# Temporal Planning in Space

Brian C. Williams
16.412J/6.834J
February 23rd, 2004

based on "Handling Time:
Constraint-based Interval Planning,"
by David E. Smith



## Outline

- Operational Planning for the Mars Exploration Rovers
- Review of Least Commitment Planning
- Constraint-based Interval Planning
- Temporal Constraint Networks
- Model-based Program Execution
  as Graph-based Temporal Planning

Based on slides by Dave Smith, NASA Ames

# Mars Exploration Rovers – Jan. 2004

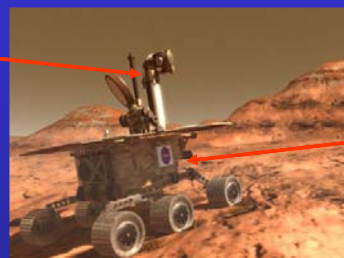


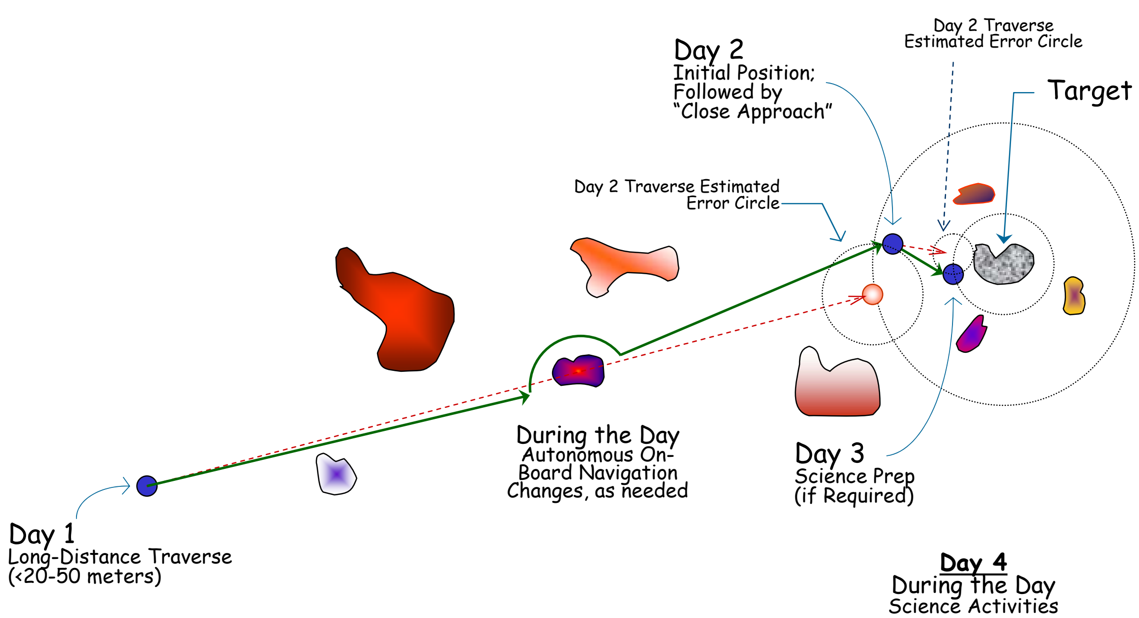

Image courtesy of JPL.

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

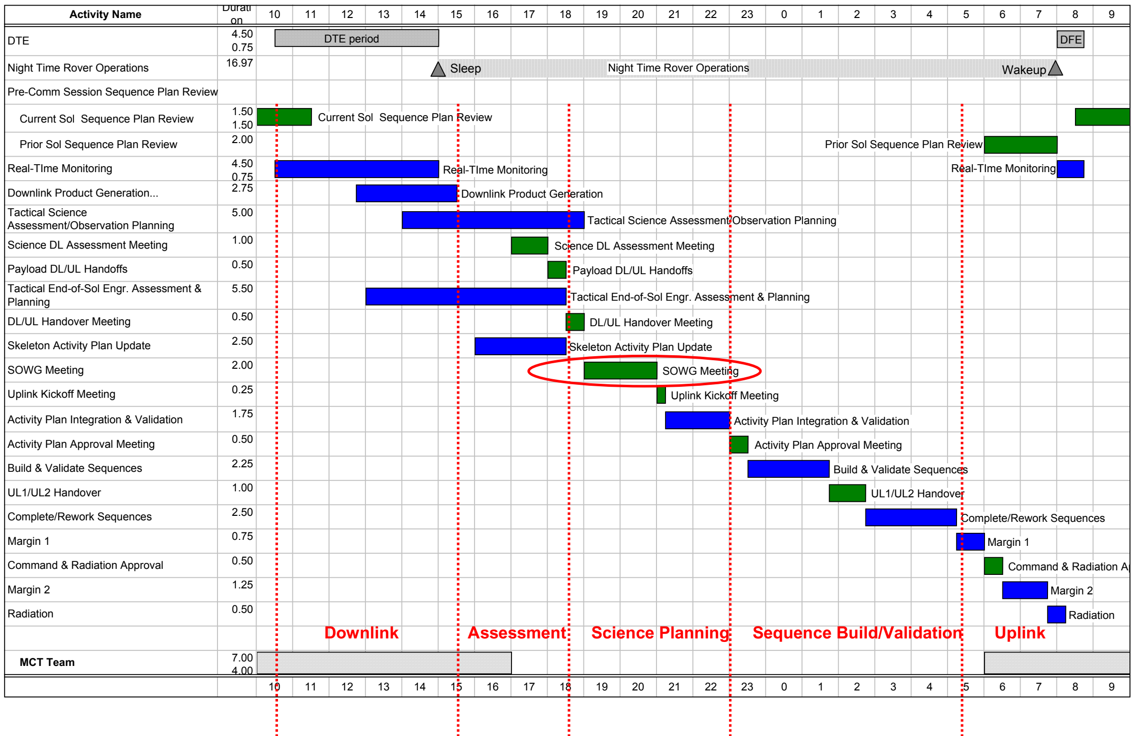
Slide courtesy of Kanna Rajan.

