

Coping with Time & Continuous Quantities

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The Ambitious Spacecraft



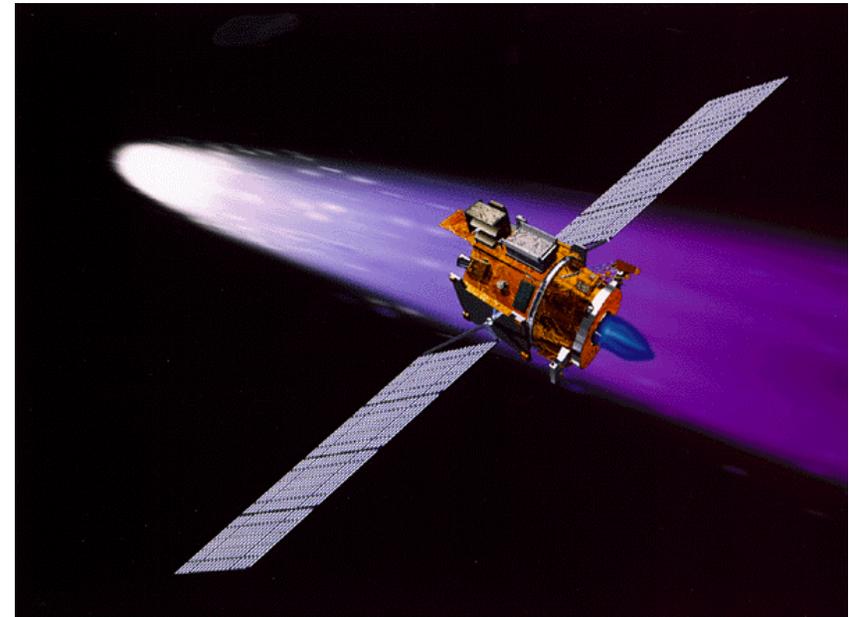
Observation-1
priority
time window
target
instruments
duration

Observation-2

Observation-3

Observation-4

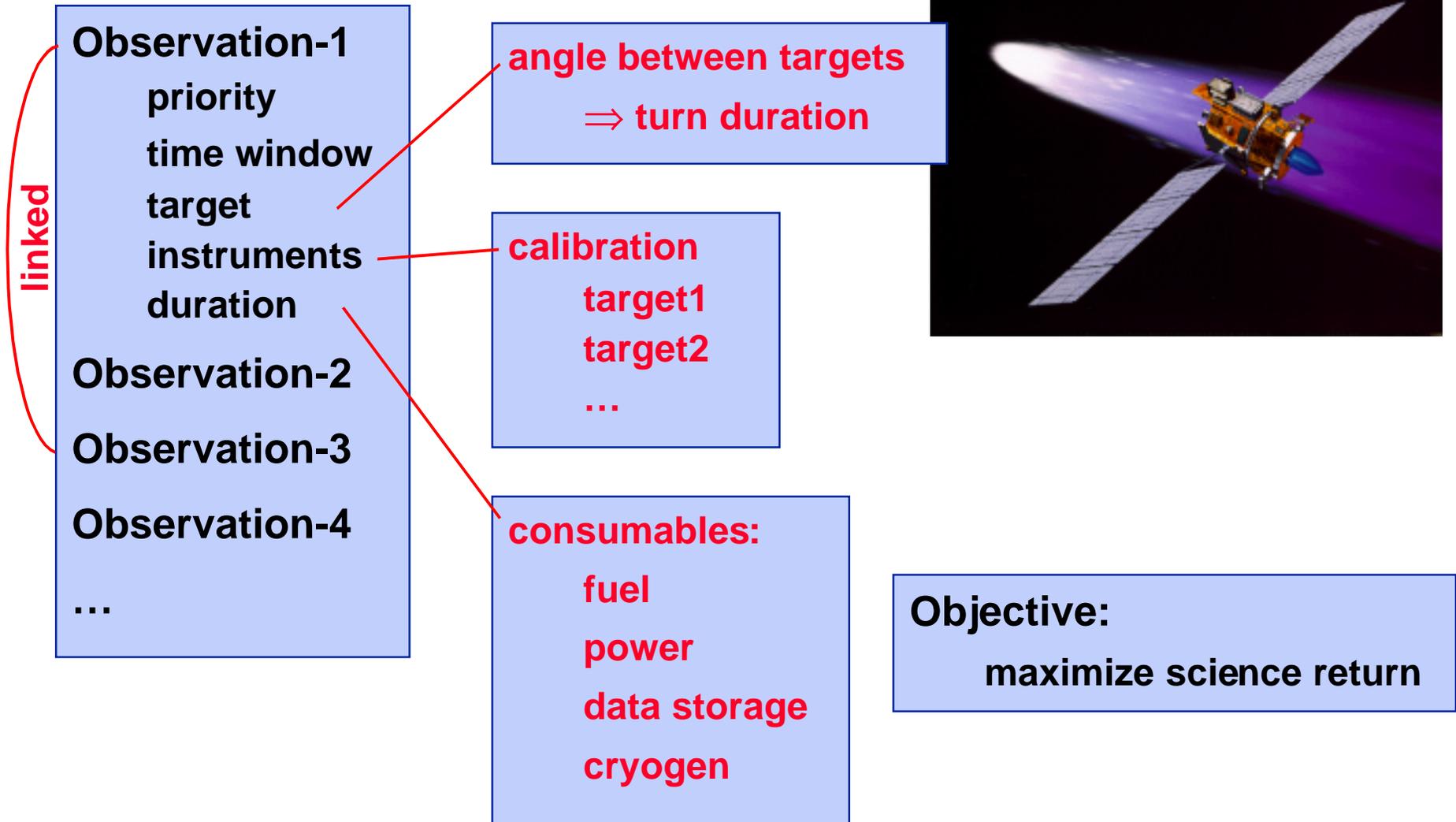
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Objective:

maximize science return

Complications



The Spacecraft's Choices



Observations

Instrument

Calibration target

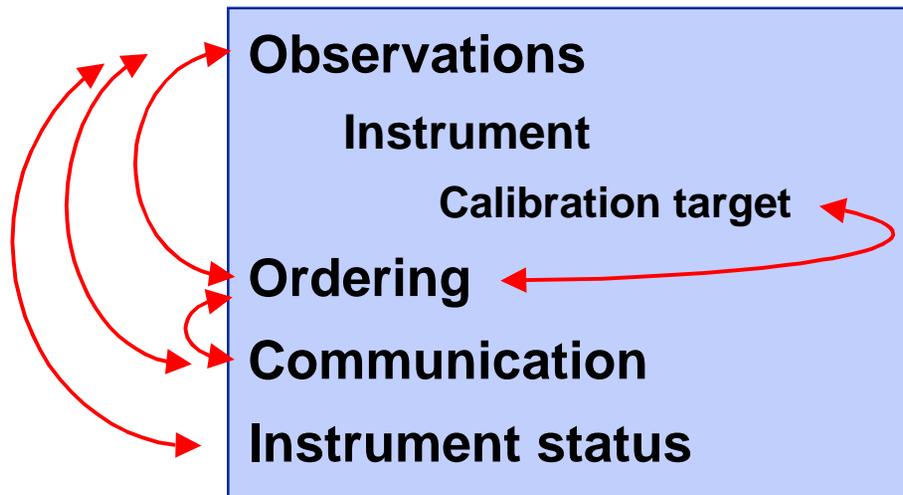
Ordering

Communication

Instrument Status



The Spacecraft's Choices



continuous time
time constraints
concurrent actions
metric resources
optimization

The Choice Spectrum



**job-shop
scheduling**

planning



The Choice Spectrum



job-shop
scheduling

planning



Job1
task1 < task2 < task3 < ...
Job2
Job3
...

