Temporal Planning

Task Planning

Classical Planning: Limits

Instantaneous actions

No temporal constraints

No concurrent actions

No continuous quantities

Spacecraft Domain

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

Observation-2

Observation-3

Observation-4

…

Objective:
maximize science return

Spacecraft Domain

linked

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

Observation-2

Observation-3

Observation-4

…

angle between targets
⇒ turn duration

calibration
- target1
- target2
- …

consumables:
- fuel
- power
- data storage
- cryogen

Objective:
maximize science return

Based on slides by Dave Smith, NASA Ames

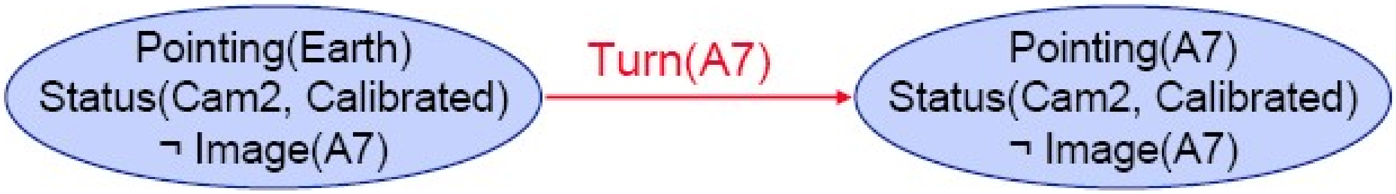
Extensions

- Time
- Resources
- Constraints
- Uncertainty
- Utility
- …

Model

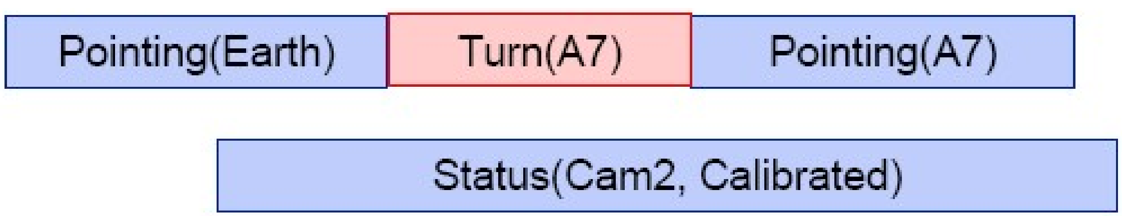
State-centric (Mc Carthy):

for each time describe propositions that are true



History-based (Hayes):

for each proposition describe times it is true



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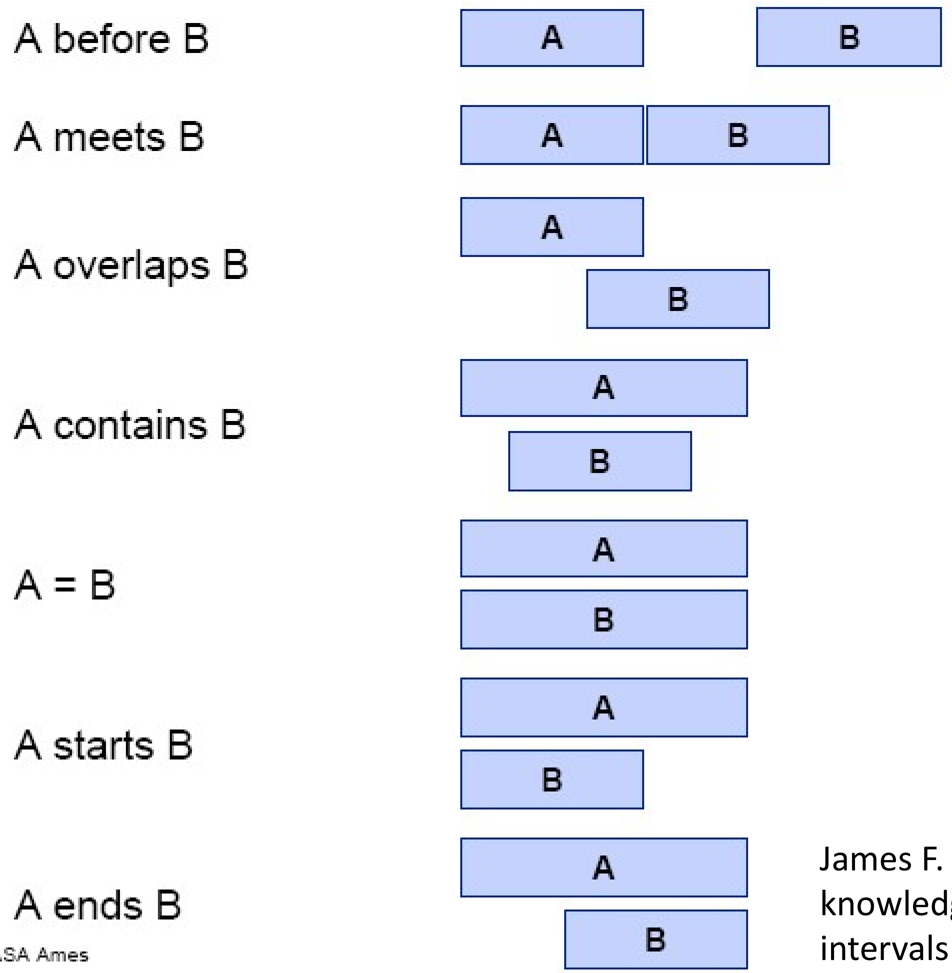
Temporal Interval Relations



Based on slides by Dave Smith, NASA Ames

James F. Allen, "Maintaining knowledge about temporal intervals 1983

Time Points vs Intervals

- Sentences:
  - We found the letter at twelve noon
  - We found the letter yesterday
  - We found the letter while John was away
  - We found the letter after we made the decision

Interval Relation	Equivalent Relations on Endpoints
t < s	t+ < s-
t = s	(t- = s-) & (t+ = s+)
t overlaps s	(t- < s-) & (t+ > s-) & (t+ < s+)
t meets s	t+ = s-
t during s	((t- > s-) & (t+ =< s+)) or ((t- >= s-) & (t+ < s+))

James F. Allen, "Maintaining knowledge about temporal intervals 1983

Relation	Symbol	Symbol for Inverse	Pictoral Example
X *before* Y	<	>	XXX YYY
X *equal* Y	=	=	XXX YYY
X *meets* Y	m	mi	XXXYYY
X *overlaps* Y	o	oi	XXX YYY
X *during* Y	d	di	XXX YYYYYY
X *starts* Y	s	si	XXX YYYYY
X *finishes* Y	f	fi	XXX YYYYY

Temporal Operators

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

↓

TakeImage (?target, ?instr)

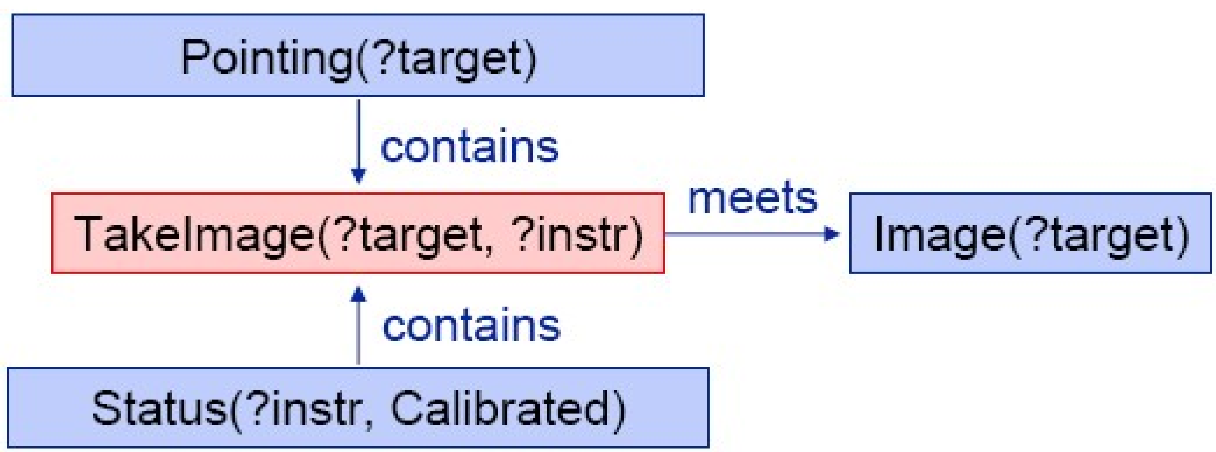
contained-by	Status(?instr, Calibrated)
contained-by	Pointing(?target)
meets	Image(?target)

Based on slides by Dave Smith, NASA Ames

Temporal Operators

TakeImage (?target, ?instr)

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



Based on slides by Dave Smith, NASA Ames

Temporal Operators

TakeImage (?target, ?instr)

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

⬇

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

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

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

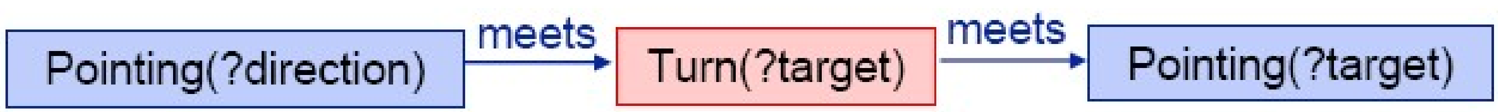
$\wedge\ \exists R\ \{\text{Image}(?\text{target})_R \ \wedge\ \text{Meets}(A, R)\}$

Based on slides by Dave Smith, NASA Ames

Temporal Operators

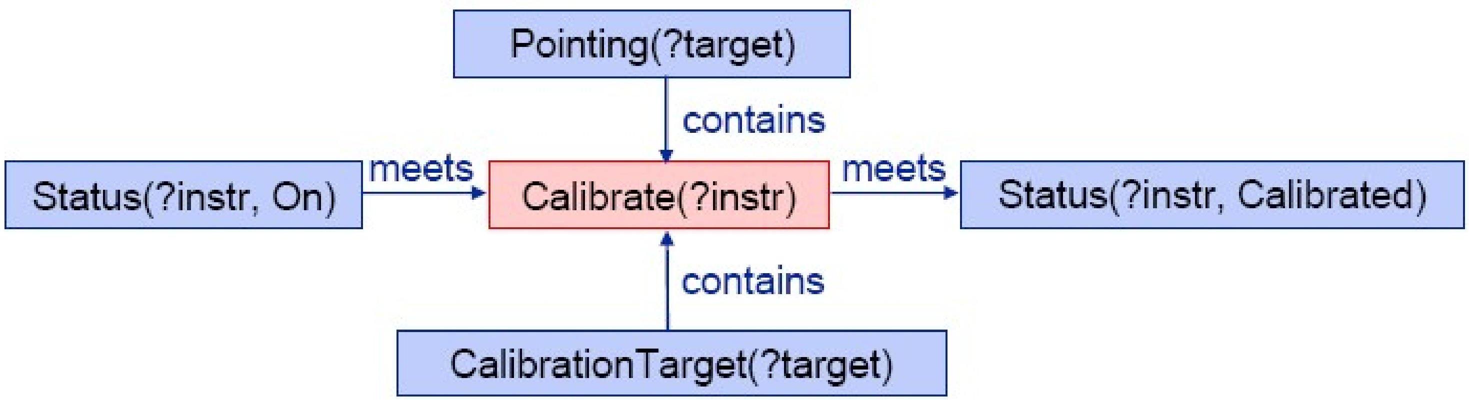
Turn (?target)