# Mars Exploration Rover Surface Operations Scenario



Slide courtesy of Kanna Rajan.

## *One day in the life of a Mars rover*

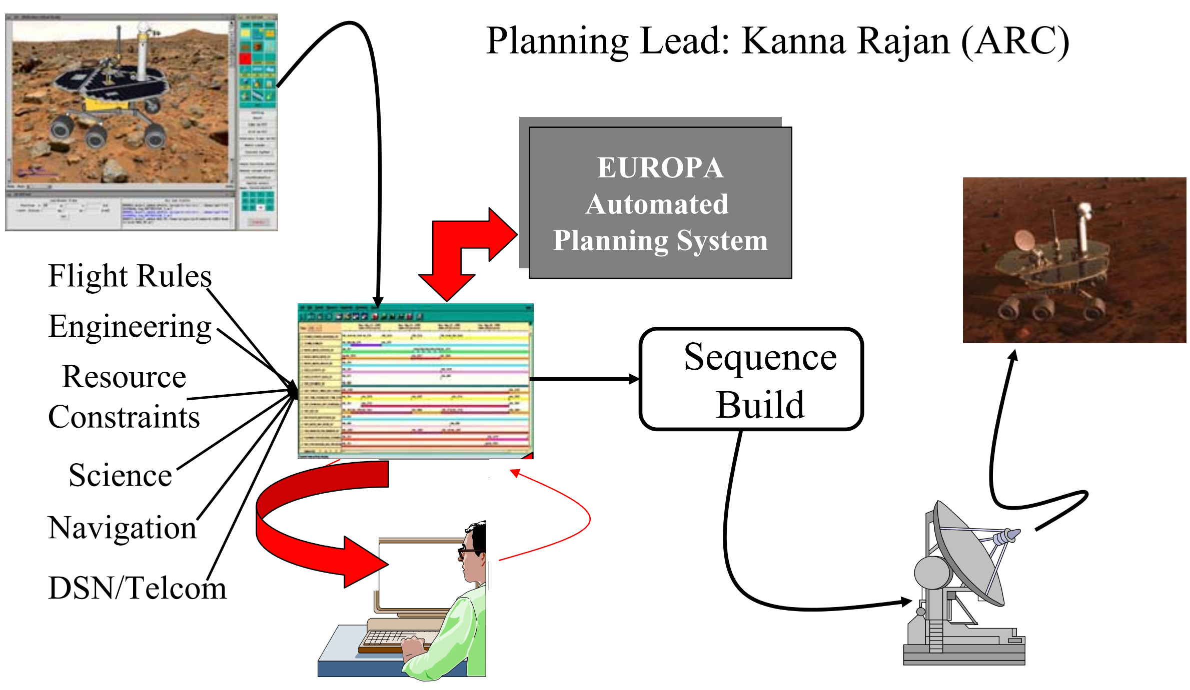



*Courtesy: Jim Erickson*

Slide courtesy of Kanna Rajan.

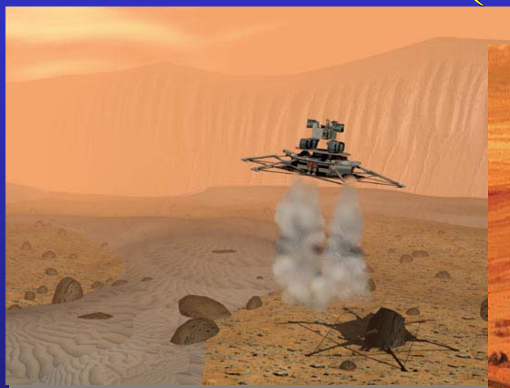
# MAPGEN: Automated Science Planning for MER

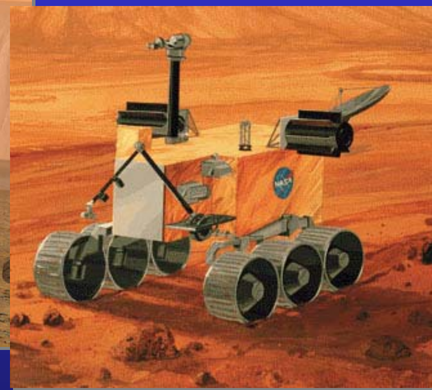
Planning Lead: Kanna Rajan (ARC)




***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).

Images courtesy of JPL.

# Course Challenge

- 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

goals

## Paradigms

**Classical planning**

(STRIPS, operator-based, first-principles)

"generative"

**HTN planning**

"practical" planning

**MDP & POMDP planning**

planning under uncertainty

## The Classical Representation

**Inits**: $P_1$ $P_2$ $P_3$ $P_4$

**Operators**:

$pre_1$, $pre_2$, $pre_3$ → Op → $eff_1$, $eff_2$

**Goals**: $Goal_1$ $Goal_2$ $Goal_3$

## Simple Spacecraft Problem

**Observation-1**

**target** — pointing

**instruments** — calibrated

**Observation-2**

**Observation-3**

**Observation-4**

**…**

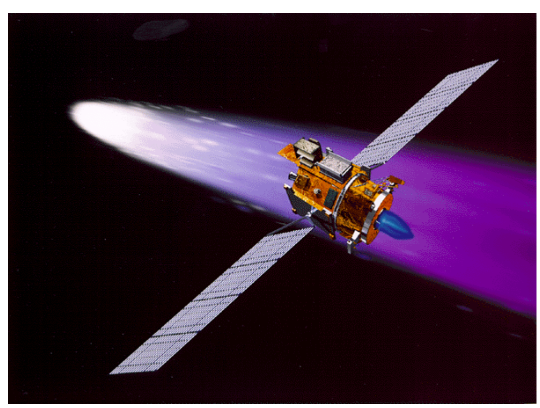
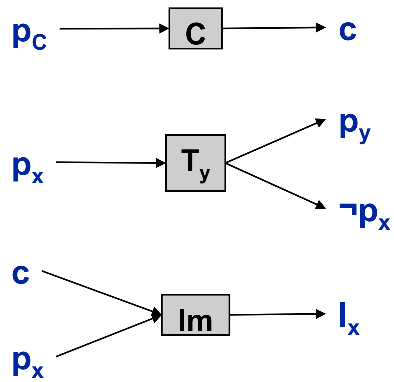


Image courtesy of JPL.