R3
R7
R1

Ordering choices only

The Choice Spectrum

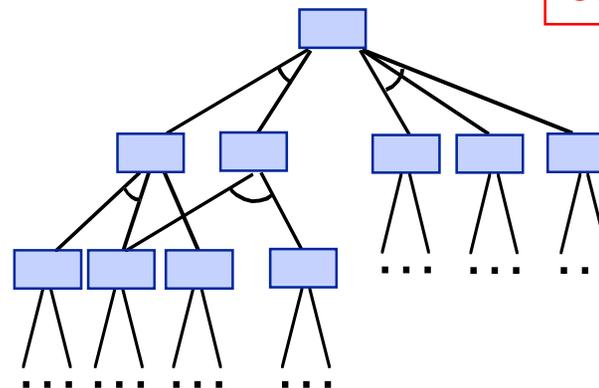


job-shop
scheduling

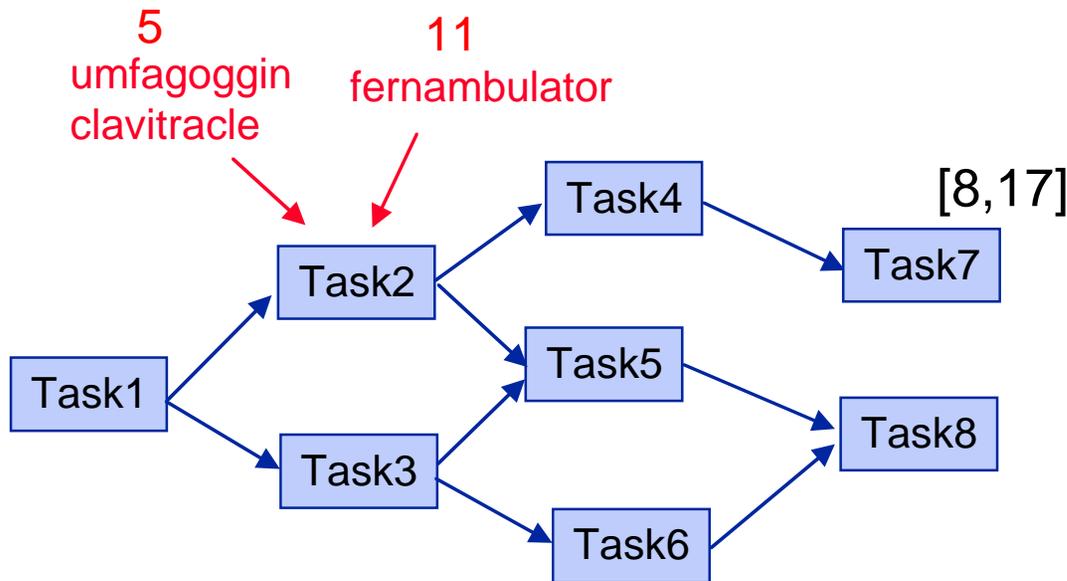
planning



cascading levels
of choice

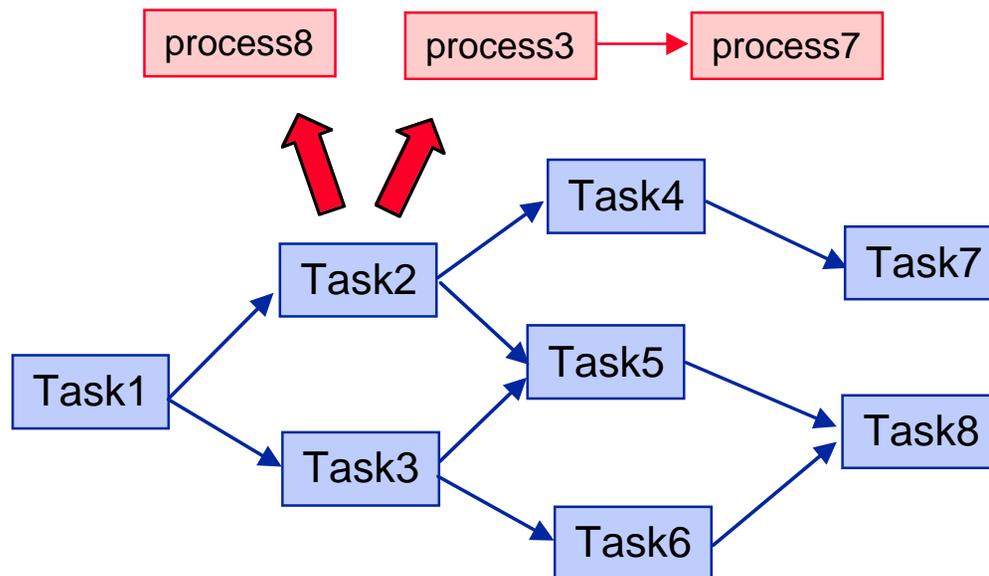
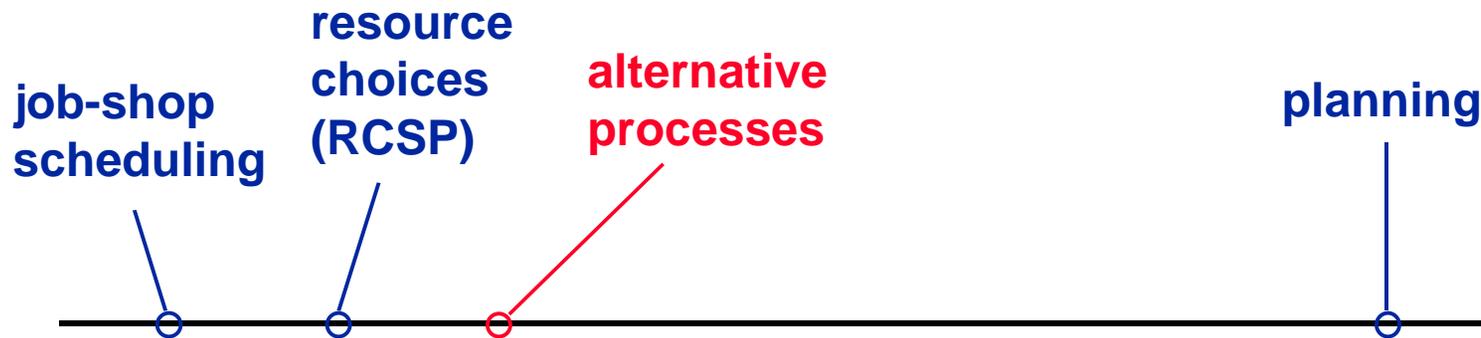