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



Temporal Operators

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



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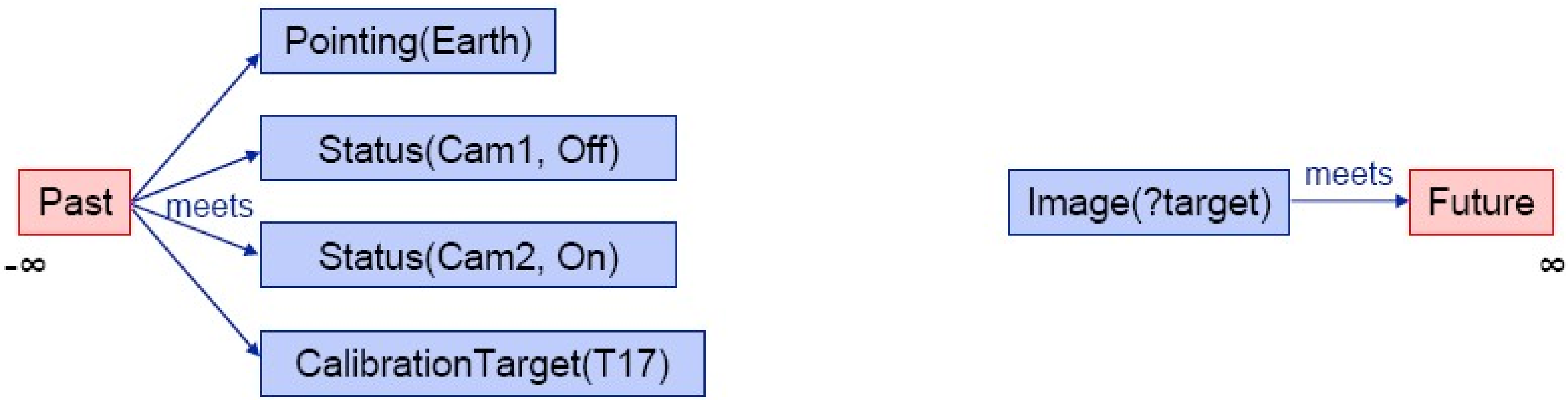
Temporal Planning Problem



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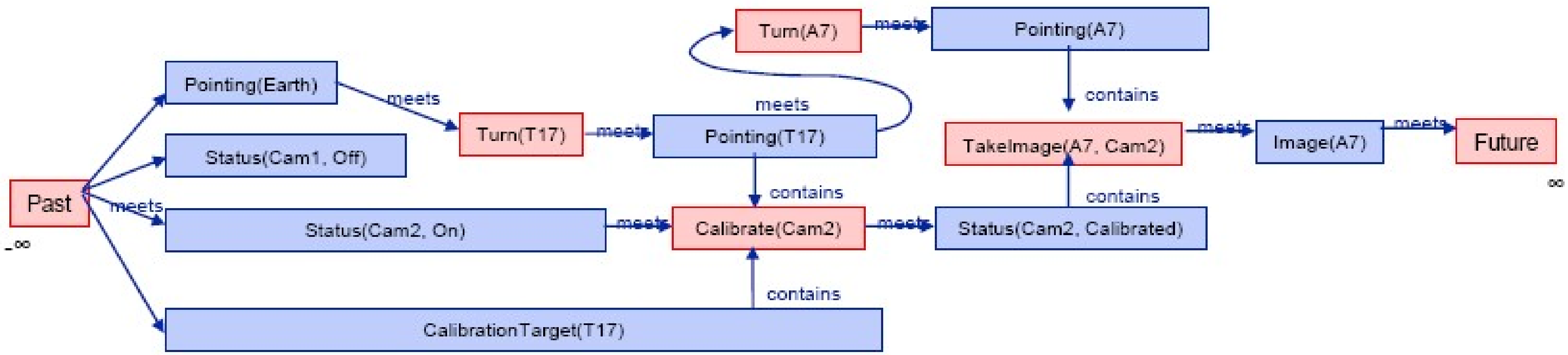
Consistent Complete Plan



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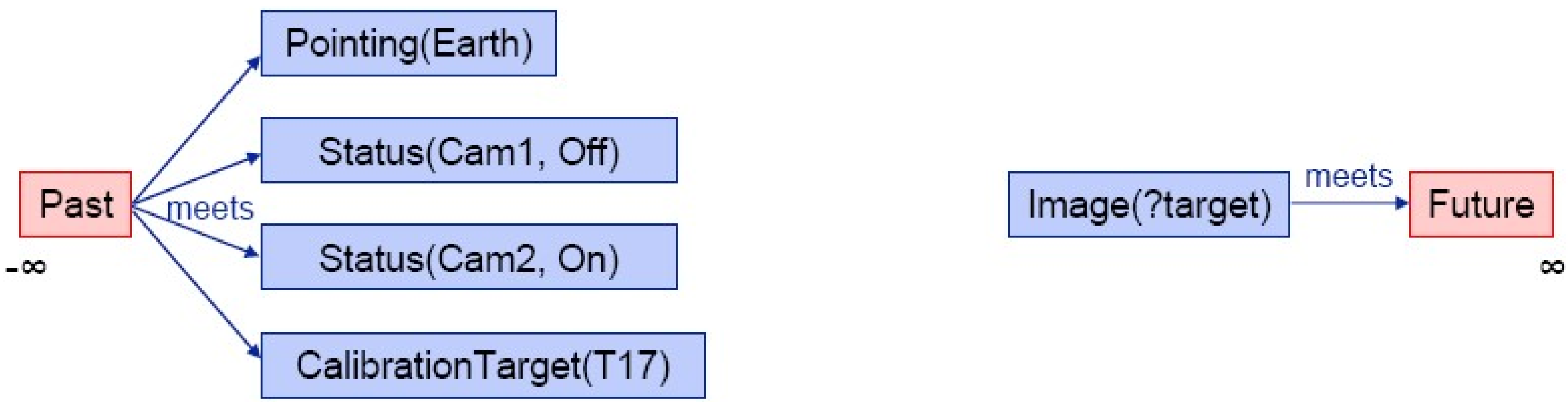
CBI-Planning

Choose:

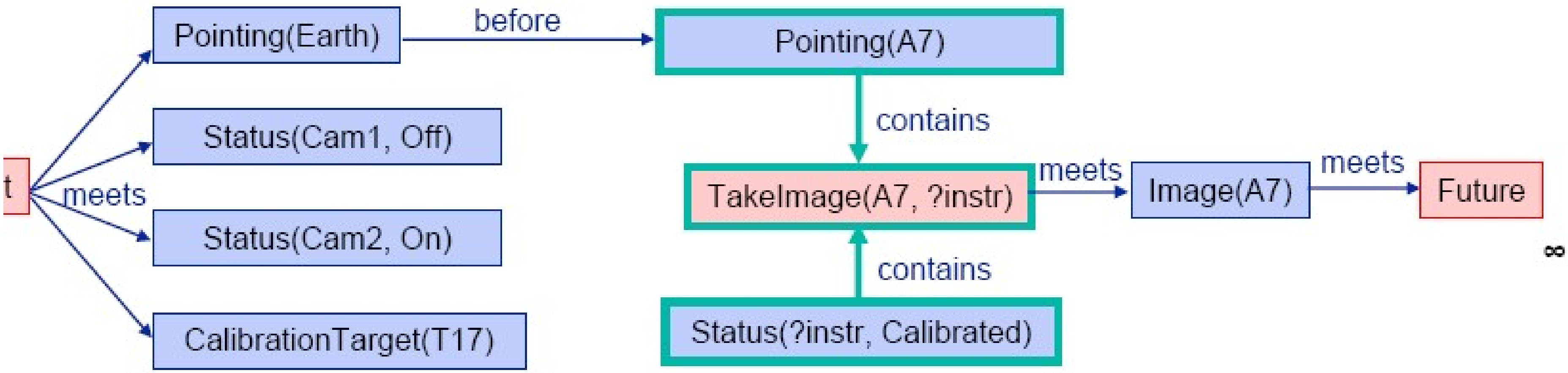
- introduce an action & instantiate constraints
- coalesce propositions

Propagate constraints

Initial Plan

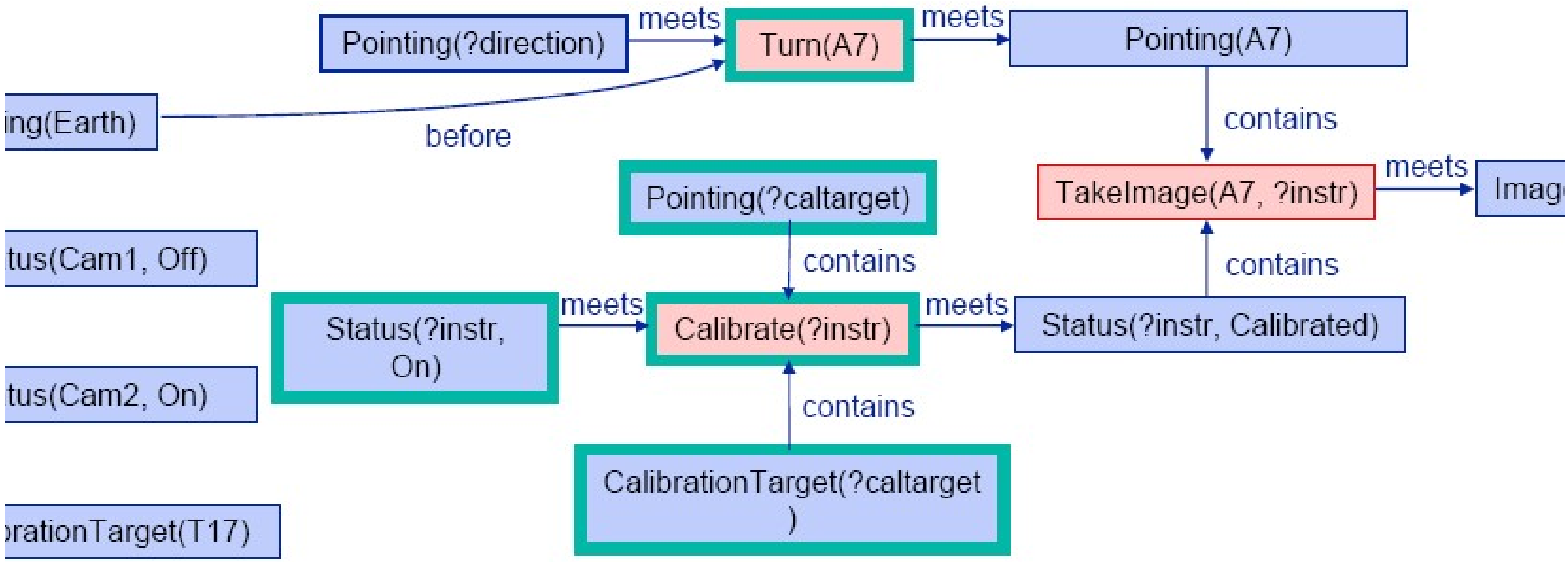


Expansion



t
meets
Pointing(Earth)
before
Pointing(A7)
Status(Cam1, Off)
contains
Status(Cam2, On)
TakeImage(A7, ?instr)
meets
Image(A7)
meets
Future
∞
contains
CalibrationTarget(T17)
Status(?instr, Calibrated)