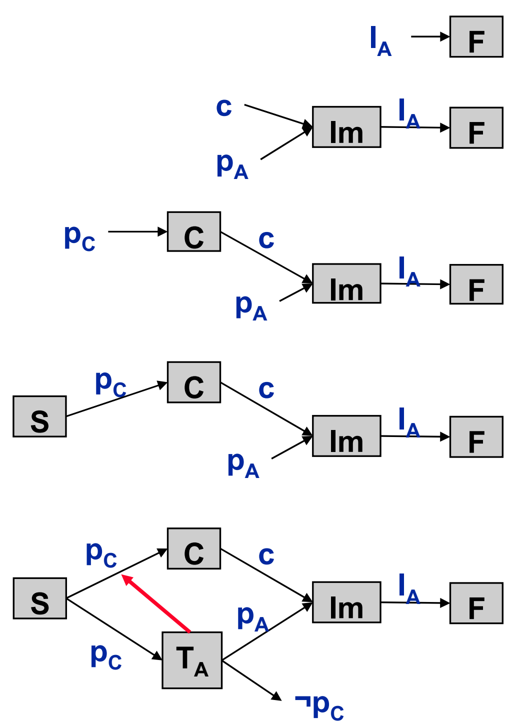
# Example

| Init | Actions | Goal |
| --- | --- | --- |
| $p_C$ |  | $I_A$ |

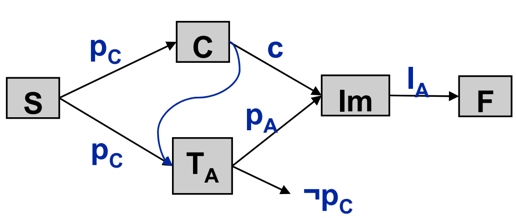


# POCL Planning
## (SNLP, UCPOP)

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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## An Autonomous Science Explorer

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

**Observation-2**

**Observation-3**

**Observation-4**

**…**

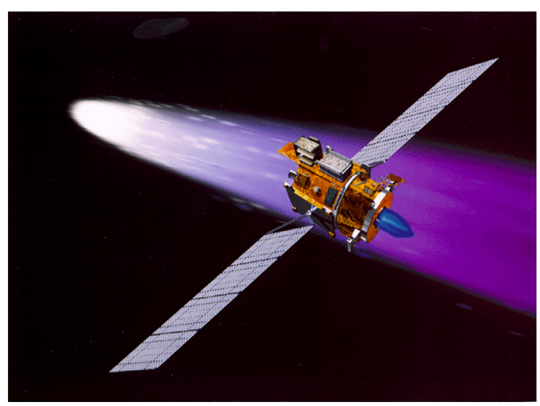


Image courtesy of JPL.

**Objective:**
**maximize science return**

Based on slides by Dave Smith, NASA Ames

# Complications

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

**Observation-2**

**Observation-3**

**Observation-4**

…

linked

angle between targets
$\Rightarrow$ turn duration

calibration
- target1
- target2
- …

consumables:
- fuel
- power
- data storage
- cryogen

Image courtesy of JPL.

**Objective:**
maximize science return



# Limitations of Classical Planning with Atomic Actions (aka STRIPS)

Instantaneous actions

No temporal constraints

No concurrent actions

No continuous quantities

## 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)

no time, no resources



## Needed Extensions

**Time**

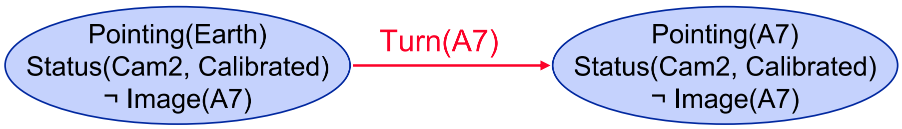
**Resources**

**Uncertainty**

# World Description

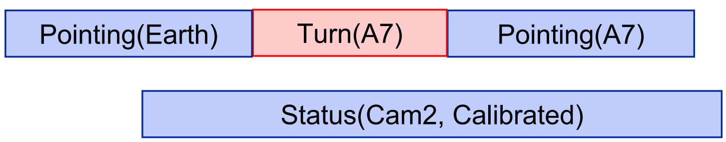
State-centric:

for each time describe propositions that are true




Proposition-centric:

for each proposition describe times it is true

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# Representing Timing: Qualitative Temporal Relations [Allen AAAI83]

A before B

A meets B

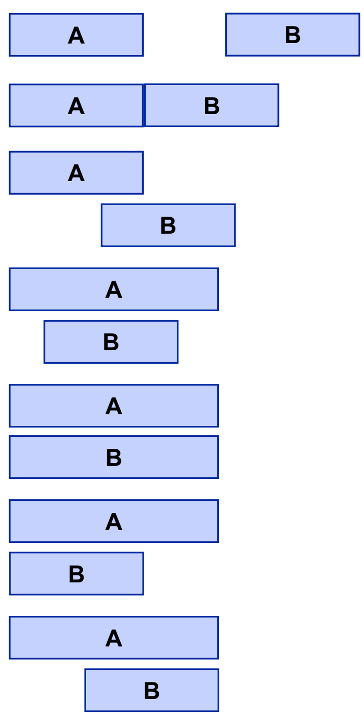
A overlaps B

A contains B

A = B

A starts B

A ends B

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## Representing Temporal Operators: TakeImage Schema

