $(a_0 \leq X_j - X_i \leq b_0)$ ~~or $(a_1 \leq X_j - X_i \leq b_1)$ or . . .~~

Sufficient to represent:
- most Allen relations
- simple metric constraints

Can't represent:
- Disjoint activities

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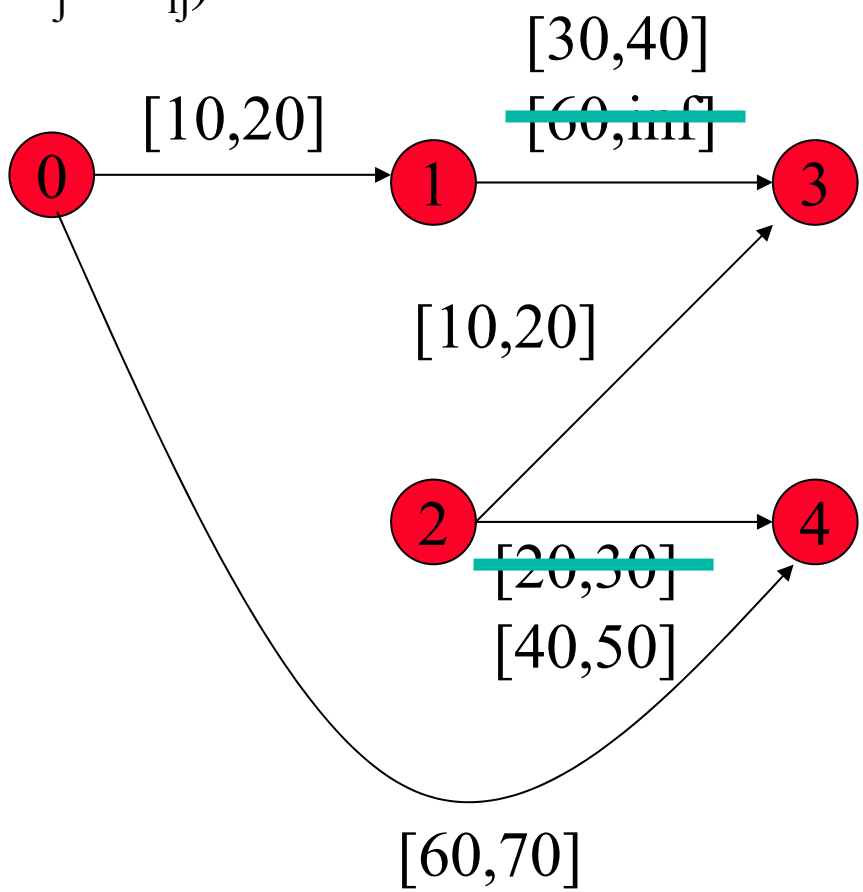
Simple Temporal Network

- $T_{ij} = (a_{ij} \leq X_i - X_j \leq b_{ij})$



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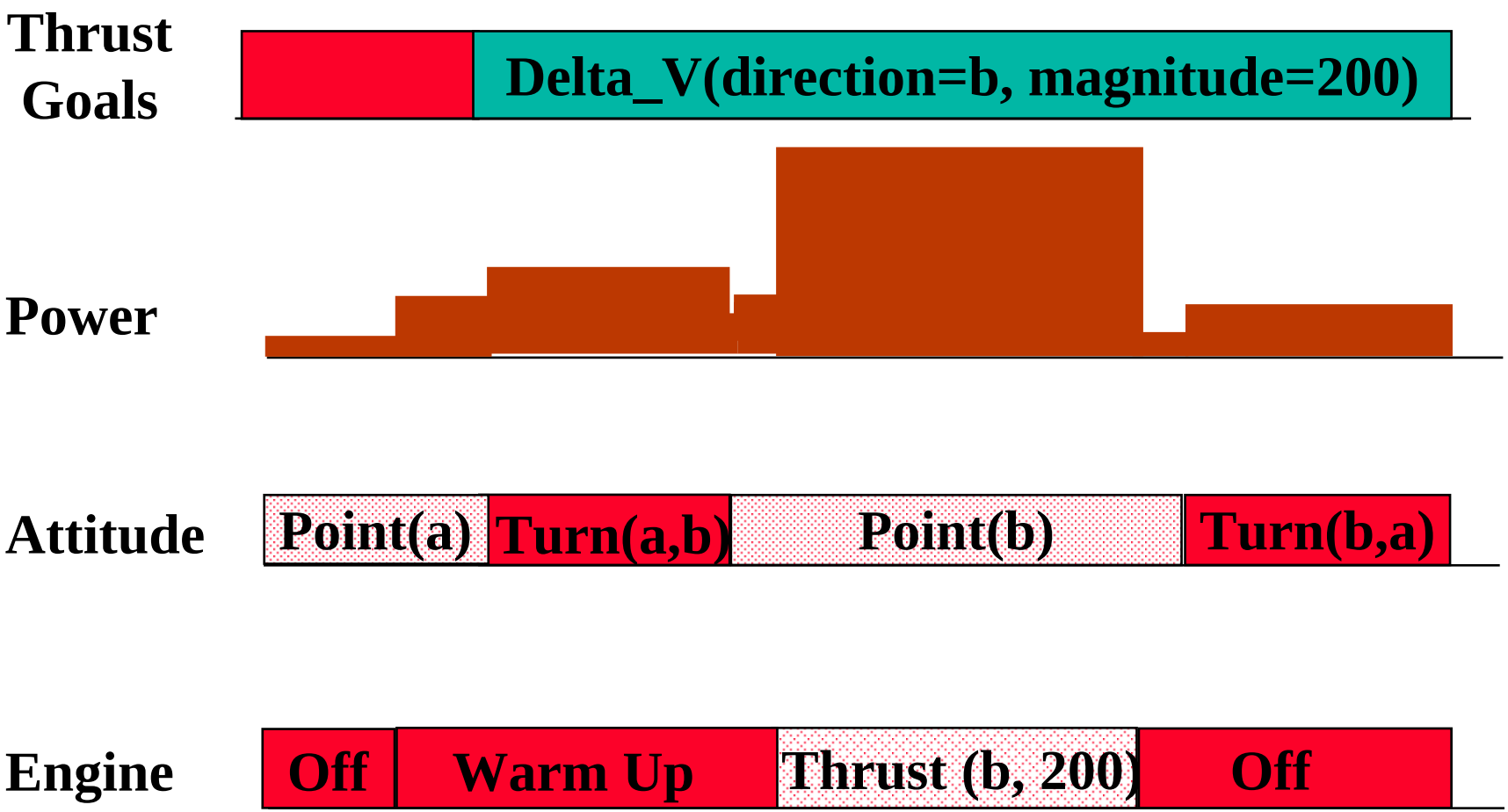
A Completed Plan Forms an STN