Expansion



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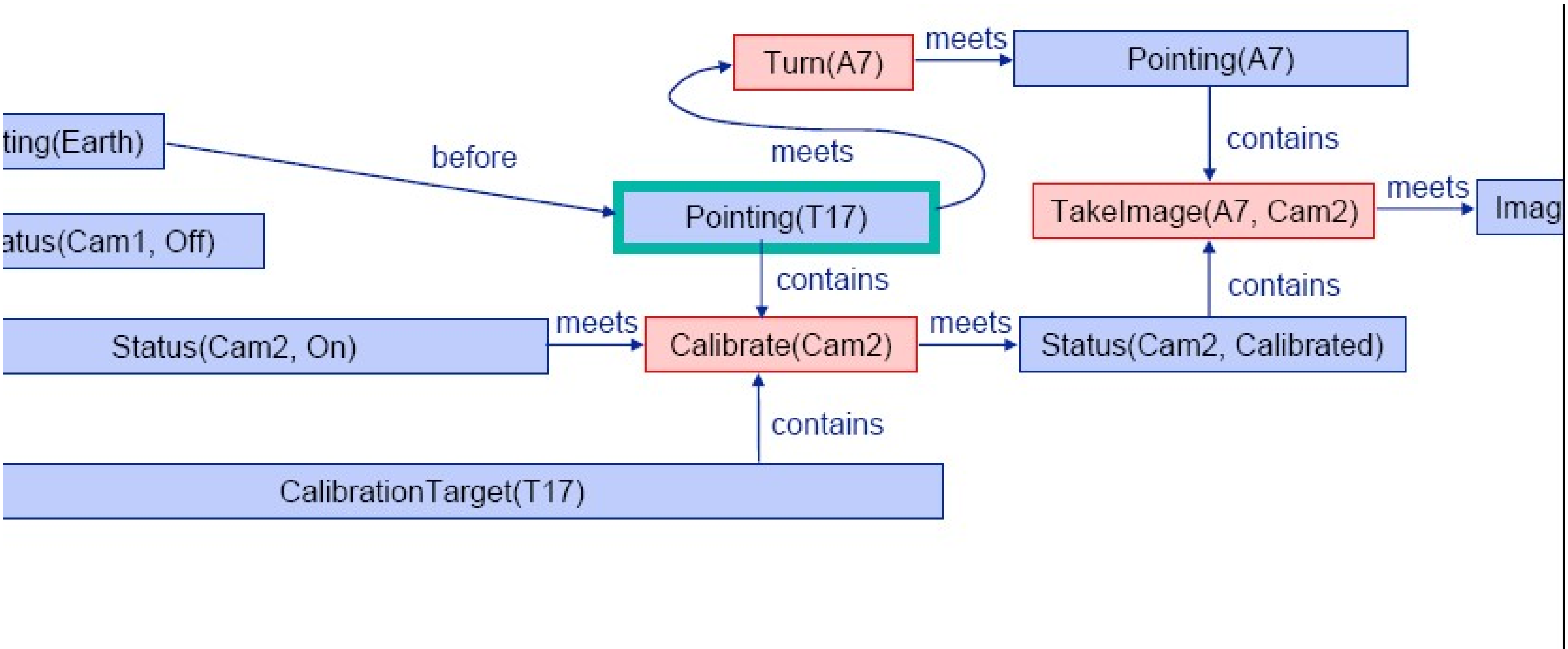
Coalescing


Turn(A7)
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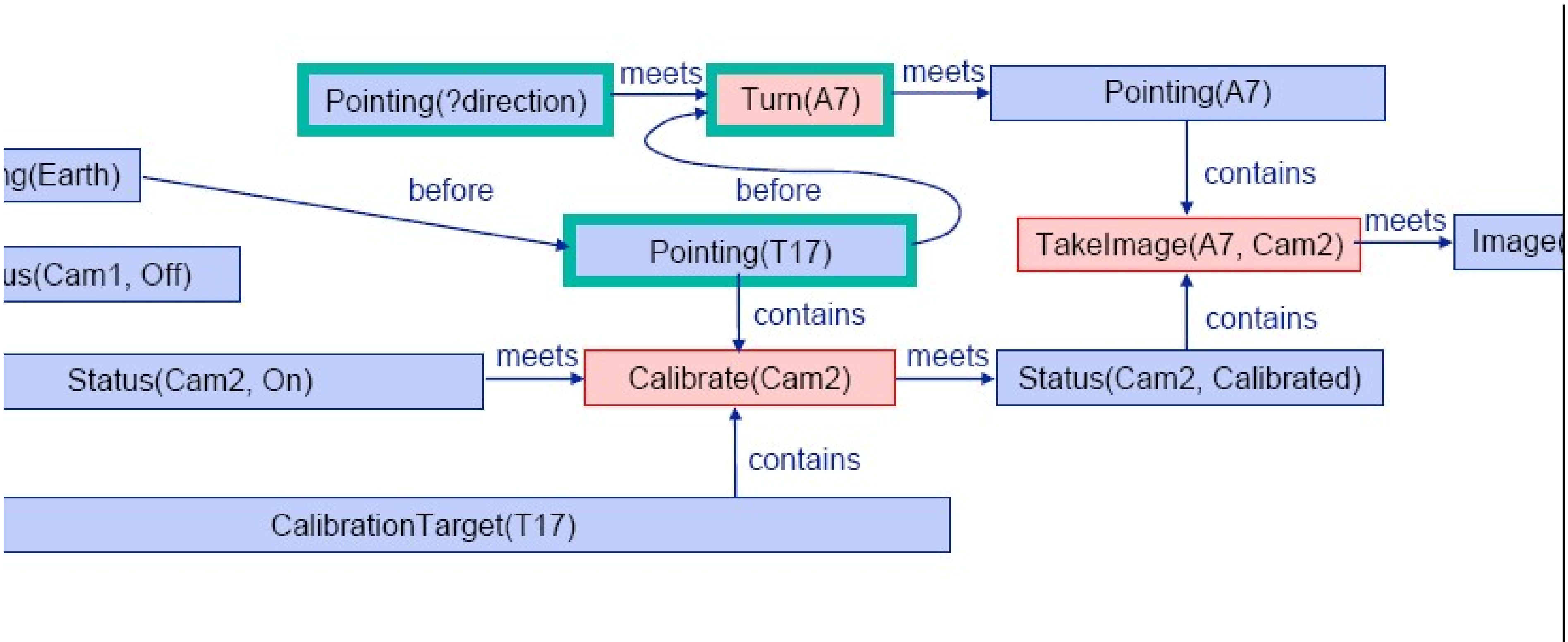
Pointing(A7)
ting(Earth)
before
meets
contains
Pointing(T17)
TakeImage(A7, Cam2)
meets
Imag
atus(Cam1, Off)
contains
contains
Status(Cam2, On)
meets
Calibrate(Cam2)
meets
Status(Cam2, Calibrated)
contains
CalibrationTarget(T17)

Coalescing



Pointing(?direction)
meets
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TakeImage(A7, Cam2)
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Calibrate(Cam2)
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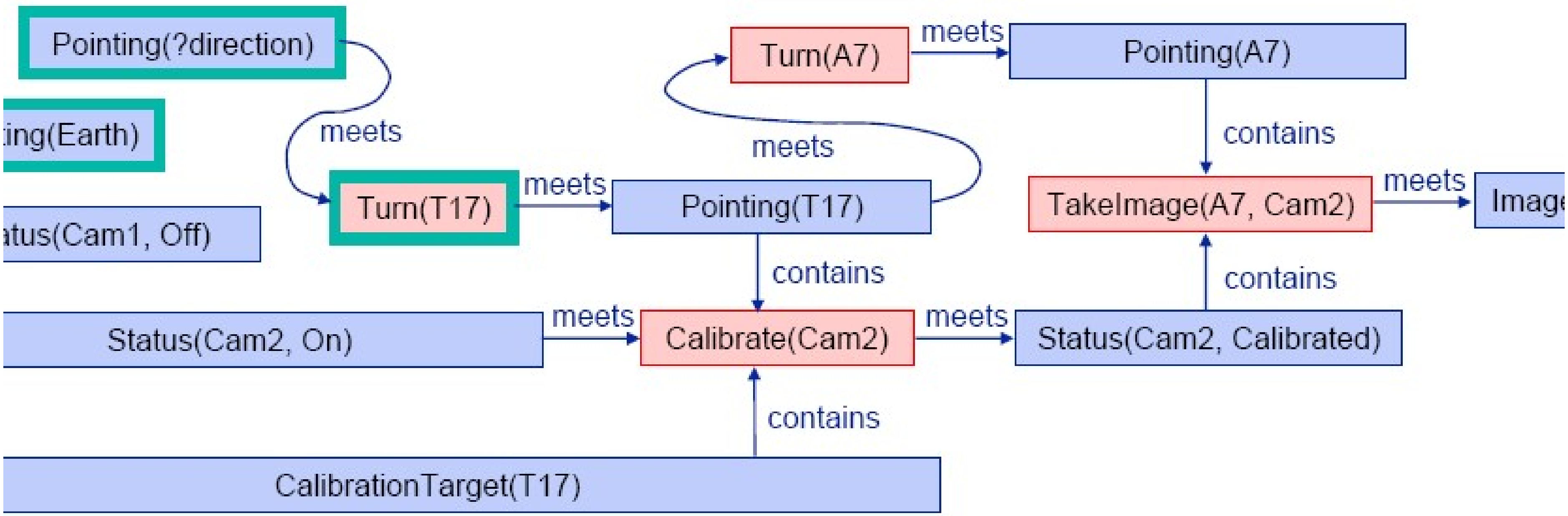
Status(Cam2, Calibrated)
contains
CalibrationTarget(T17)

Expansion



Pointing(?direction)
ing(Earth)
atus(Cam1, Off)
meets
Turn(T17)
meets
Pointing(T17)
meets
Turn(A7)
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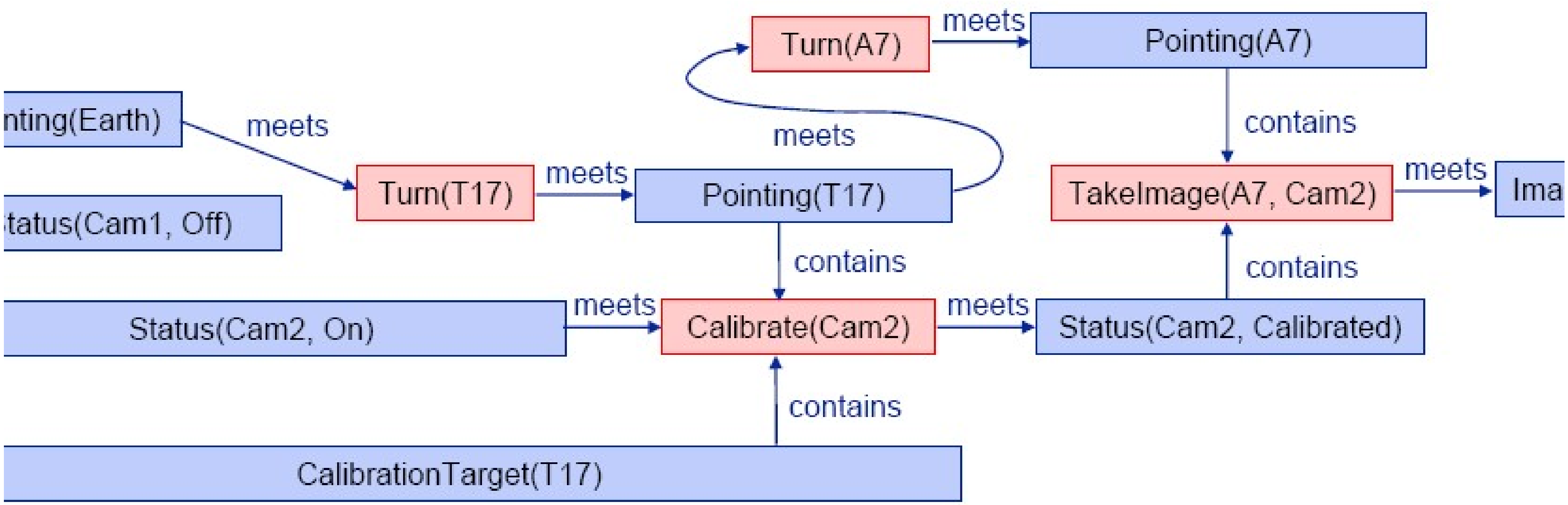
Pointing(A7)
contains
TakeImage(A7, Cam2)
meets
Image
contains
contains
Status(Cam2, On)
meets
Calibrate(Cam2)
meets
Status(Cam2, Calibrated)
contains
contains
CalibrationTarget(T17)