The Choice Spectrum



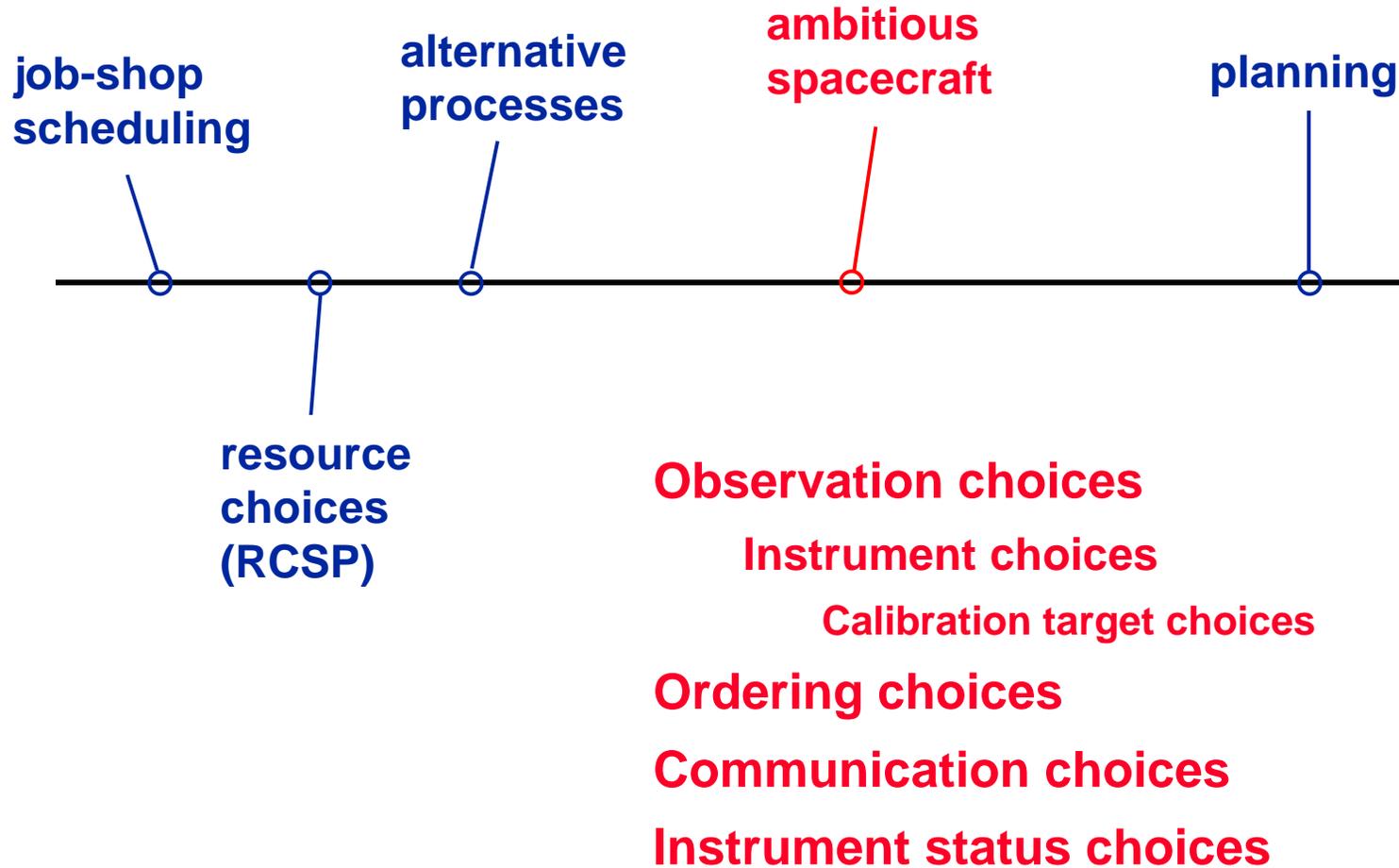
Ordering choices
Resource choices

The Choice Spectrum

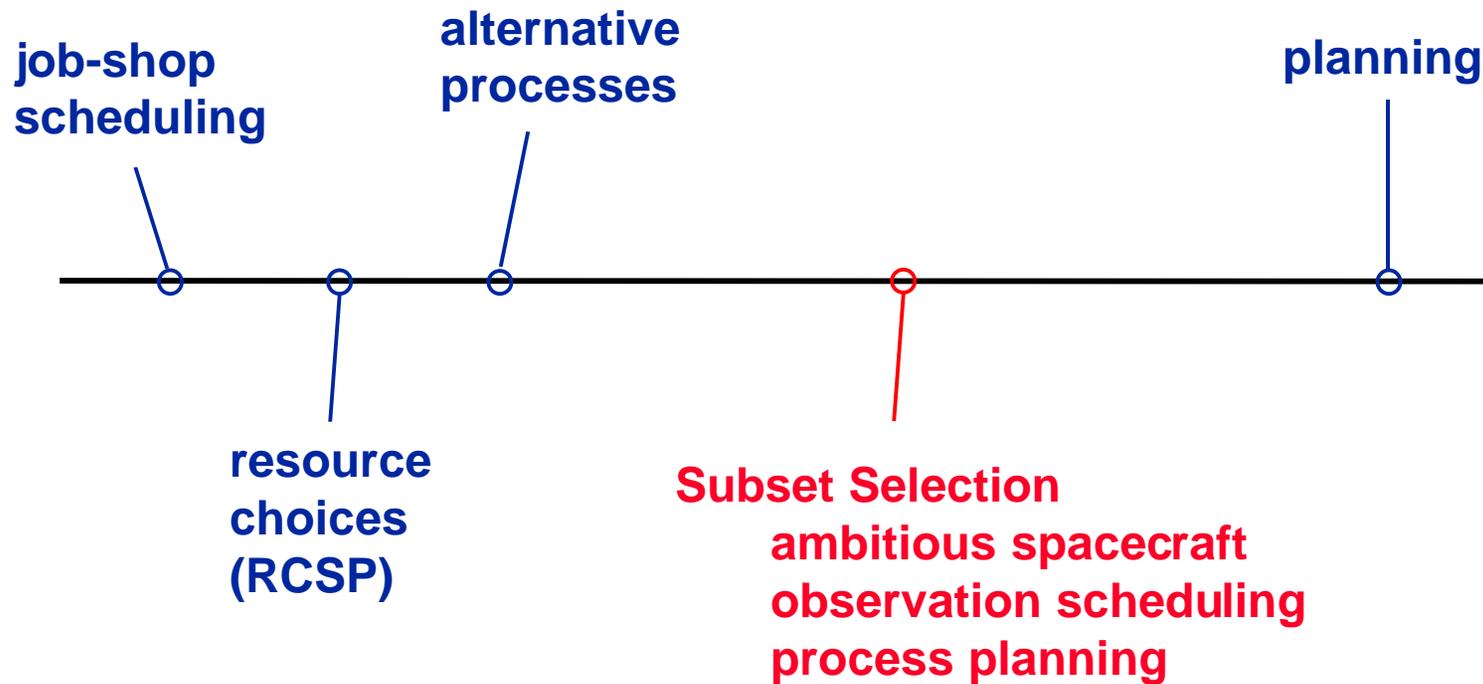


Ordering choices
Resource choices
Process choices

The Choice Spectrum



The Choice Spectrum



Strips Assumptions

Instantaneous actions

No time constraints

No concurrent actions

No continuous quantities

Bleak?

Some STRIPS Operators



TakelImage (?target, ?instr):

Pre: Status(?instr, Calibrated), Pointing(?target)

Eff: Image(?target)

Calibrate (?instrument):

Pre: Status(?instr, On), Calibration-Target(?target), Pointing(?target)

Eff: \neg Status(?instr, On), Status(?instr, Calibrated)

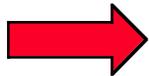
Turn (?target):

Pre: Pointing(?direction), ?direction \neq ?target

Eff: \neg Pointing(?direction), Pointing(?target)

no time, no resources

Outline



Resources

Reusable

Consumable

Time

Uncertainty?

Resources



	Discrete single/multiple	Continuous (metric)
Reusable	instruments	bandwidth
Consumable	solid rockets	fuel

Reusable Resources (single-capacity)



TakeImage (?target, ?instr):

Res: ?instr

Pre: Status(?instr, Calibrated), Pointing(?target)

Eff: Image(?target)

Prevent concurrent actions

Mutual exclusion between actions:

Graphplan trivial

Satplan $\neg A_1 \vee \neg A_2$

POCL $A_1 < A_2 \vee A_2 < A_1$

Reusable Resources (multiple-capacity)



Suppose: 2 cameras
Simple approach: name the cameras

TakeImage (?target, ?instr):

Res: ?instr

Pre: Status(?instr, Calibrated), Pointing(?target)

Eff: Image(?target)

Mutual exclusion between actions:

Graphplan trivial

Satplan $\neg A_1 \vee \neg A_2$

POCL $?instr_1 \neq ?instr_2 \vee A_1 < A_2 \vee A_2 < A_1$

Reusable Resources (multiple-capacity)



2 Cameras:
Not named

TakeImage (?target):

Res: Camera(1)
Pre: Pointing(?target)
Eff: Image(?target)

Capacity(Camera)=2

Explicit checking of concurrent actions to ensure:

$$\sum \text{usage} \leq \text{capacity}$$

Reusable Resources (multiple-capacity)



$$\Sigma \text{ usage} > \text{ capacity}$$

Mutual exclusion between sets of actions:

Graphplan

n-ary mutex

Satplan

$$\neg(A_1 \wedge A_2 \wedge A_3 \wedge \dots)$$

POCL

$$A_1 < A_2 \vee A_2 < A_1 \vee A_1 < A_3 \vee A_3 < A_1 \vee \dots$$

Graph Techniques
IxTeT

Profiling heuristics
Sadeh, Fox, Beck
O-Plan

Summary



Resources

Reusable

Single-capacity \Rightarrow binary mutex

easy

Multiple-capacity \Rightarrow n-ary mutex

tricky

specialized algorithms

search heuristics

Consumable

Time

Uncertainty?