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

TakeImage (?target, ?instr)

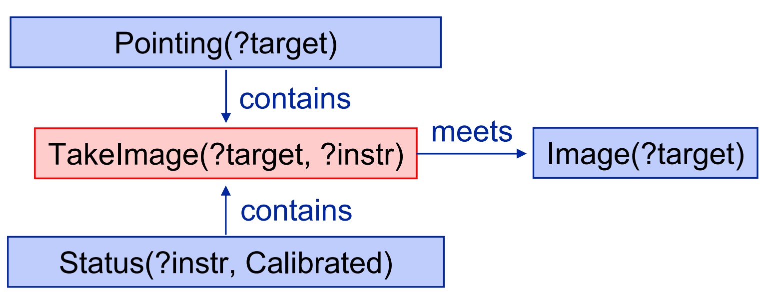
| | |
|---|---|
| contained-by | Status(?instr, Calibrated) |
| contained-by | Pointing(?target) |
| meets | Image(?target) |

Based on slides by Dave Smith, NASA Ames

## Pictorially

TakeImage (?target, ?instr)

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

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## TakeImage Schema Semantics

TakeImage (?target, ?instr)

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

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



## Turn

Turn (?target)

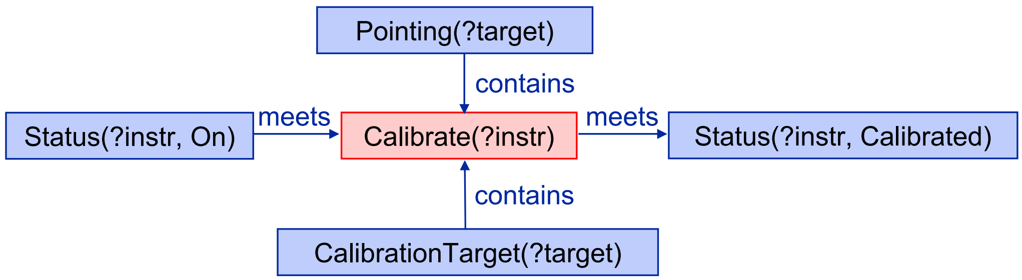
| | |
|---|---|
| met-by | Pointing(?direction) |
| meets | Pointing(?target) |

$$\mathrm{Pointing}(?direction) \xrightarrow{\text{meets}} \mathrm{Turn}(?target) \xrightarrow{\text{meets}} \mathrm{Pointing}(?target)$$

Based on slides by Dave Smith, NASA Ames

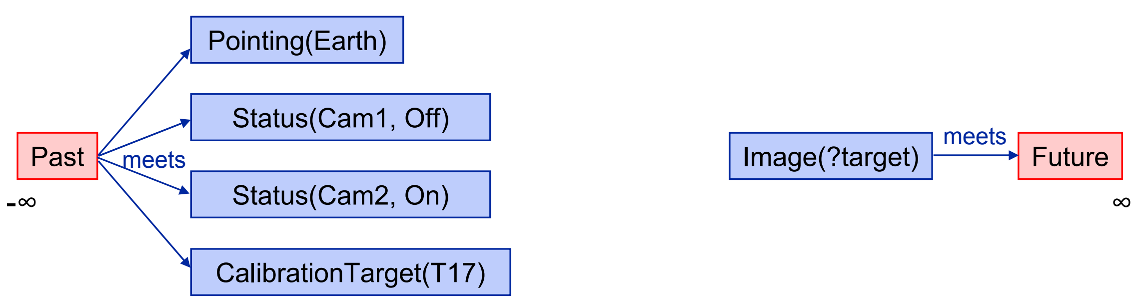
# Calibrate

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

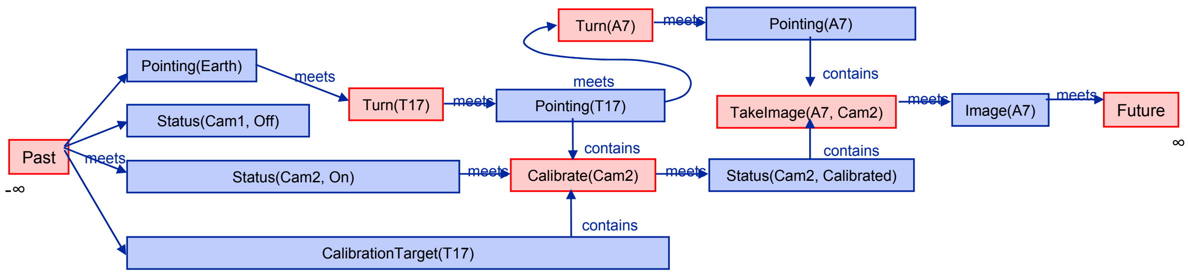





# A Temporal Planning Problem



# A Consistent Complete Temporal Plan




Based on slides by Dave Smith, NASA Ames

# CBI Planning Algorithm

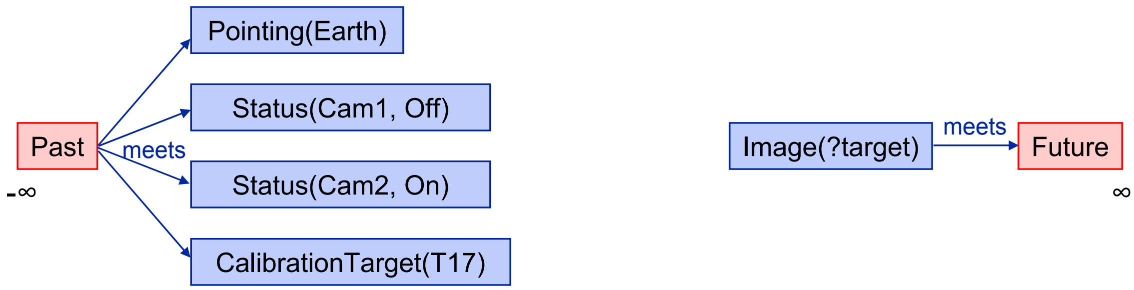
Choose:

- introduce an action & instantiate constraints
- coalesce propositions

Propagate constraints

Based on slides by Dave Smith, NASA Ames

# Initial Plan

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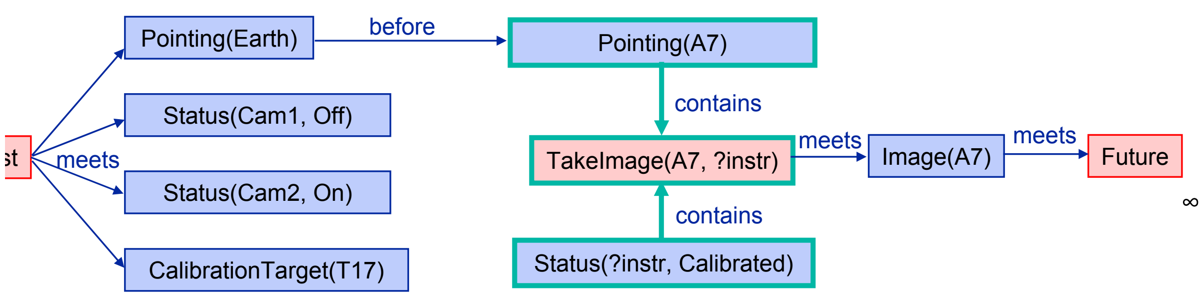
# Expansion 1

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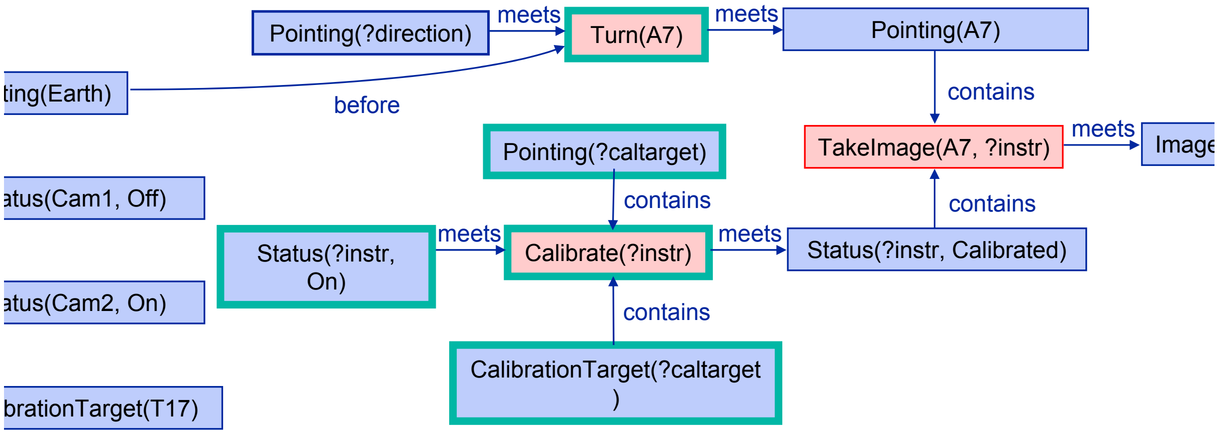
# Expansion 2

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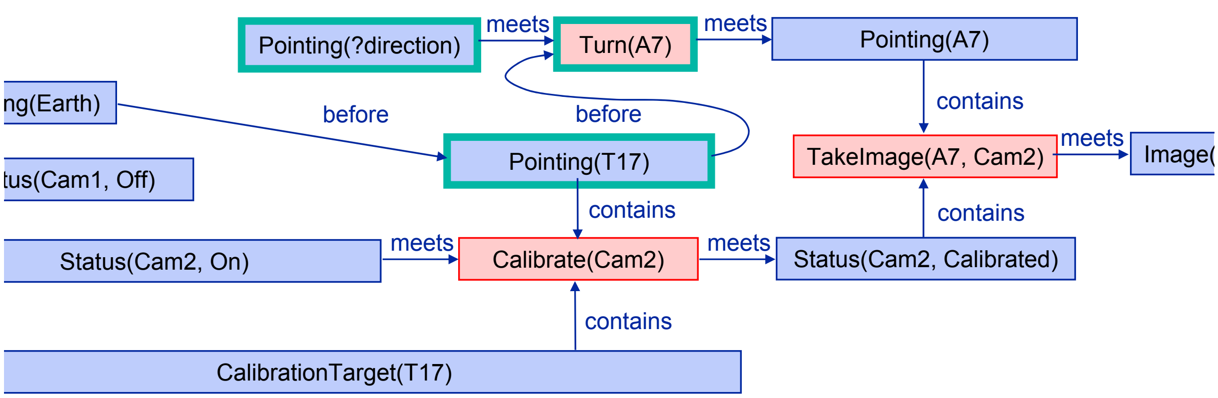
# Coalescing

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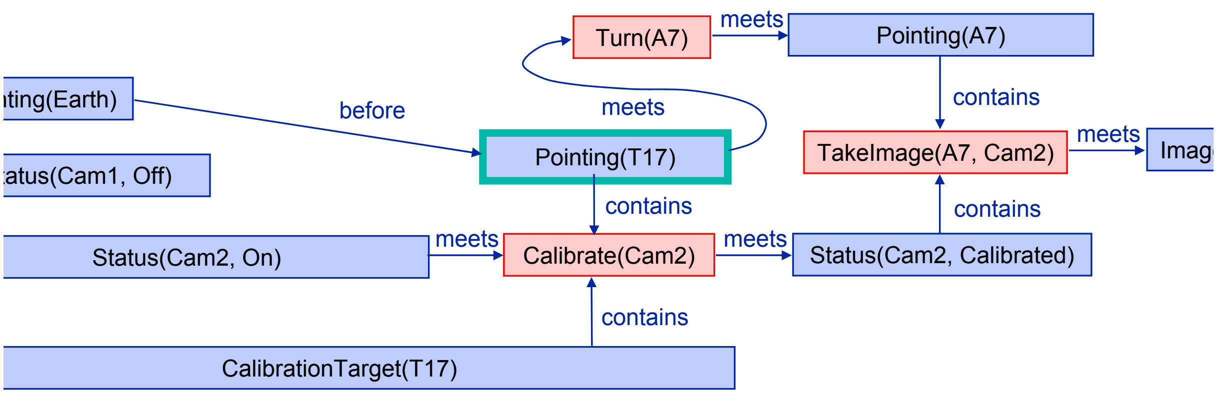
# Coalescing