Coalescing



Turn(A7)
meets
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nting(Earth)
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meets
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Turn(T17)
meets
Pointing(T17)
TakeImage(A7, Cam2)
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tatus(Cam1, Off)
contains
contains
Status(Cam2, On)
meets
Calibrate(Cam2)
meets
Status(Cam2, Calibrated)
contains
CalibrationTarget(T17)

CBI-Algorithm

Expand(TQAs, constraints)

1. If the constraints are inconsistent, **fail**
2. If all TQAs have causal explanations, **return**(TQAs, constraints)
3. Select a $g \in$ TQAs with no causal explanation
4. **Choose**:

    Choose another $p \in$ TQAs such that g can be coalesced with p under constraints C

        Expand(TQAs-g, constraints $\cup$ C)

    Choose an action that would provide a causal explanation for g

        Let A be a new TQA for the action,
        and let R be the set of new TQAs implied by the axioms for A

        Let C be the constraints between A and R

        Expand(TQAs $\cup$ {A} $\cup$ R, constraints $\cup$ C)

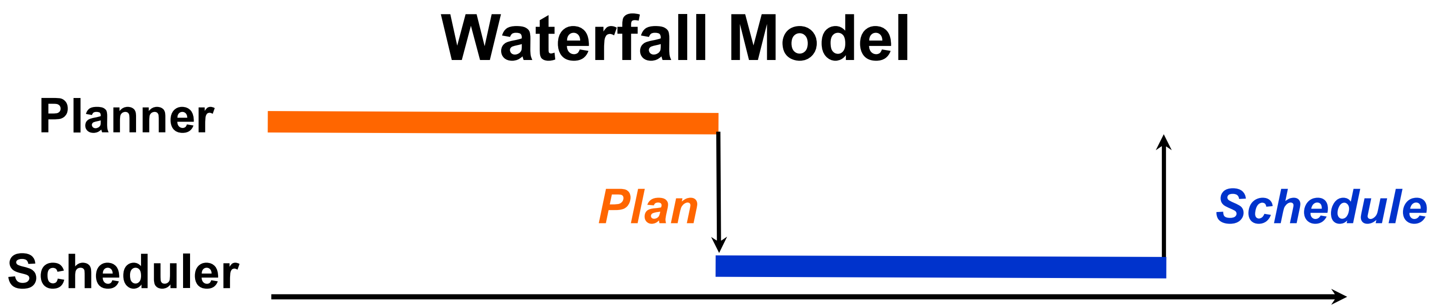
CBI-Planners

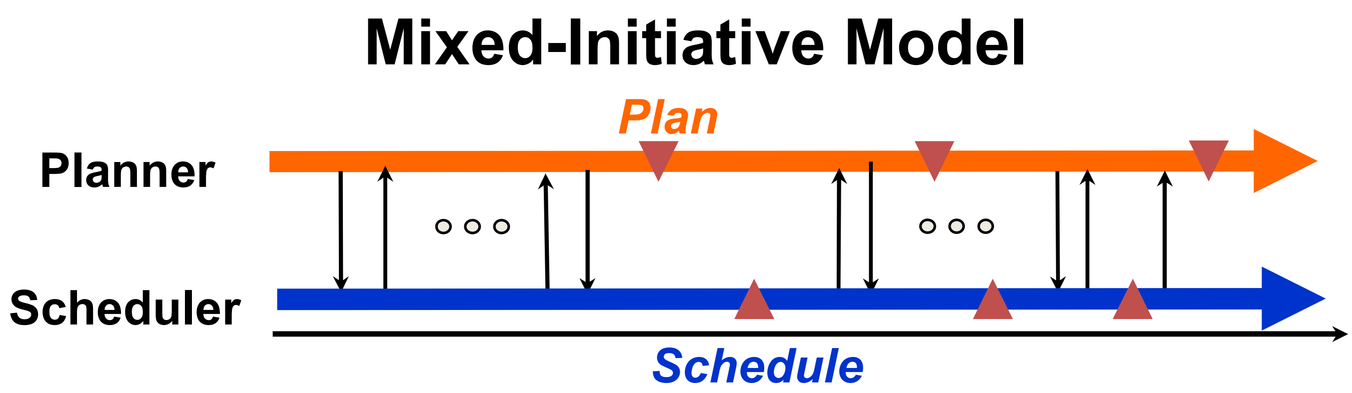
Zeno (Penberthy)	intervals, no CSP
Trains (Allen)	
Descartes (Joslin)	extreme least commitment
IxTeT (Ghallab)	functional rep.
HSTS (Muscettola)	functional rep., activities
EUROPA (Jonsson)	functional rep., activities

CBI vs POP

- CBI is similar to POP because least commitment and partial order
- But, temporal constraints in CBI ...
- Contraints Temporal Network associated with a plan
- Constraint propagation

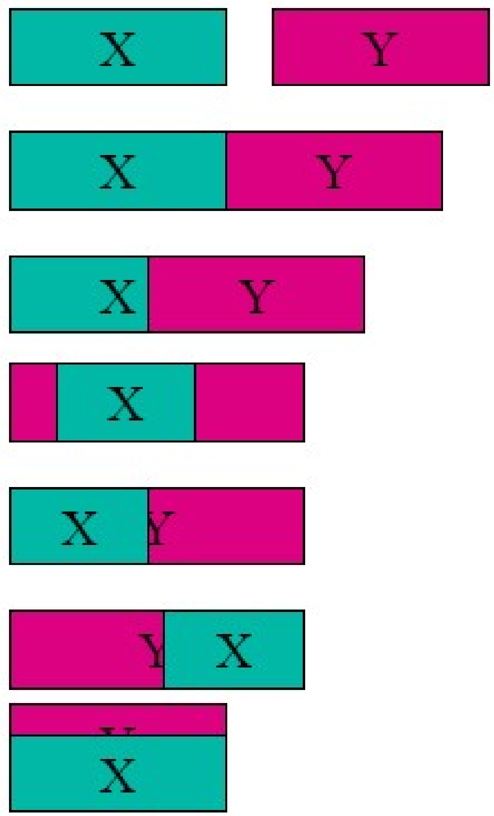
Planning & Scheduling





Temporal Constraints

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

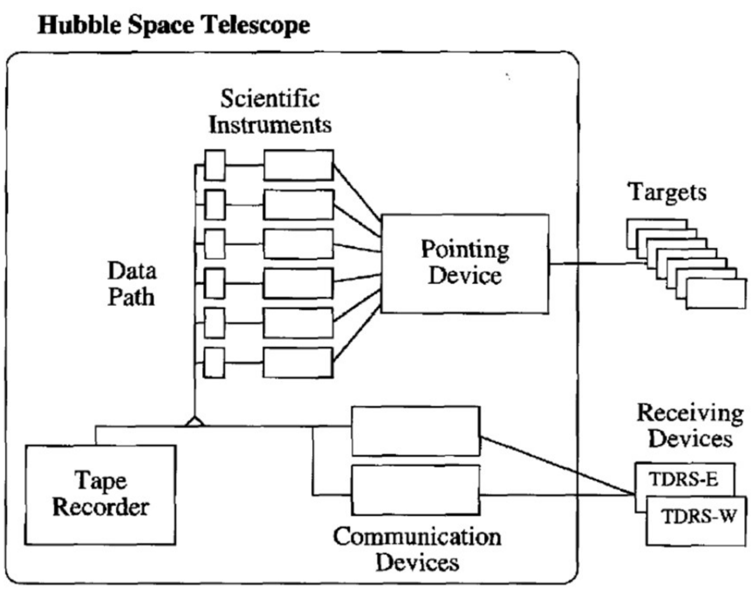


- y after x
- y met-by x
- y overlapped-by x
- y contains x
- y started-by x
- y finished-by x
- y equals x

HSTS: *Integrating* Planning and Scheduling

HSTS: Integrating Planning and Scheduling, Nicola Muscettola CMU-RI-TR-93-05

- HSTS (Heuristic Scheduling Testbed System):
  - representation and problem solving framework that provides an integrated view of planning and scheduling.
  - Leaving as much temporal flexibility as possible during the planning and scheduling process
  - planner and scheduler for short term scheduling of the Hubble Space Telescope



The pointing subsystem is responsible for orienting HST toward a target and locking it at the center of the field of view of the instrument.

6 scientific instruments, but power does not allow all of them to be operational simultaneously. Moving an instrument between operation and quiescence requires complex reconfiguration sequences

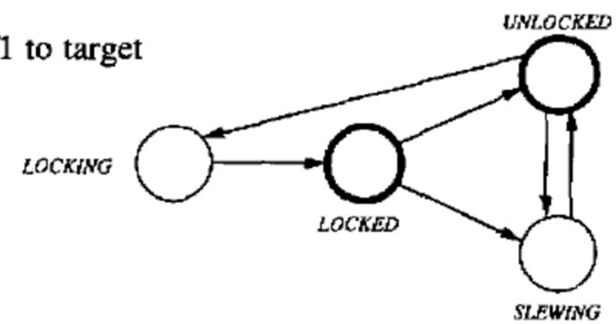
HSTS: *Integrating* Planning and Scheduling

HSTS: Integrating Planning and Scheduling, Nicola Muscettola CMU-RI-TR-93-05

- HSTS (Heuristic Scheduling Testbed System):
  - representation and problem solving framework that provides an integrated view of planning and scheduling.
  - Leaving as much temporal flexibility as possible during the planning and scheduling process
  - planner and scheduler for short term scheduling of the Hubble Space Telescope

- *UNLOCKED*(?*T*) : the telescope is pointing in the generic direction of target ?*T*;
- *LOCKED*(?*T*) : the telescope is actively tracking target ?*T*;
- *LOCKING*(?*T*) : the tracking device is locking onto target ?*T*;
- *SLEWING*(?*T*1, ?*T*2) : the telescope changes its direction from target ?*T*1 to target ?*T*2.