Consumable Resources

Turn (?target):

Pre: Pointing(?direction), ?direction \neq ?target

$\text{Fuel} \geq \text{Angle}(\text{?direction}, \text{?target}) * \text{ConsumptionRate}$

Eff: \neg Pointing(?direction), Pointing(?target)

$\text{Fuel} -= \text{Angle}(\text{?direction}, \text{?target}) * \text{ConsumptionRate}$

Simple approach:

wait until all variables are instantiated

LP Approaches

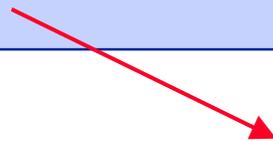


Zeno:

open conditions: $P_1, P_2, P_3, P_4, P_5, E_1, E_2, E_3$

constraints: Fuel ≤ 10

Simplex



LP Approaches: LPSAT



Turn (?target):

Pre: Pointing(?direction), ?direction \neq ?target

$Fuel \geq Angle(?direction, ?target) * ConsumptionRate$

Eff: \neg Pointing(?direction), Pointing(?target)

$Fuel -= Angle(?direction, ?target) * ConsumptionRate$



$\neg Turn-T3-T7_1 \vee$

$\{ Pointing-T3_1 \wedge C1_1$

$\wedge \neg Pointing-T3_2 \wedge Pointing-T7_2 \wedge C2_2 \}$

SAT engine

$C1_1 \Rightarrow Fuel_1 \geq Angle(T3, T7) * ConsumptionRate$

$C2_2 \Rightarrow Fuel_2 = Fuel_1 - Angle(T3, T7) * ConsumptionRate$

Simplex

ILP planning



$$\neg \text{Turn-T3-T7}_1 \vee \{ \text{Pointing-T3}_1 \wedge C1_1 \wedge \neg \text{Pointing-T3}_2 \wedge \text{Pointing-T7}_2 \wedge C2_2 \}$$

$$C1_1 \Rightarrow \text{Fuel}_1 \geq \text{Angle}(\text{T3}, \text{T7}) * \text{ConsumptionRate}$$

$$C2_2 \Rightarrow \text{Fuel}_2 = \text{Fuel}_1 - \text{Angle}(\text{T3}, \text{T7}) * \text{ConsumptionRate}$$


$$\neg \text{Turn-T3-T7}_1 \vee \text{Pointing-T3}_1$$

$$\neg \text{Turn-T3-T7}_1 \vee C1_1$$

$$\neg \text{Turn-T3-T7}_1 \vee \neg \text{Pointing-T3}_2$$

$$\neg \text{Turn-T3-T7}_1 \vee \text{Pointing-T7}_2$$

$$\neg \text{Turn-T3-T7}_1 \vee C2_2$$

$$C1_1 \Rightarrow \text{Fuel}_1 \geq \text{Angle}(\text{T3}, \text{T7}) * \text{ConsumptionRate}$$

$$C2_2 \Rightarrow \text{Fuel}_2 = \text{Fuel}_1 - \text{Angle}(\text{T3}, \text{T7}) * \text{ConsumptionRate}$$

Kautz & Walser
Vossen et al.

ILP planning



$\neg \text{Turn-T3-T7}_1 \vee \text{Pointing-T3}_1$
 $\neg \text{Turn-T3-T7}_1 \vee C1_1$
 $\neg \text{Turn-T3-T7}_1 \vee \neg \text{Pointing-T3}_2$
 $\neg \text{Turn-T3-T7}_1 \vee \text{Pointing-T7}_2$
 $\neg \text{Turn-T3-T7}_1 \vee C2_2$
 $C1_1 \Rightarrow \text{Fuel}_1 \geq \text{Angle}(\text{T3}, \text{T7}) * \text{ConsumptionRate}$
 $C2_2 \Rightarrow \text{Fuel}_2 = \text{Fuel}_1 - \text{Angle}(\text{T3}, \text{T7}) * \text{ConsumptionRate}$



$(1 - \text{Turn-T3-T7}_1) + \text{Pointing-T3}_1 \geq 1$
 $M(1 - \text{Turn-T3-T7}_1) + (1 + D1_1) \geq 1$
 $(1 - \text{Turn-T3-T7}_1) + (1 - \text{Pointing-T3}_2) \geq 1$
 $(1 - \text{Turn-T3-T7}_1) + \text{Pointing-T7}_2 \geq 1$
 $M(1 - \text{Turn-T3-T7}_1) + (1 \pm D2_1) \geq 1$
 $D1_1 = \text{Fuel}_1 - \text{Angle}(\text{T3}, \text{T7}) * \text{ConsumptionRate}$
 $D2_2 = \text{Fuel}_2 - (\text{Fuel}_1 - \text{Angle}(\text{T3}, \text{T7}) * \text{ConsumptionRate})$

Summary



Resources

Reusable

Consumable

Equality and Inequality conditions

POCL + LP

slow

SAT + LP

fast

ILP

medium

Graphplan

?

Concurrent continuous change

ugly!

Time

Uncertainty?



Concurrent Continuous Change



Turn (?target):

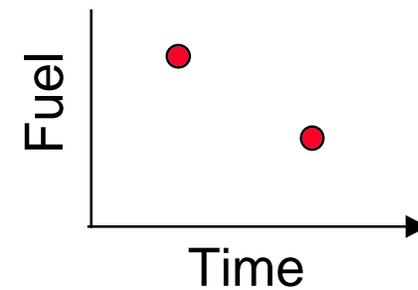
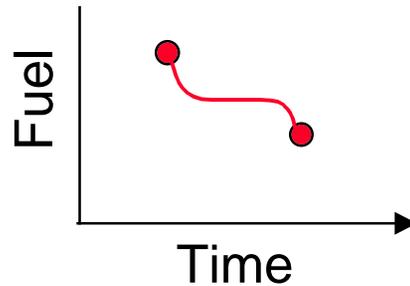
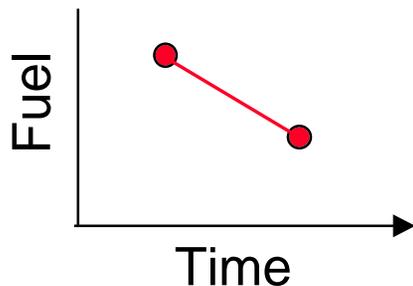
Pre: Pointing(?direction), ?direction \neq ?target

Fuel \geq Angle(?direction,?target) *ConsumptionRate

Eff: \neg Pointing(?direction), Pointing(?target)

Fuel $-=$ Angle(?direction,?target) *ConsumptionRate

Fuel = F(t)



Outline



Resources

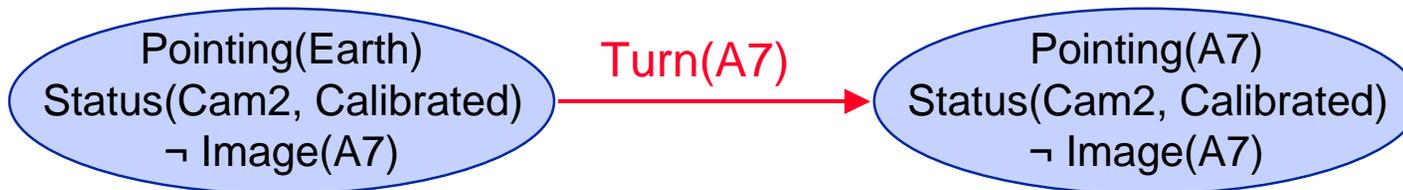
Time

Uncertainty?