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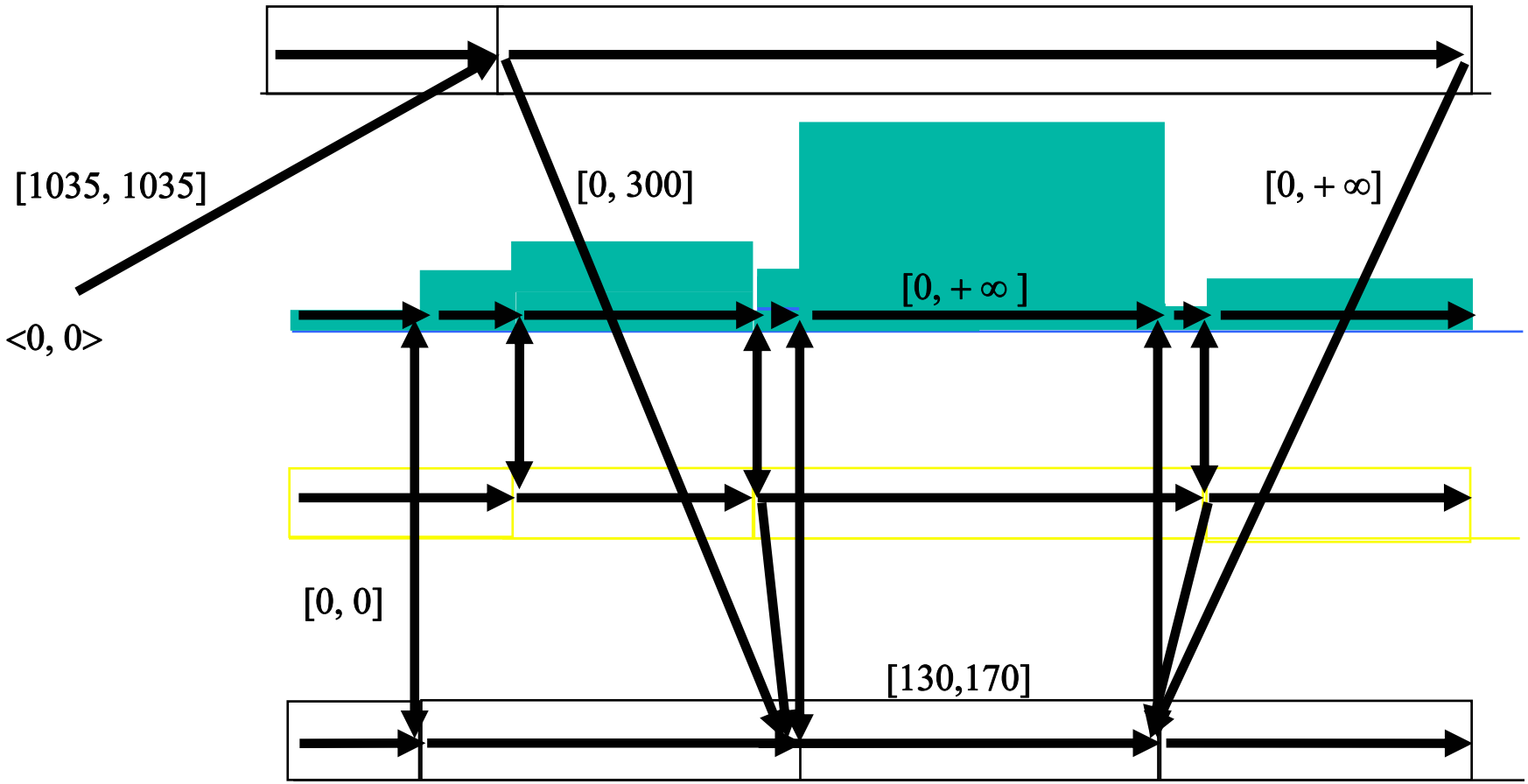
A Completed Plan Forms an STN



Based on slides by Dave Smith, NASA Ames

Outline

- Operational Planning for the Mars Exploration Rovers
- Review of Least Commitment Planning
- Constraint-based Interval Planning
- Temporal Constraint Networks
- Temporal Constraints with Preference

Based on slides by Dave Smith, NASA Ames