$<$*VALUE–TOKEN*, **state**(*POINTING–DEVICE*),{*SLEWING*(?*T*, 3C267)}, t_1, $t_2$$>$



DS1: Remote Agent

Remote Agent Experiment: RAX

Remote Agent Experiment

See rax.arc.nasa.gov

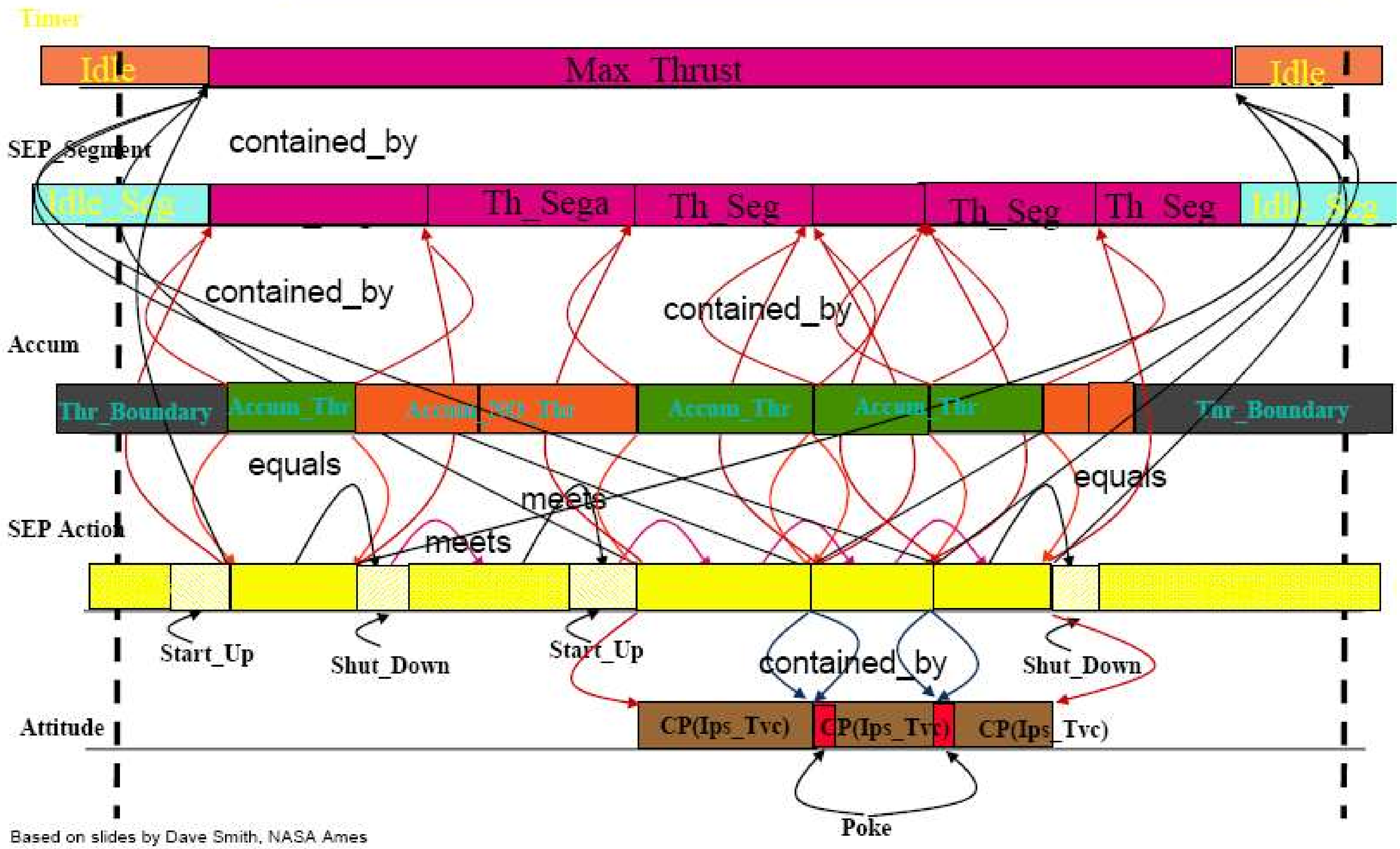
May 17-18th experiment

- Generate plan for course correction and thrust
- Diagnose camera as stuck on
  - Power constraints violated, abort current plan and replan
- Perform optical navigation
- Perform ion propulsion thrust

May 21th experiment.

- Diagnose faulty device and
  - Repair by issuing reset.
- Diagnose switch sensor failure.
  - Determine harmless, and continue plan.
- Diagnose thruster stuck closed and
  - Repair by switching to alternate method of thrusting.
- Back to back planning

RAX Example: DS1



Based on slides by Dave Smith, NASA Ames

Temporal Constraints as Inequalities

- 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:

$$X^+ - Y^- < [-inf, 0]$$

Metric Constraints

- Going to the store takes at least 10 minutes and at most 30 minutes.
  → $10 \leq [T^+(store) - T^-(store)] \leq 30$
- Bread should be eaten within a day of baking.
  → $0 \leq [T^+(baking) - T^-(eating)] \leq 1$ day
- Inequalities, $X^+ < Y^-$, may be expressed as binary interval relations:
  → $-\inf < [X^+ - Y^-] < 0$

Temporal Constraint Networks

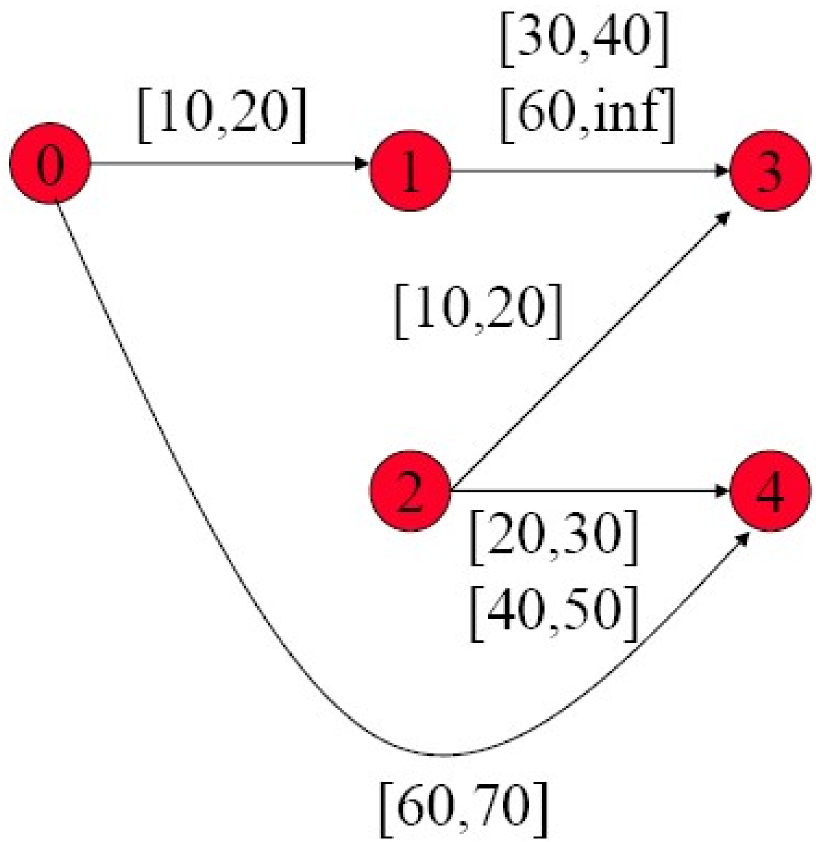
- A set of time points X_i at which events occur.
- Unary constraints

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

- 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



Simple Temporal Networks

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

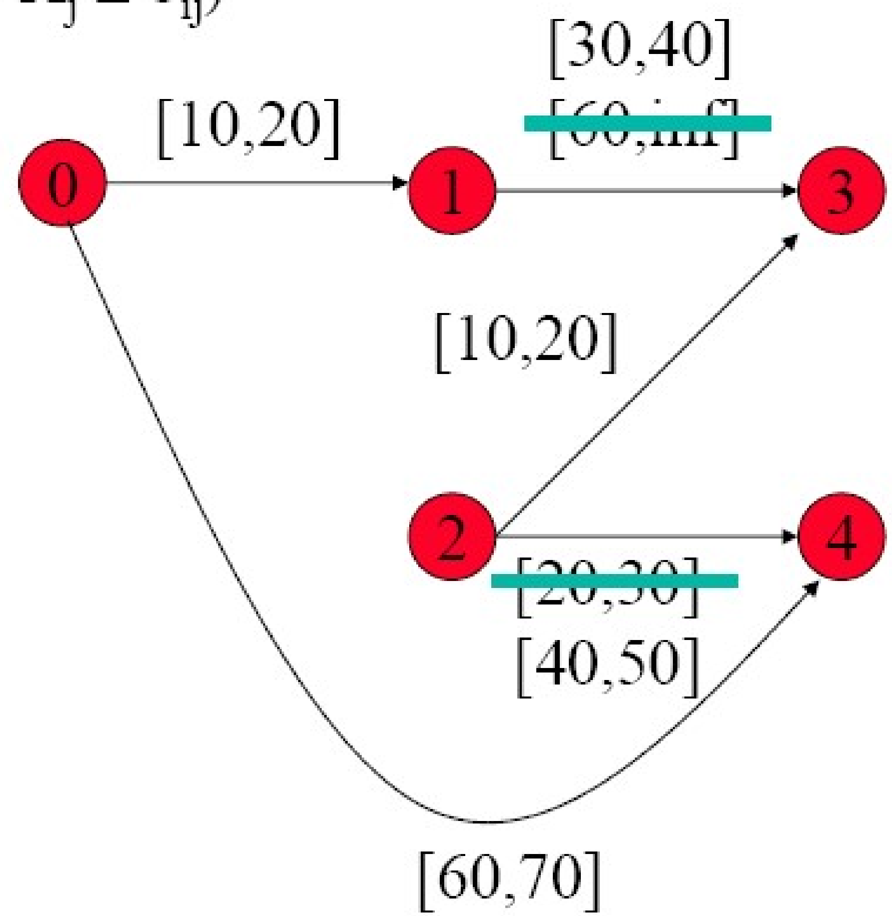
  $(a_0 \leq X_j - X_i \leq b_0)$ ~~or $(a_1 \leq X_j - X_i \leq b_1)$ or . . .~~

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

Can't represent:
- Disjoint activities

Simple Temporal Networks

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



Based on slides by Dave Smith, NASA Ames

TCSP Queries

(Dechter, Meiri, Pearl, AIJ91)

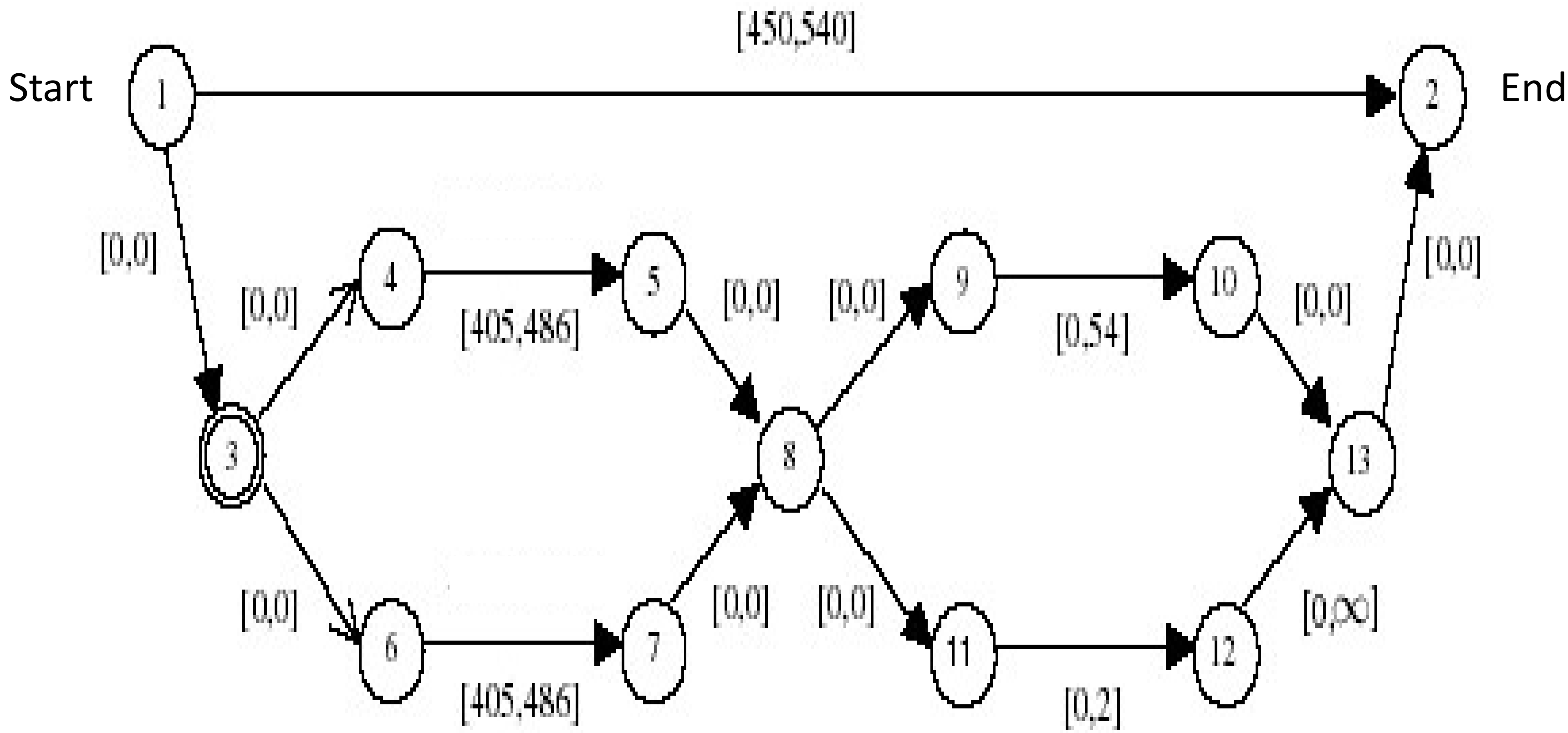
- Is the TCSP consistent?
- What are the feasible times for each X_i?
- What are the feasible durations between each X_i and X_j?
- What is a consistent set of times?
- What are the earliest possible times?
- What are the latest possible times?