World Description

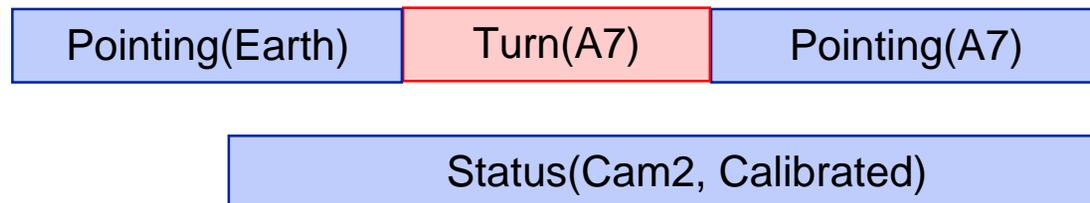
State-centric:

for each time describe propositions that are true



Proposition-centric:

for each proposition describe times it is true



Allen's Ordering Relationships

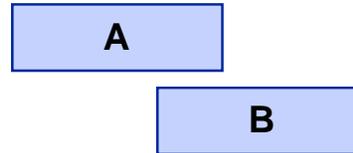
A before B



A meets B



A overlaps B



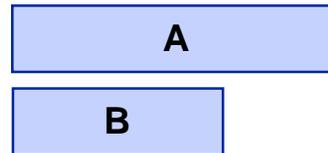
A contains B



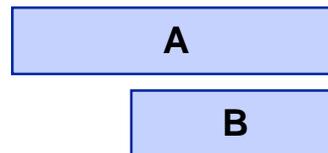
A = B



A starts B



A ends B



TakelImage Schema

TakelImage (?target, ?instr):

Pre: Status(?instr, Calibrated), Pointing(?target)

Eff: Image(?target)



$\text{TakelImage}(\text{?target}, \text{?instr})_A$

$\Rightarrow \exists P \{ \text{Status}(\text{?instr}, \text{Calibrated})_P \wedge \text{Contains}(P, A) \}$

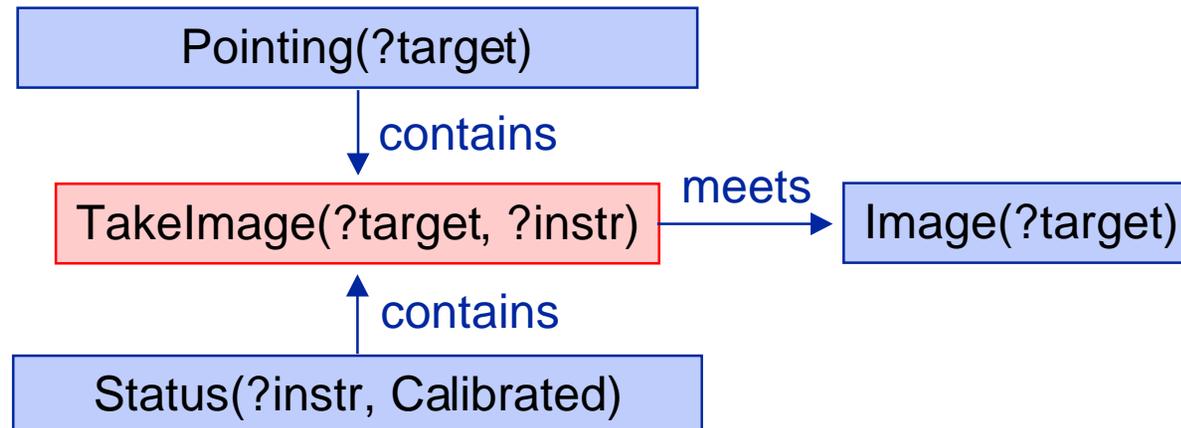
$\wedge \exists Q \{ \text{Pointing}(\text{?target})_Q \wedge \text{Contains}(Q, A) \}$

$\wedge \exists R \{ \text{Image}(\text{?target})_R \wedge \text{Meets}(A, R) \}$

Shorthand



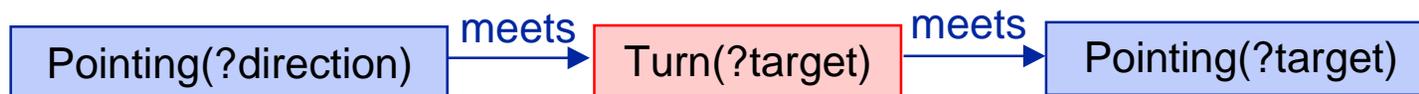
TakeImage (?target, ?instr)
contained-by Status(?instr, Calibrated)
contained-by Pointing(?target)
meets Image(?target)



Turn



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



Calibrate



Calibrate (?instr)

met-by

contained-by

contained-by

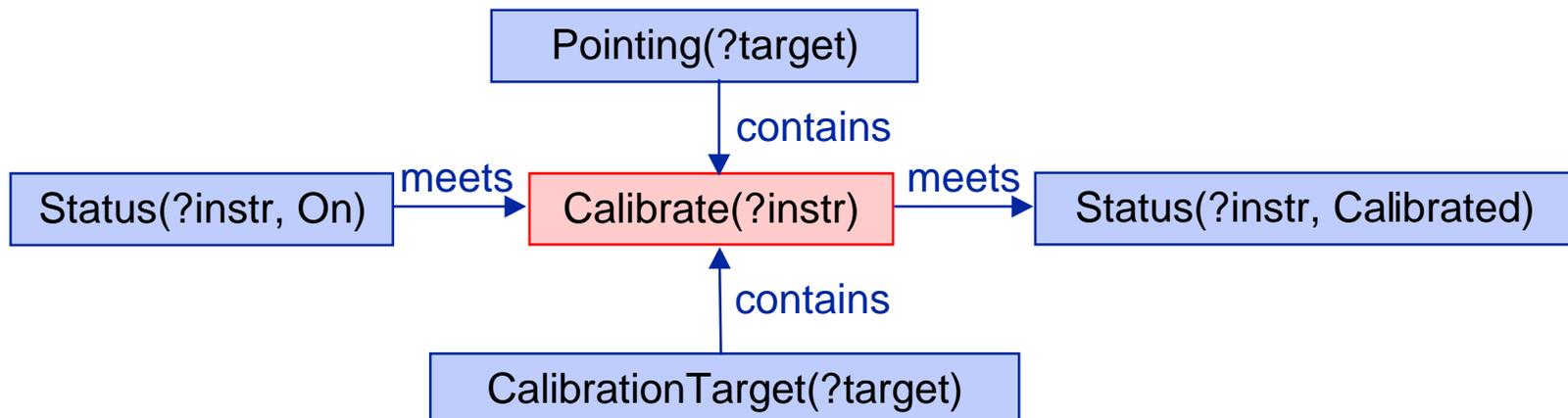
meets

Status(?instr, On)

CalibrationTarget(?target)

Pointing(?target)

Status(?instr, Calibrated)



Algorithm



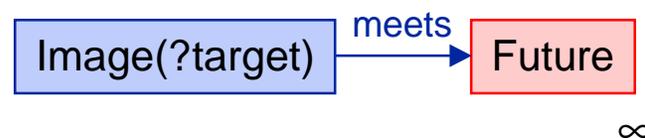
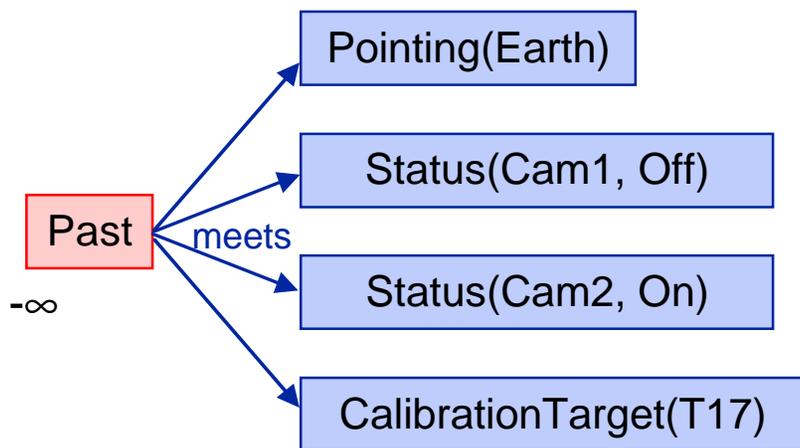
Choose:

introduce an action & instantiate constraints

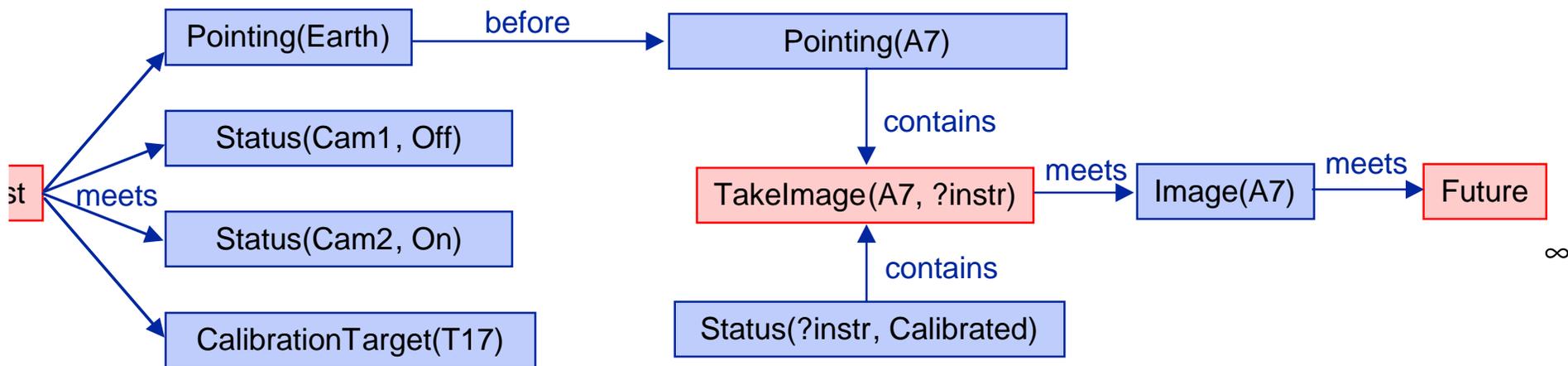
coalesce propositions

Propagate constraints

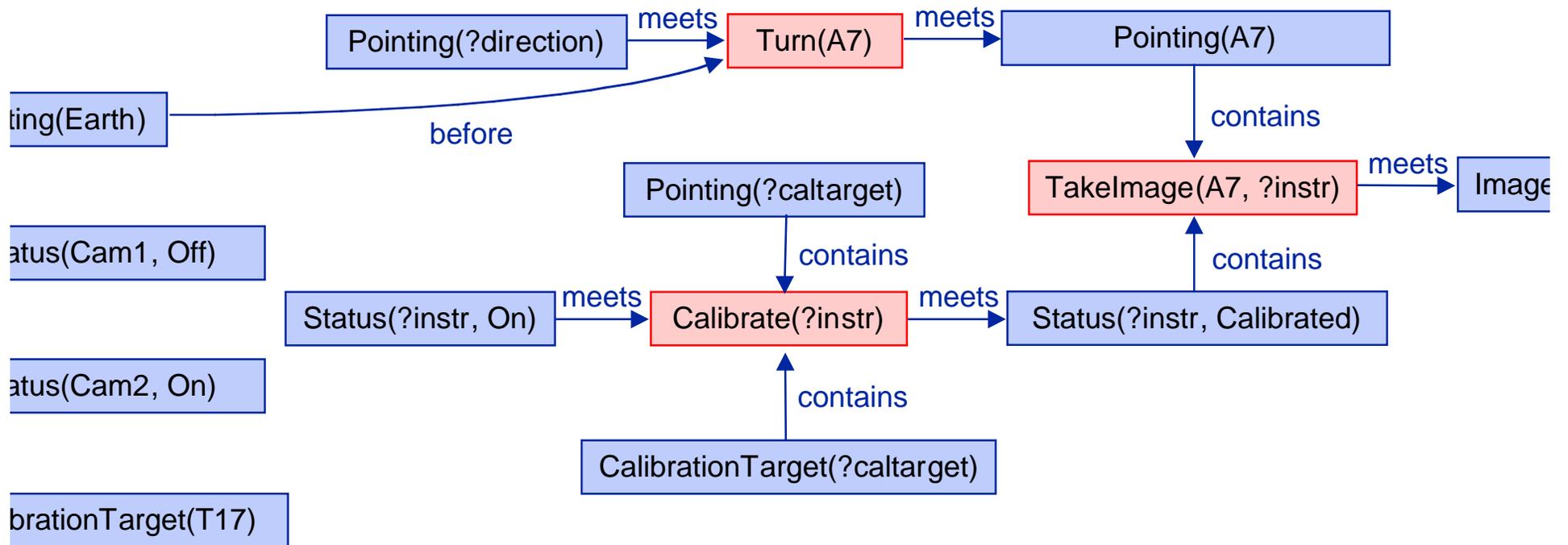
Initial Plan



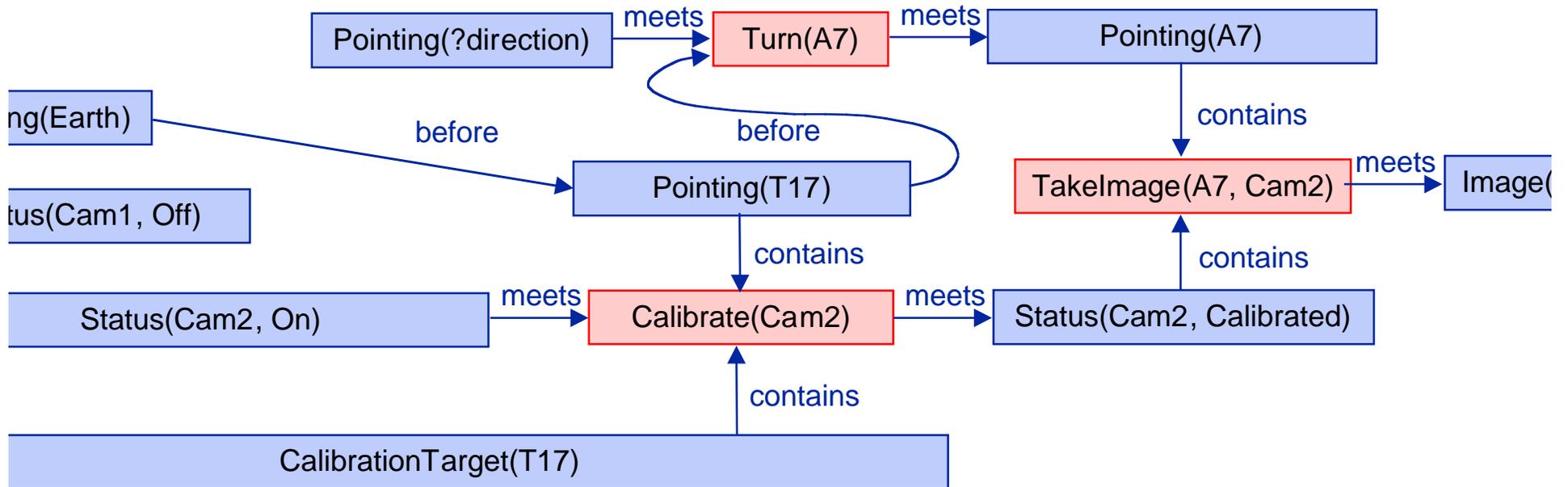
Expansion 1



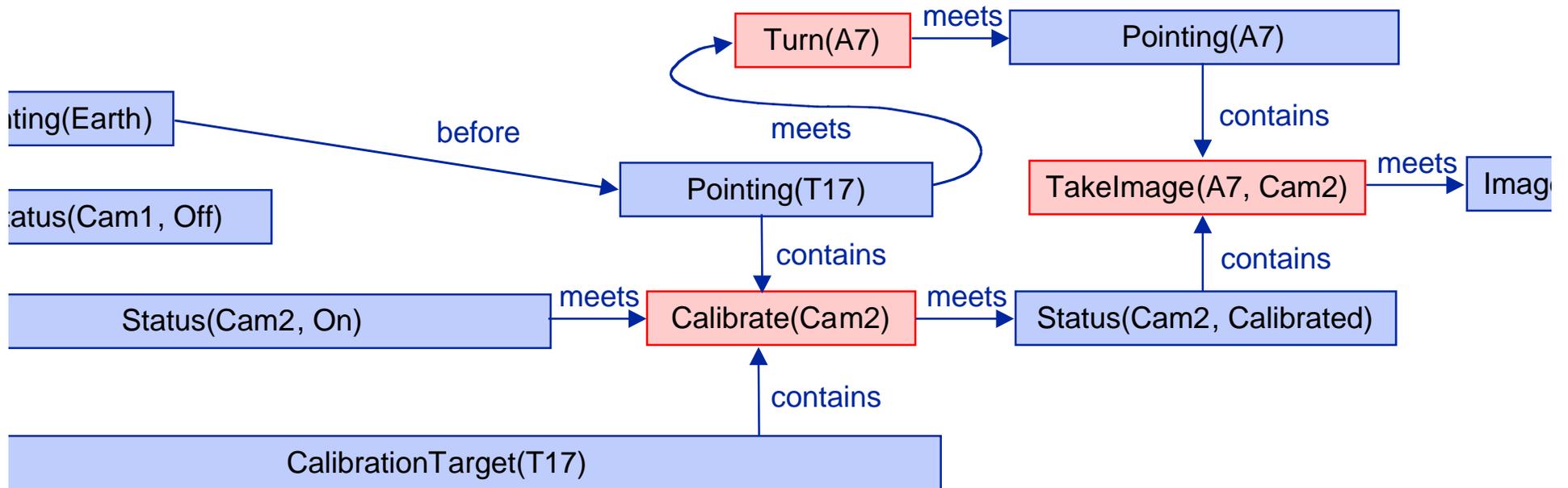
Expansion 2



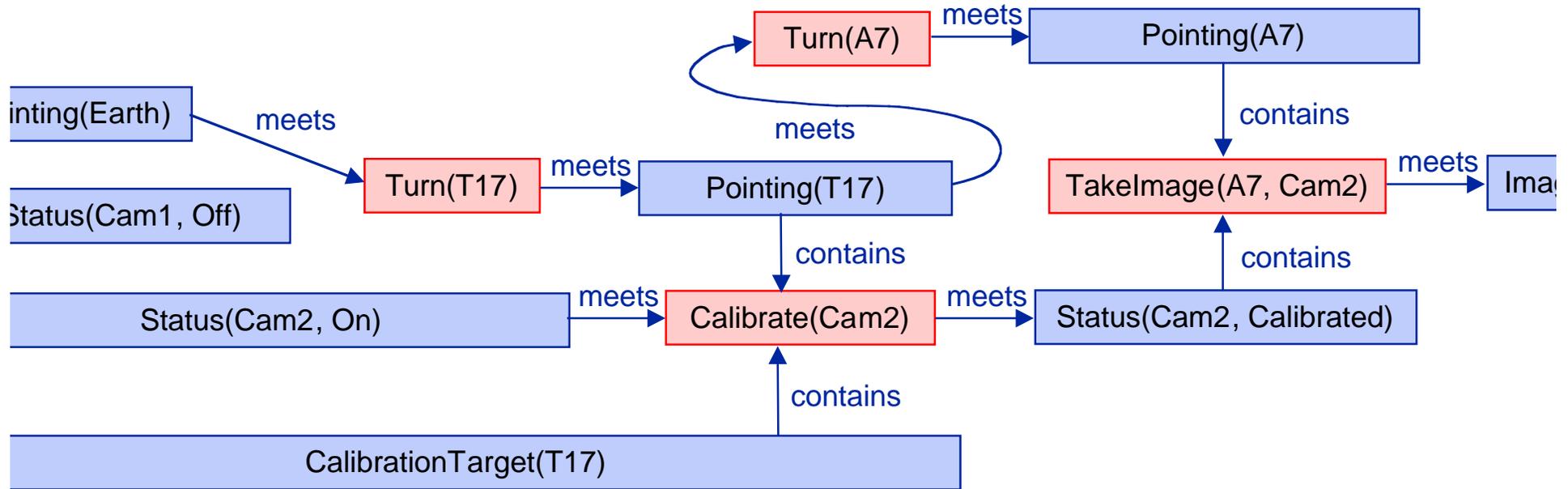
Coalescing



Coalescing



Coalescing



POCL vs CBI



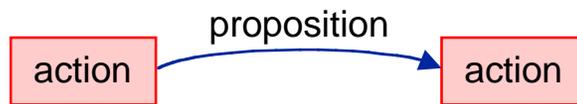
	POCL	CBI
search strategy	goal-directed	goal-directed
temporal reasoning	before/after	complex
protection	causal links	meets
conflicts	threats	mutex
conflict resolution	proactive	lazy

Causal Links & Threats

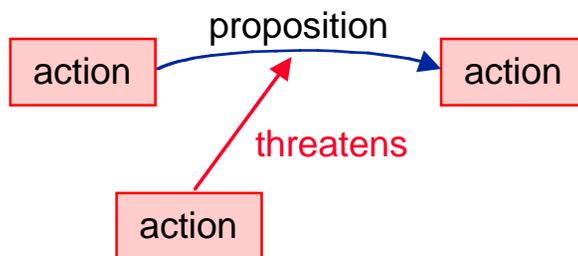


POCL