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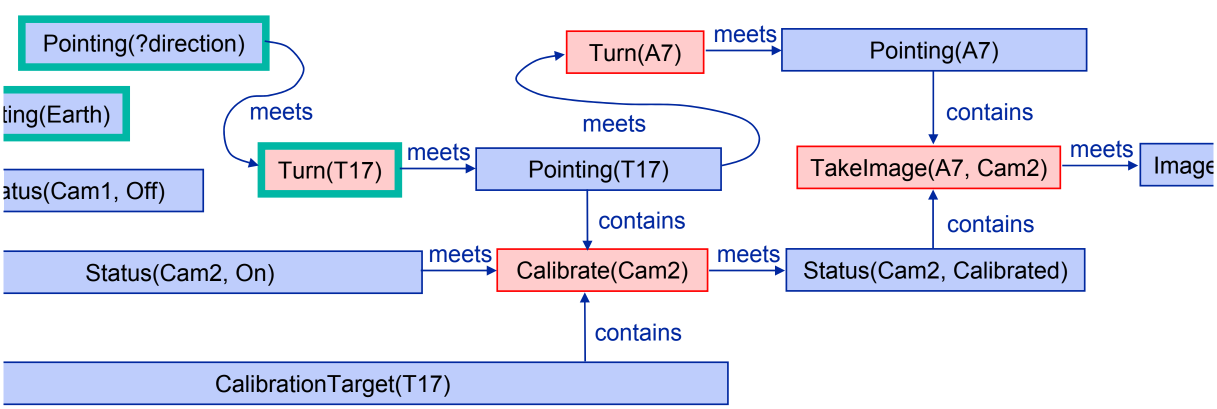
# Expansion 3

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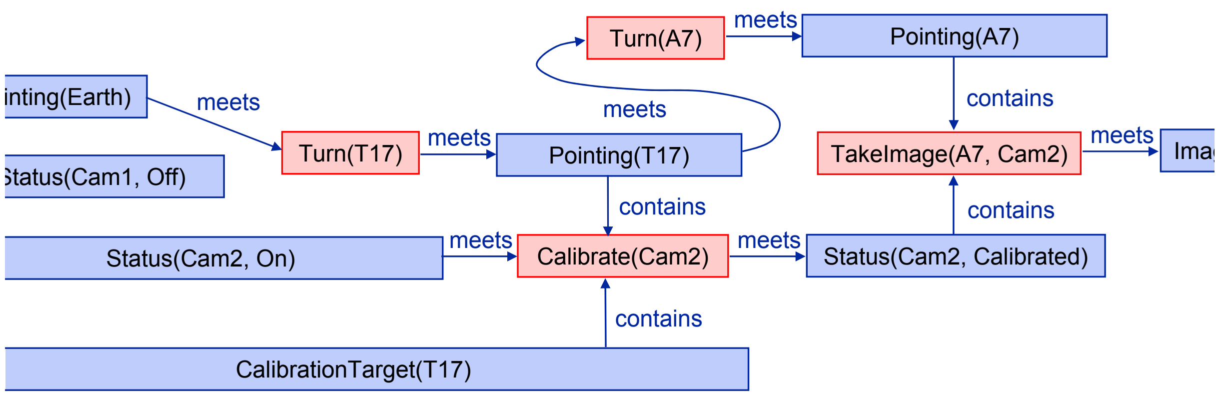
# Coalescing

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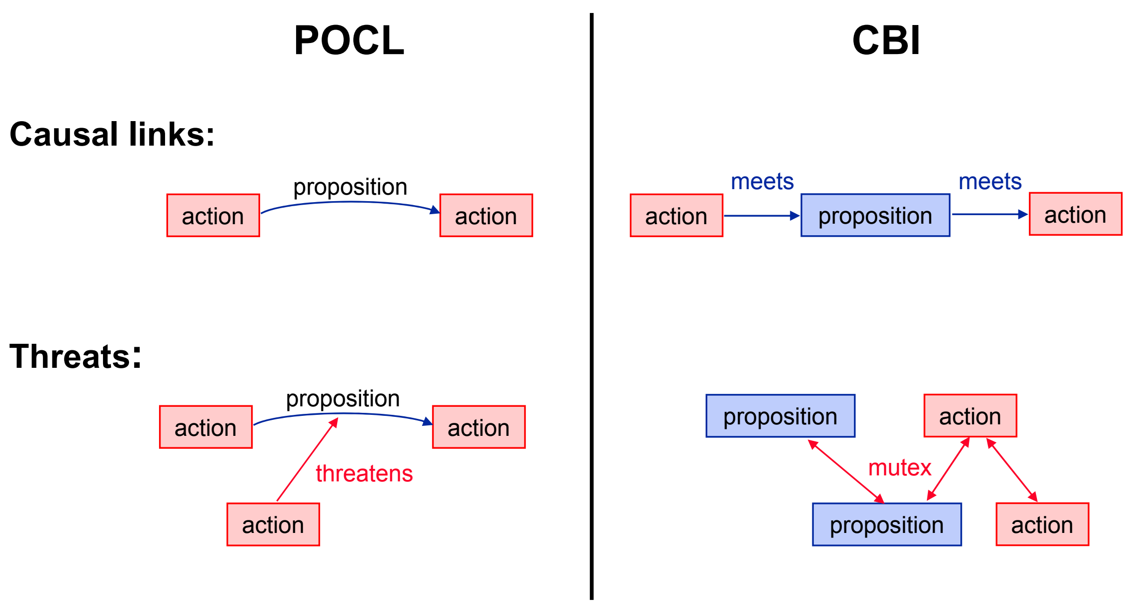
# Relation to Causal Links & Threats