TCSP Queries

(Dechter, Meiri, Pearl, AIJ91)

- Is the TCSP consistent? *Planning*
- What are the feasible times for each X_i?
- What are the feasible durations between each X_i and X_j?
- What is a consistent set of times?
- What are the earliest possible times? *Execution*
- What are the latest possible times?

STN example



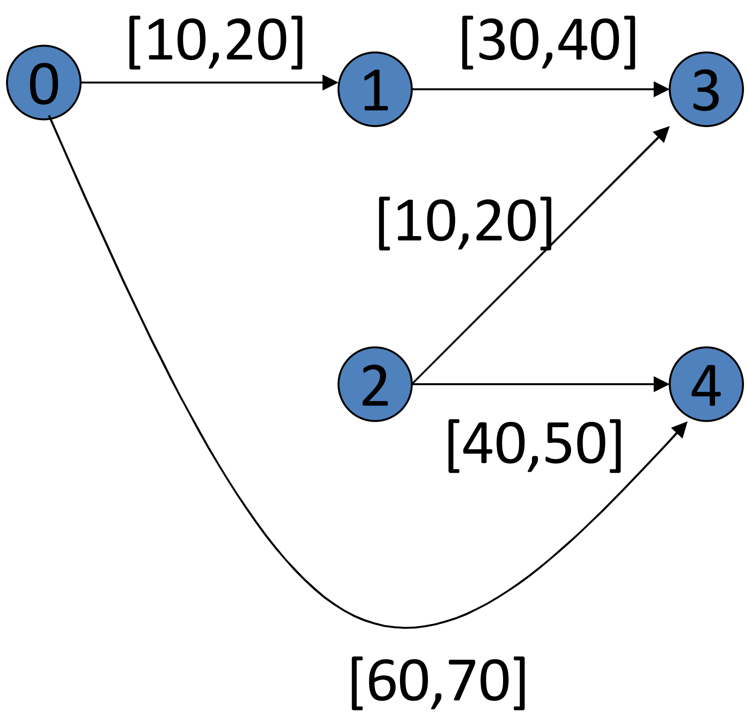
[450,540]
Start
1
2
End
[0,0]
[0,0]
4
5
[405,486]
[0,0]
[0,0]
9
10
[0,54]
[0,0]
[0,0]
3
8
13
[0,0]
6
7
[405,486]
[0,0]
[0,0]
11
12
[0,2]
[0,∞]

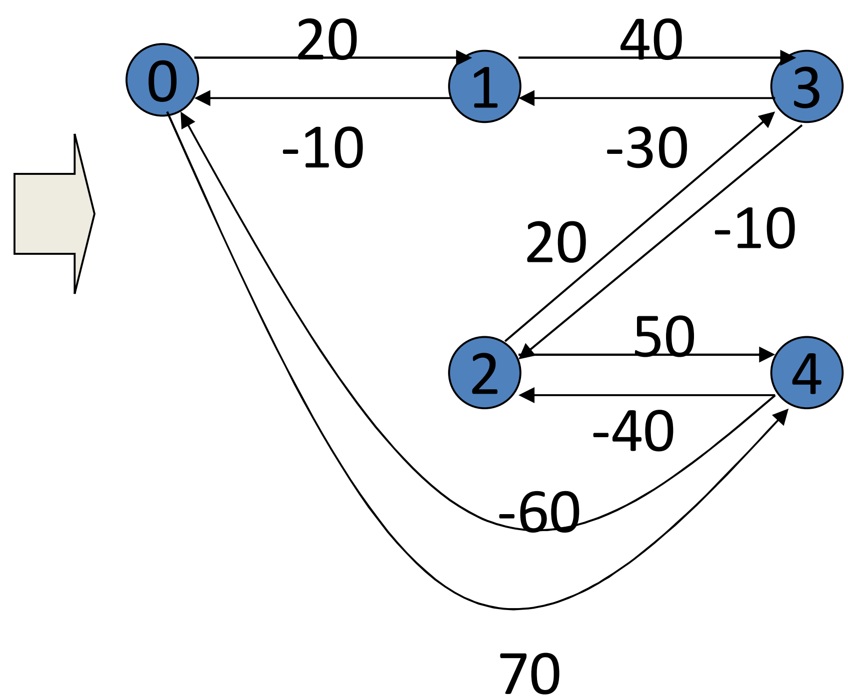
To Query STN Map to Distance Graph $G_d = < V, E_d >$

Edge encodes an upper bound on distance to target from source.

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

$$X_j - X_i \leq b_{ij}$$
$$X_i - X_j \leq - a_{ij}$$





Induced Constraints for G_d

constraint: $i_0 = i, i_1 = \ldots, i_k = j$

$$X_j - X_i \le \sum_{j=1}^{k} a_{i_{j-1}, i_j}$$

→Intersected path constraints:

$$X_j - X_i \le d_{ij}$$

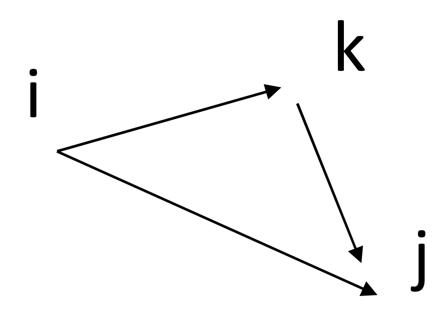
where d_{ij} is the shortest path from i to j

Compute Intersected Paths by All Pairs Shortest Path

(e.g., Floyd-Warshall's algorithm)

1. for i := 1 to n do $d_{ii} \leftarrow 0$;
2. for i, j := 1 to n do $d_{ij} \leftarrow a_{ij}$;

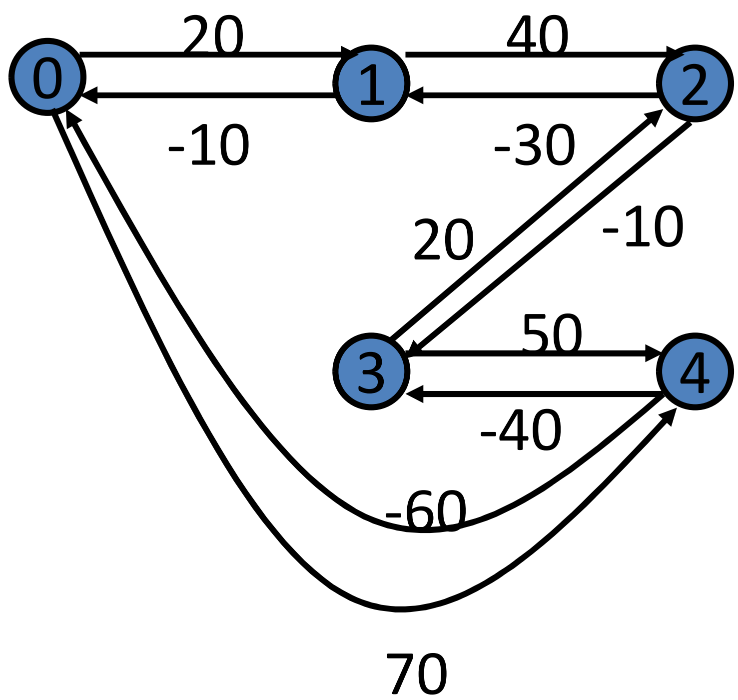
3. for k := 1 to n do
4.   for i, j := 1 to n do
5. $d_{ij} \leftarrow \min\{d_{ij}, d_{ik} + d_{kj}\}$;



Shortest Paths of G_d

	0	1	2	3	4
0	0	20	50	30	70
1	-10	0	40	20	60
2	-40	-30	0	-10	30
3	-20	-10	20	0	50
4	-60	-50	-20	-40	0

d-graph



STN Minimum Network

	0	1	2	3	4
0	0	20	50	30	70
1	-10	0	40	20	60
2	-40	-30	0	-10	30
3	-20	-10	20	0	50
4	-60	-50	-20	-40	0

d-graph

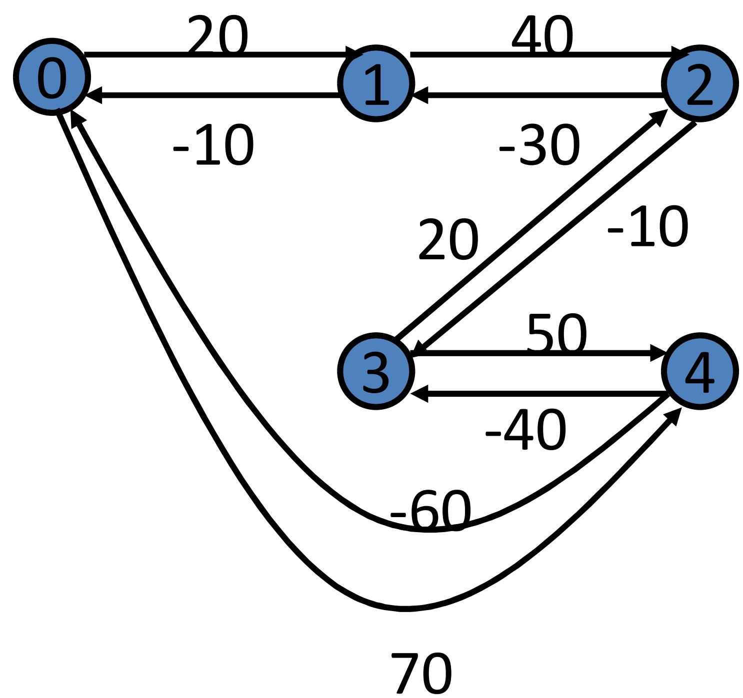
	0	1	2	3	4
0	[0]	[10,20]	[40,50]	[20,30]	[60,70]
1	[-20,-10]	[0]	[30,40]	[10,20]	[50,60]
2	[-50,-40]	[-40,-30]	[0]	[-20,-10]	[20,30]
3	[-30,-20]	[-20,-10]	[10,20]	[0]	[40,50]
4	[-70,-60]	[-60,-50]	[-30,-20]	[-50,-40]	[0]

STN minimum network

Test Consistency:
No Negative Cycles

	0	1	2	3	4
0	0	20	50	30	70
1	-10	0	40	20	60
2	-40	-30	0	-10	30
3	-20	-10	20	0	50
4	-60	-50	-20	-40	0

d-graph

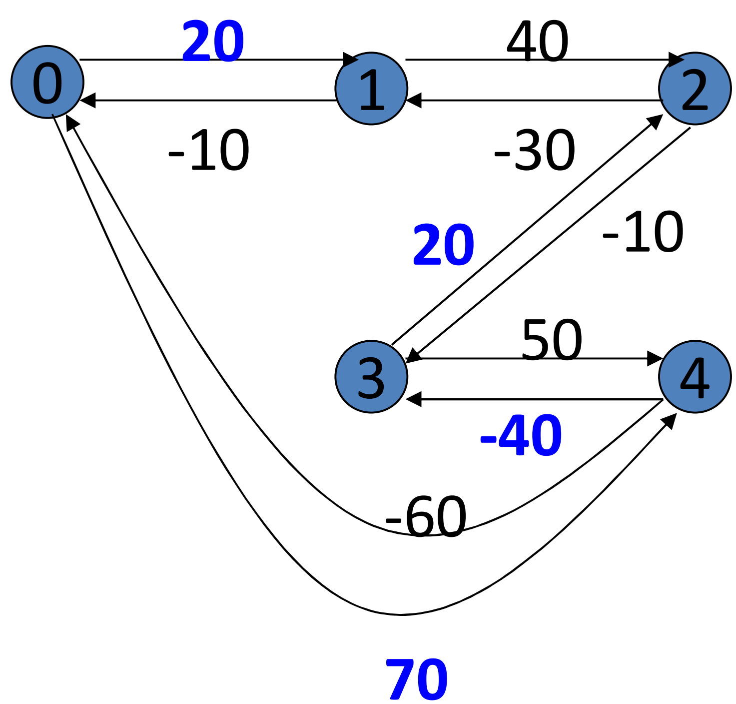


Latest Solution

Node 0 is the reference.