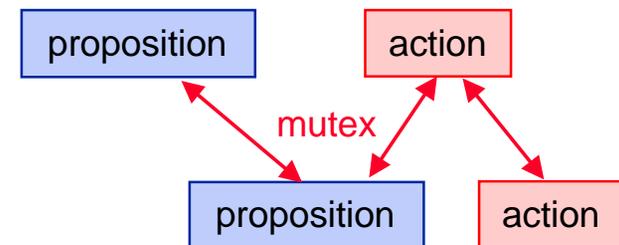
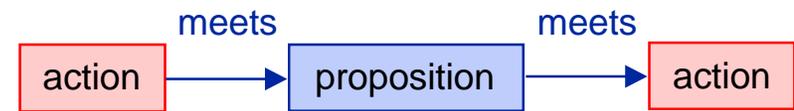
Causal links:



Threats:



CBI



CBI Planners

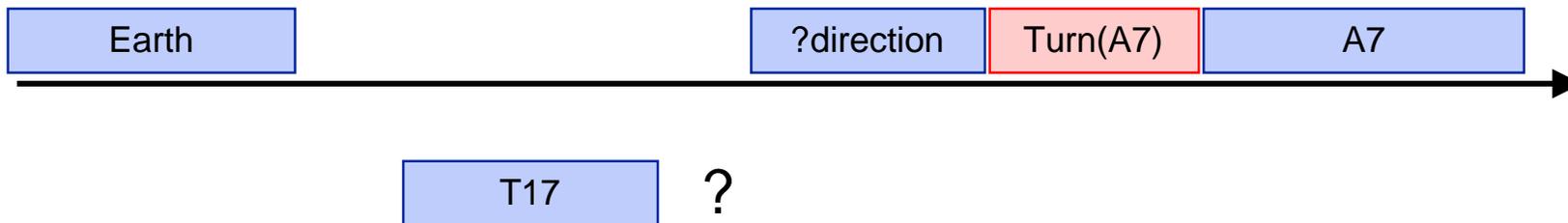


Zeno (Penberthy)	intervals, no CSP
Trains (Allen)	
Descartes (Joslin)	extreme least commitment
IxTeT (Ghallab)	functional rep.
HSTS (Muscettola)	functional rep., activities

Timelines

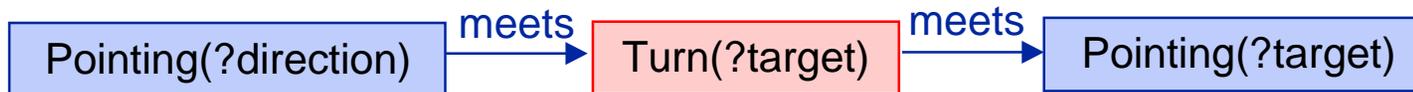


Pointing:



Explanatory Frame Axioms

Turn (?target) met-by meets	Pointing(?direction) Pointing(?target)
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Pointing(?target) met-by or met-by	Past Turn (?target)
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A Stupid Question

Why should CBI perform any better than POCL?