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 |



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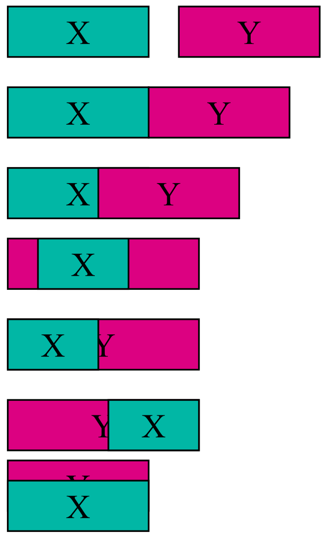
## Qualitative Temporal Constraints
### (Allen 83)

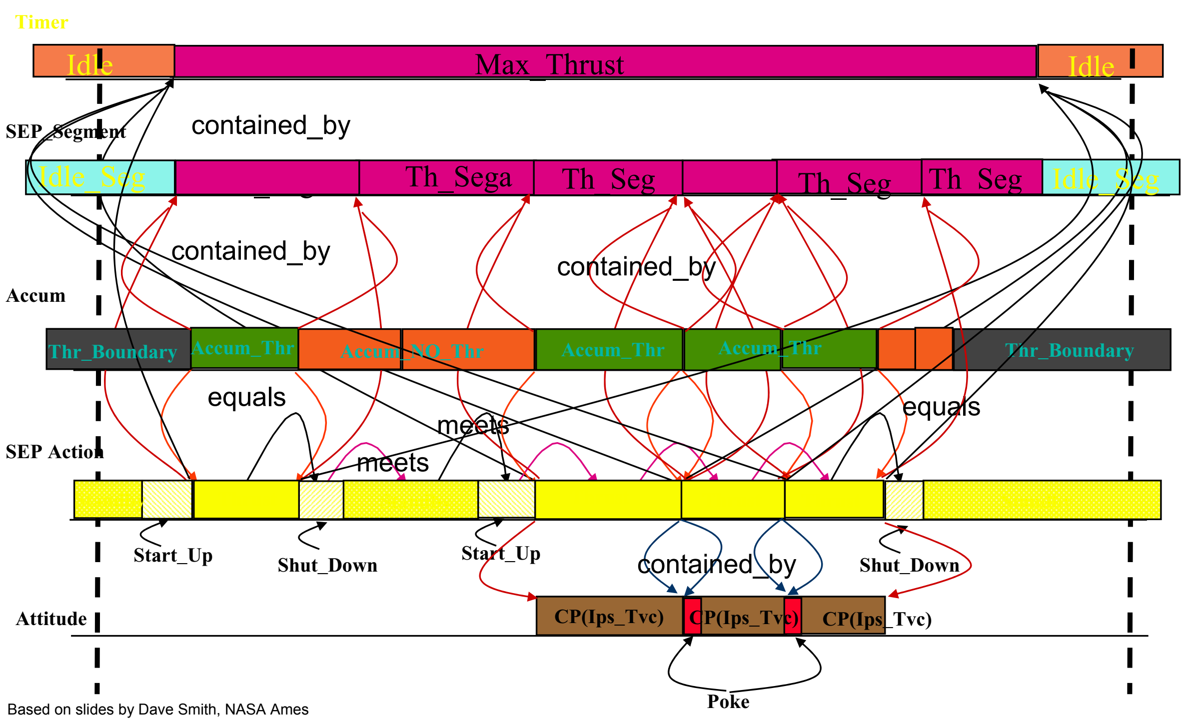
- x before y
- x meets y
- x overlaps y
- x during y
- x starts y
- x finishes y
- x equals y




- 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

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## 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.
  $\rightarrow$ $10 \leq [T^+(\text{store}) - T^-(\text{store})] \leq 30$
- Bread should be eaten within a day of baking.
  $\rightarrow$ $0 \leq [T^+(\text{baking}) - T^-(\text{eating})] \leq 1$ day
- Inequalities, $X^+ < Y^-$, may be expressed as binary interval relations:
  $\rightarrow$ $-\text{inf} < [X^+ - Y^-] < 0$

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

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



# Temporal Constraint Satisfaction Problem (TCSP)

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

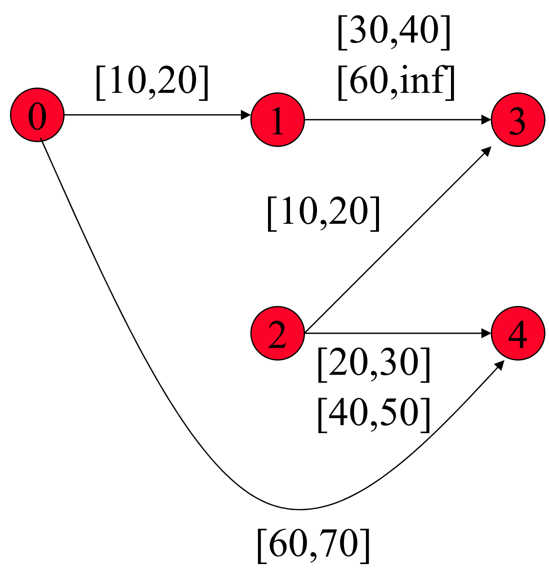
- $X_i$ continuous variables
- $T_i, T_{ij}$ interval constraints

  $\{I_1, \ldots, I_n\}$ 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]