	0	1	2	3	4
0	0	20	50	30	70
1	-10	0	40	20	60
2	-40	-30	0	-10	30
3	-20	-10	20	0	50
4	-60	-50	-20	-40	0

d-graph

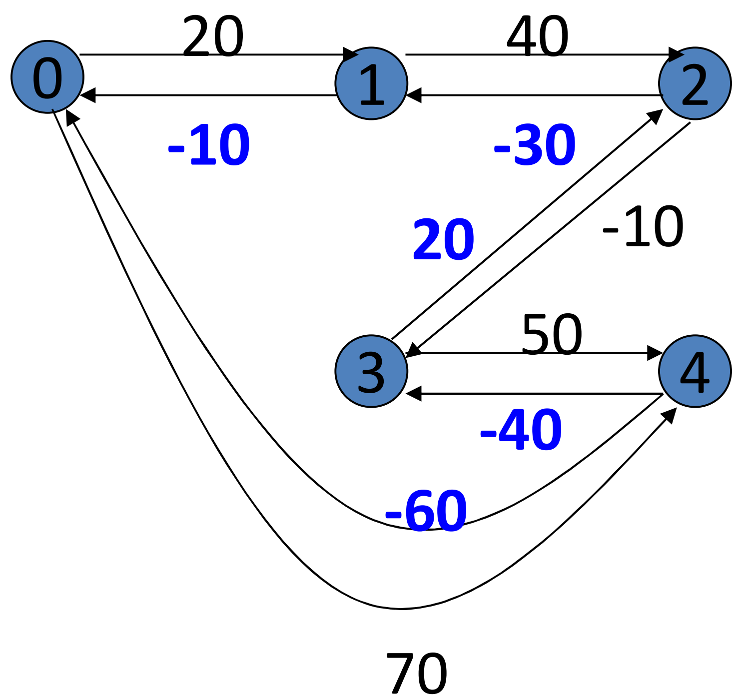


Earliest Solution

Node 0 is the reference.

	0	1	2	3	4
0	0	20	50	30	70
1	-10	0	40	20	60
2	-40	-30	0	-10	30
3	-20	-10	20	0	50
4	-60	-50	-20	-40	0

d-graph



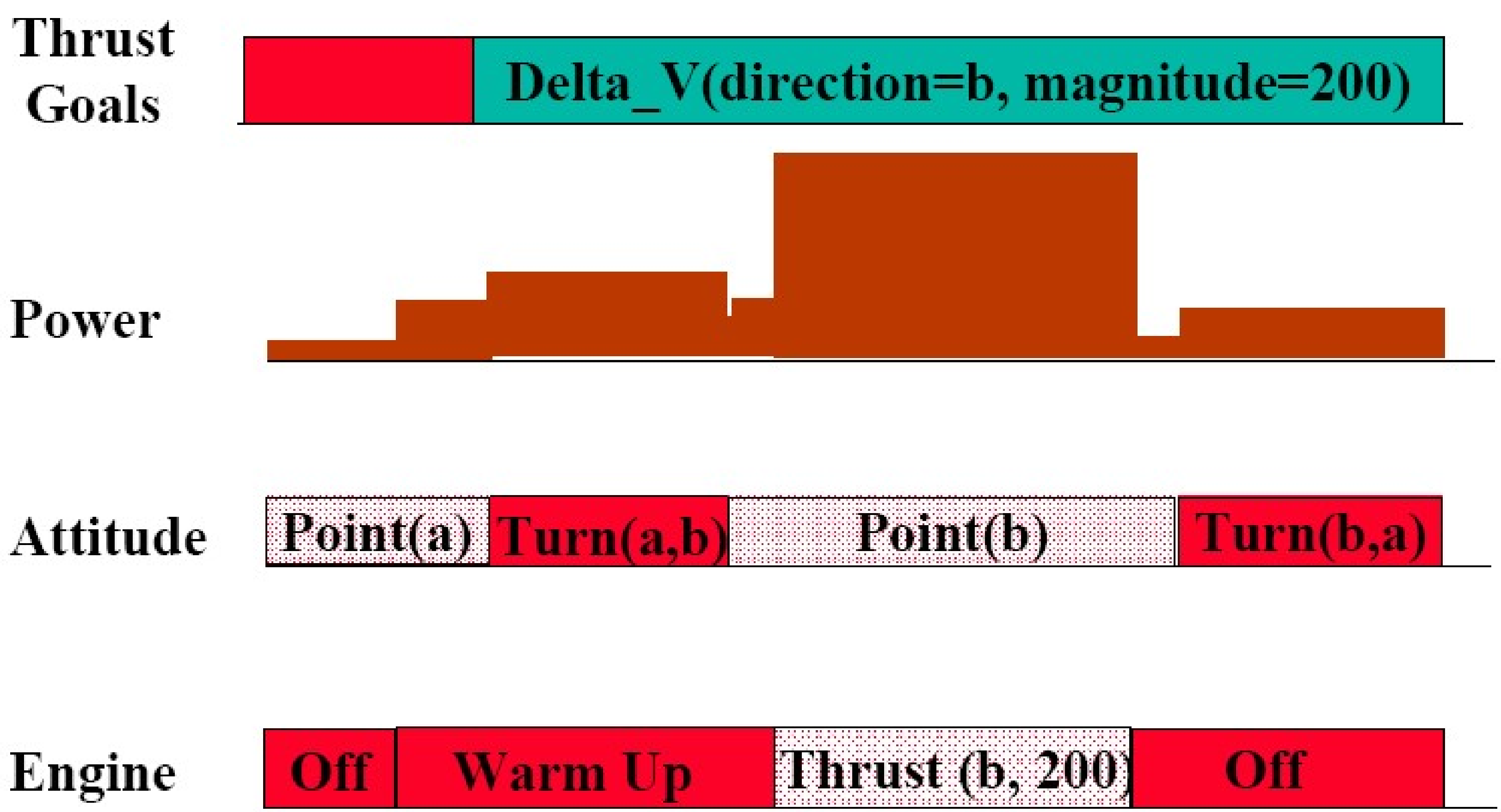
Feasible Values

	0	1	2	3	4
0	0	20	50	30	70
1	-10	0	40	20	60
2	-40	-30	0	-10	30
3	-20	-10	20	0	50
4	-60	-50	-20	-40	0

d-graph

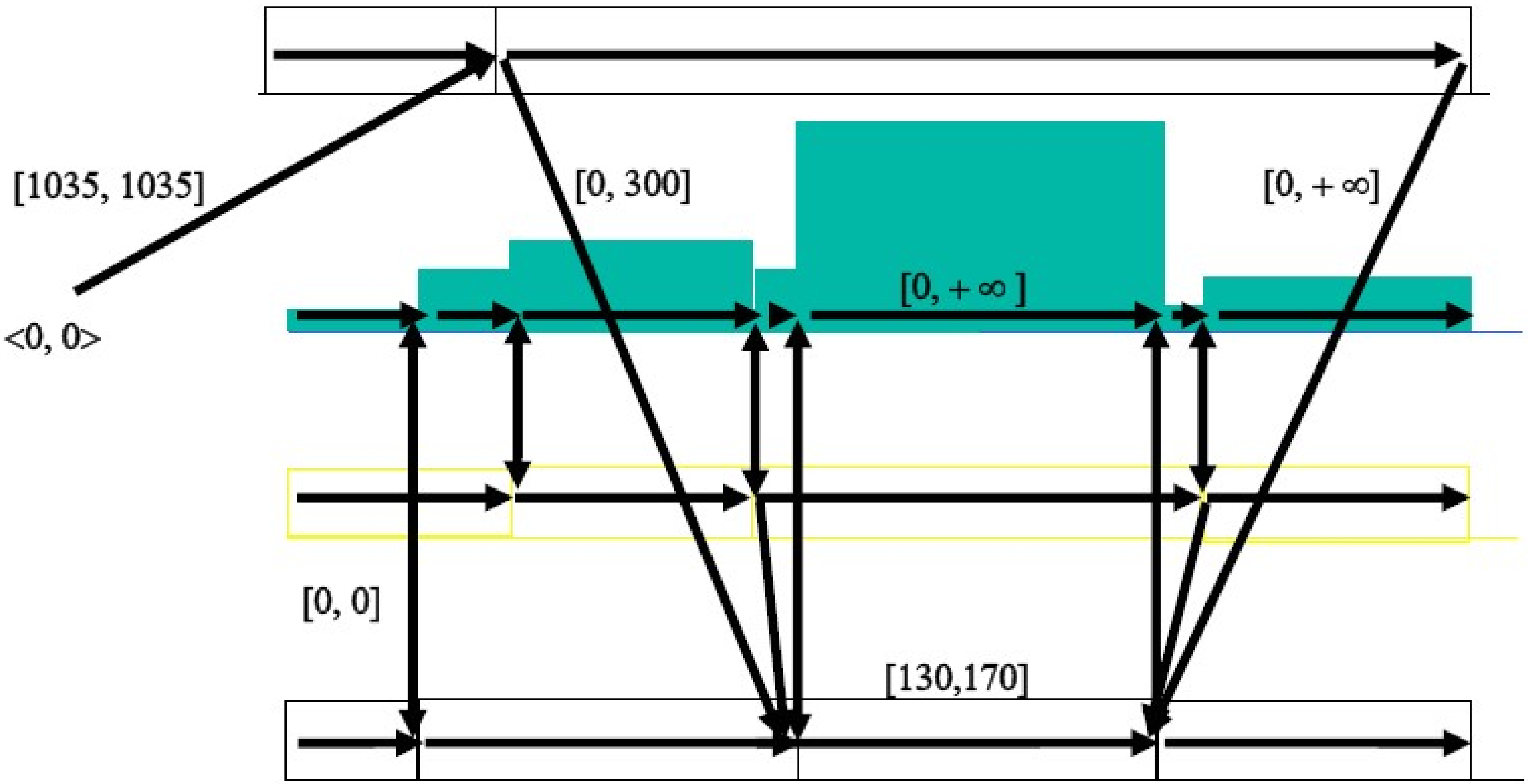
- X_1 in [10, 20]
- X_2 in [40, 50]
- X_3 in [20, 30]
- X_4 in [60, 70]