- less commitment
- better propagation
- timelines

A Stupid Question

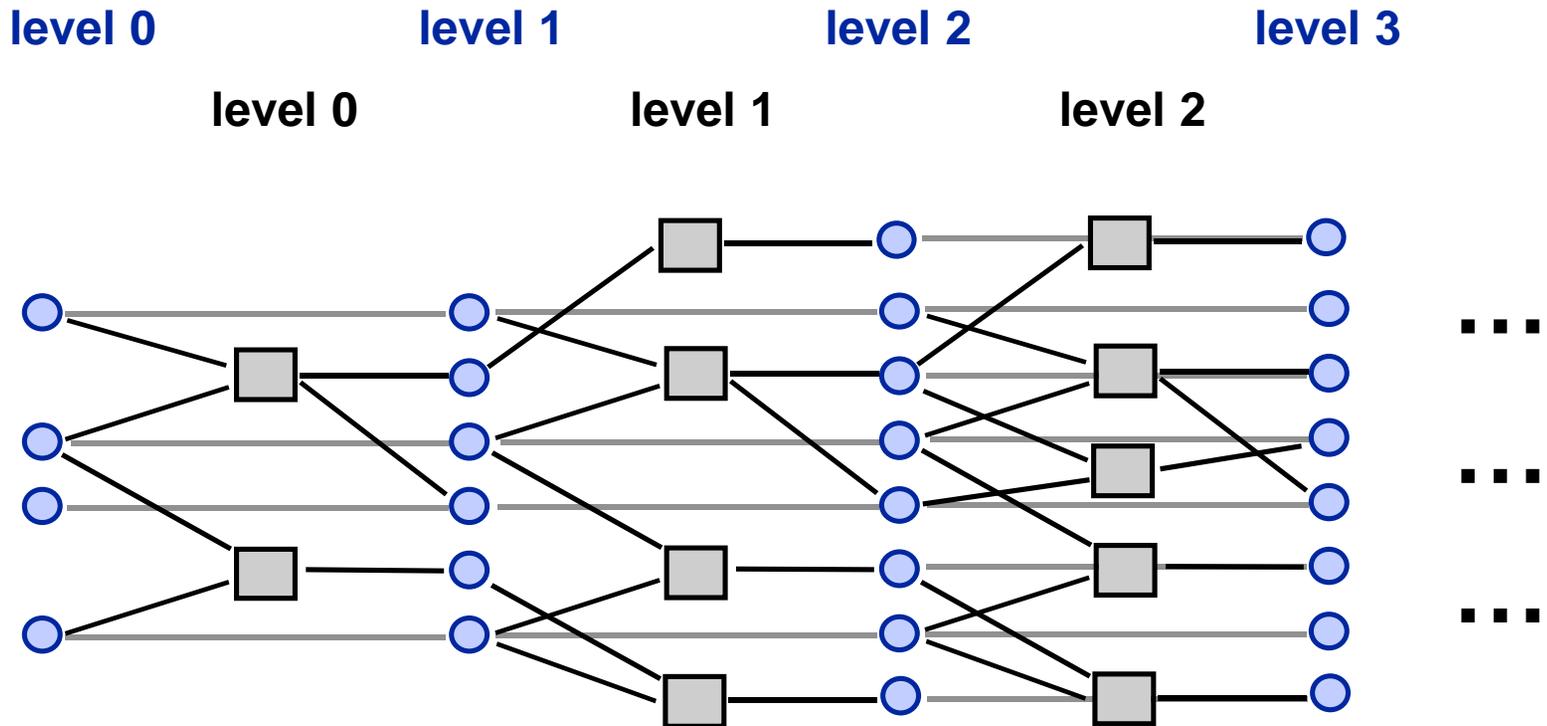
Why should CBI perform any better than POCL?

- less commitment
- better propagation
- timelines

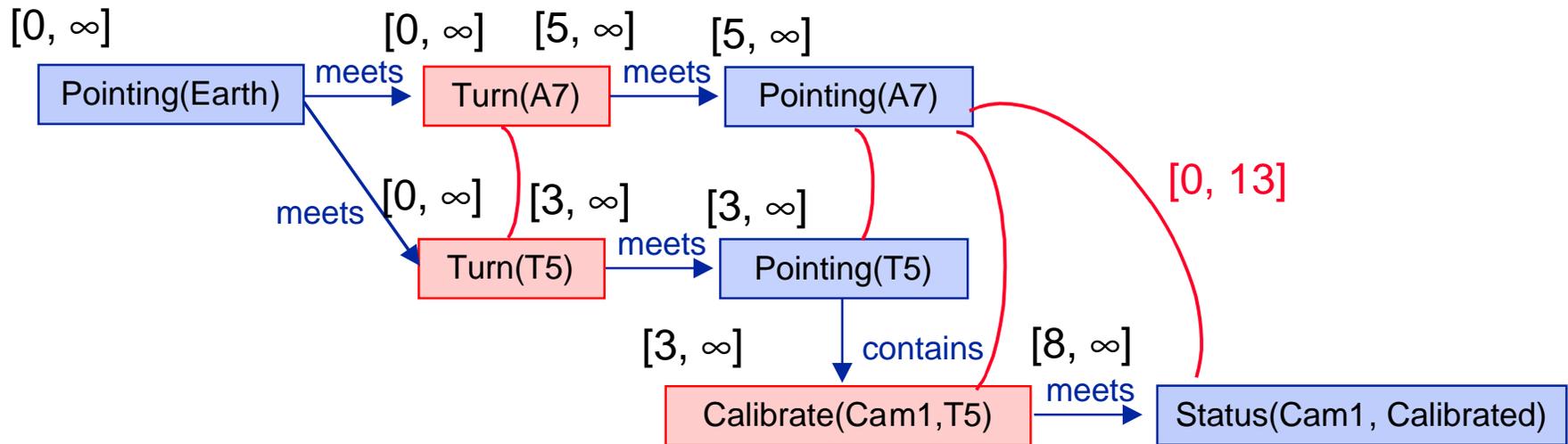
- reachability analysis
- heuristic estimators

Reachability Analysis

Graphplan:
optimistic projection of achievability



Reachability Analysis



mutex rules more complex
 (Smith & Weld - IJCAI99)

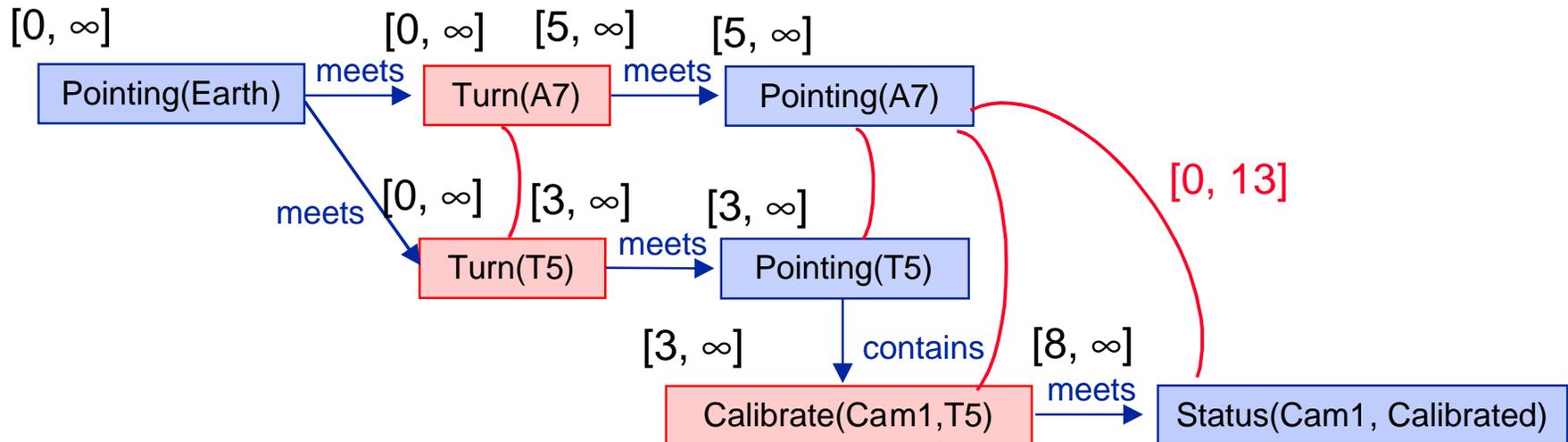
Benefits?



1. Pruning during plan construction
2. Basis for heuristic distance measures
 - McDermott (UNPOP)
 - Geffner (HSP-R)
 - RAO

Extracting Heuristic Estimates

Distance metrics
time required
fuel required
...



Summary



	Multi-capacity Resources	Metric Quantities	Optimization	Continuous Time	Speed
Graphplan	hard?	hard IPP	hard?	hard TGP	good
SAT planning	moderate?	moderate LPSAT	moderate?	very hard?	good
ILP planning	easy?	easy ILP-plan	easy ILP-plan	very hard?	fair?
CBI planning	moderate IxTeT	moderate Zeno	moderate?	easy HSTS	fair?

Critical Issues



	Multi-capacity Resources	Metric Quantities	Optimization	Continuous Time	Speed
Graphplan	hard?	hard IPP	hard?	hard TGP	good
SAT planning	moderate?	moderate LPSAT	moderate?	very hard?	good
ILP planning	easy?	easy ILP-plan	easy ILP-plan	very hard?	fair?
CBI planning	moderate IxTeT	moderate Zeno	moderate?	easy HSTS	fair?