## TCSP Are Visualized Using Directed Constraint Graphs






## Simple Temporal Networks
### (Dechter, Meiri, Pearl 91)

Simple Temporal Networks:

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

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

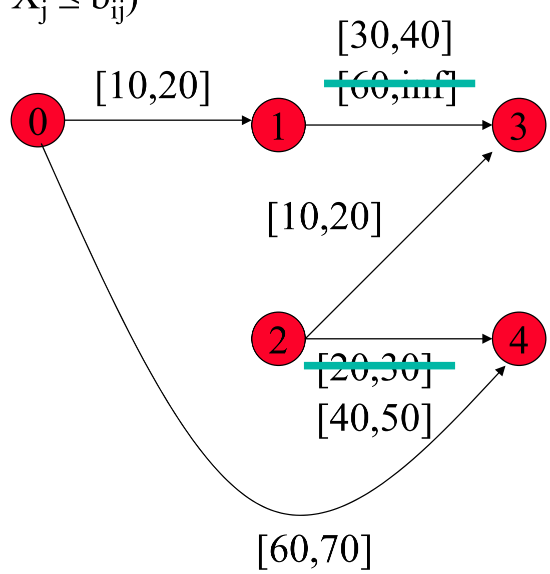
  $(a_0 \le X_j - X_i \le b_0)$ ~~or ($a_1 \le X_j - X_i \le b_1$) or . . .~~

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

Can't represent:
- Disjoint tokens

## Simple Temporal Network

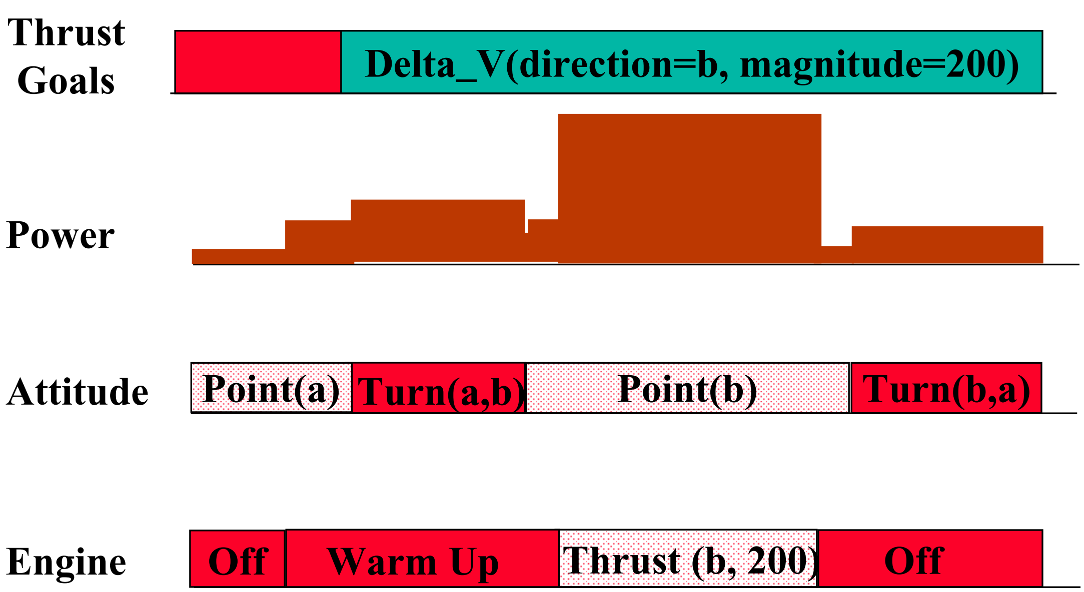
- $T_{ij} = (a_{ij} \le X_i - X_j \le b_{ij})$




Based on slides by Dave Smith, NASA Ames

Slide courtesy of Nicola Muscettola.

## A Completed Plan Forms an STN

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Slide courtesy of Nicola Muscettola.

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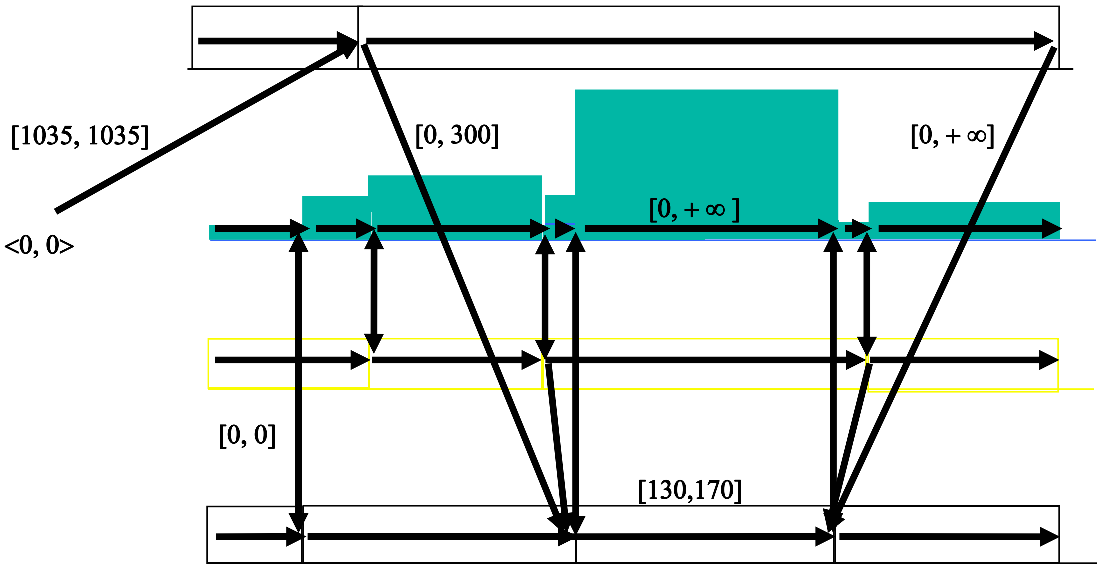




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