A Complete CBI-Plan is a STN



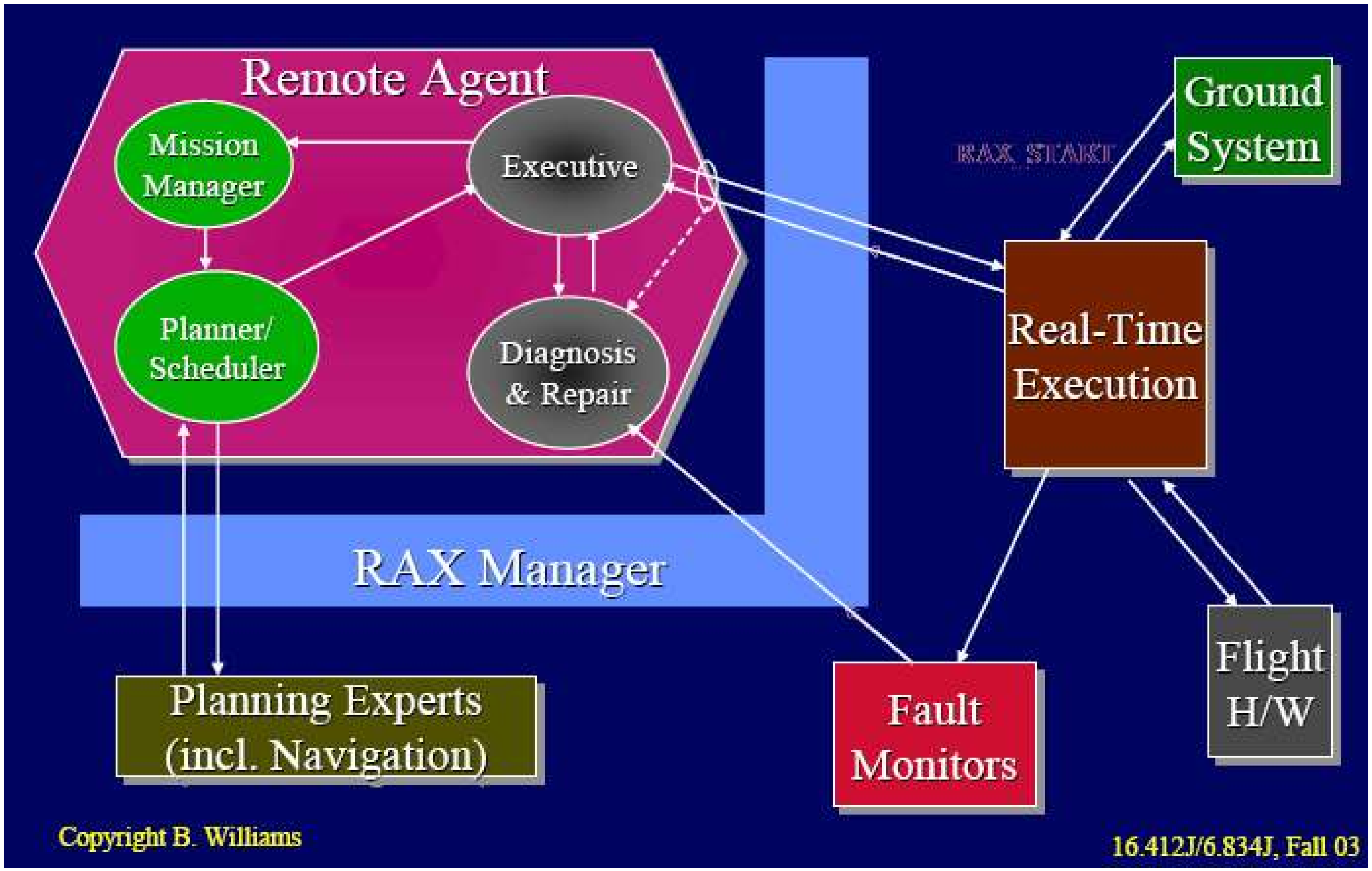
Based on slides by Dave Smith, NASA Ames

A Complete CBI-Plan is a STN

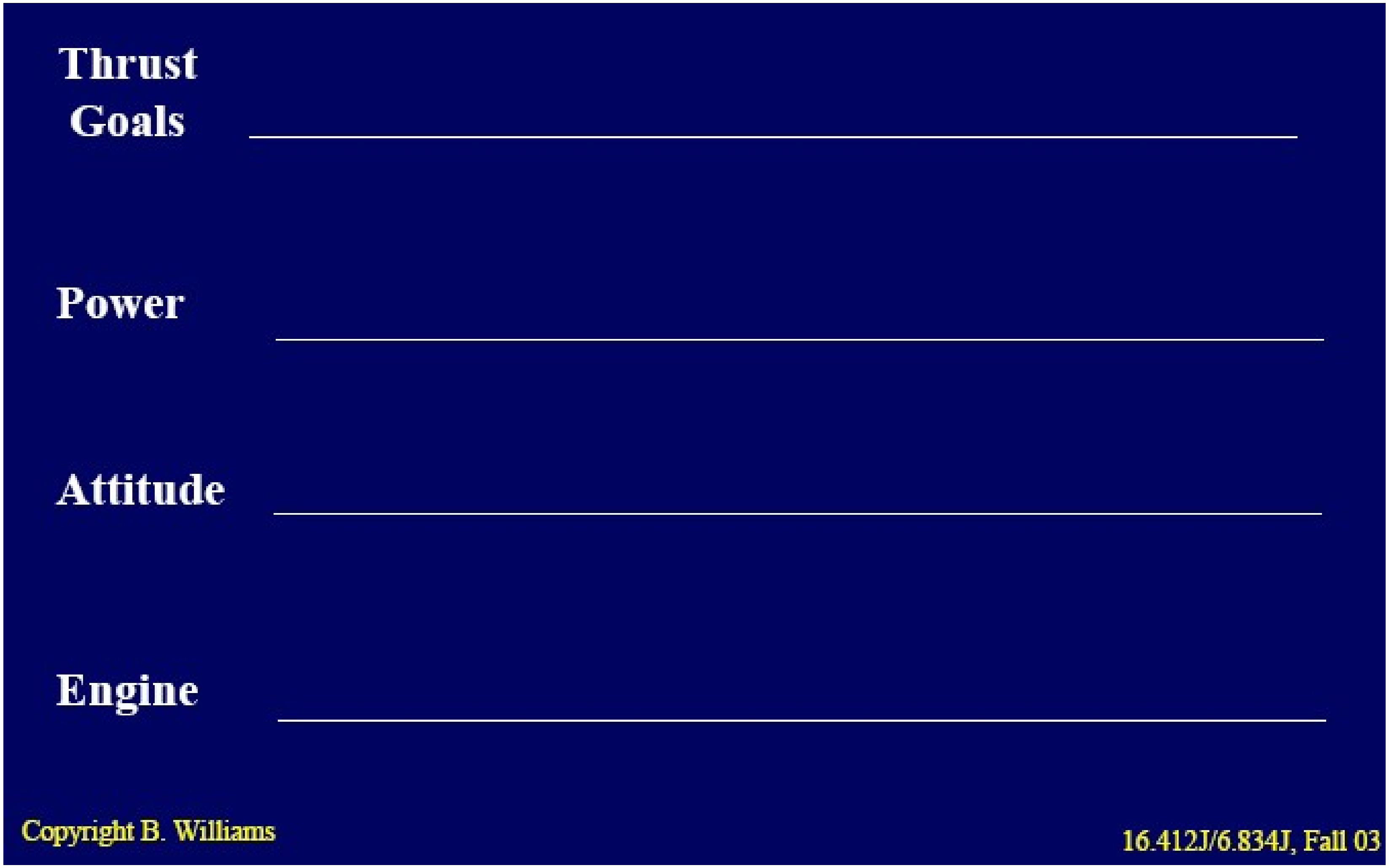


Based on slides by Dave Smith, NASA Ames

Remote Agent

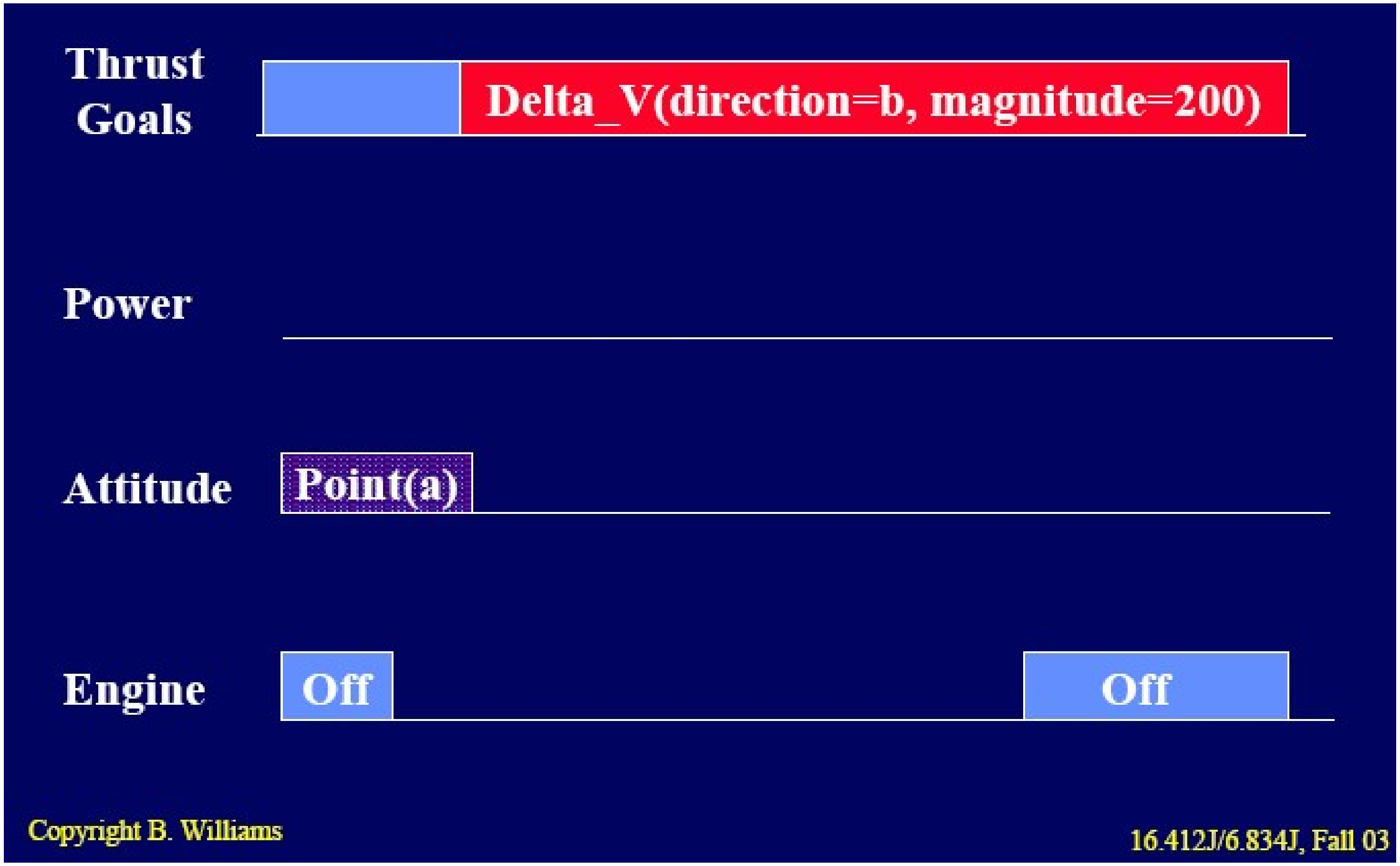


Remote Agent



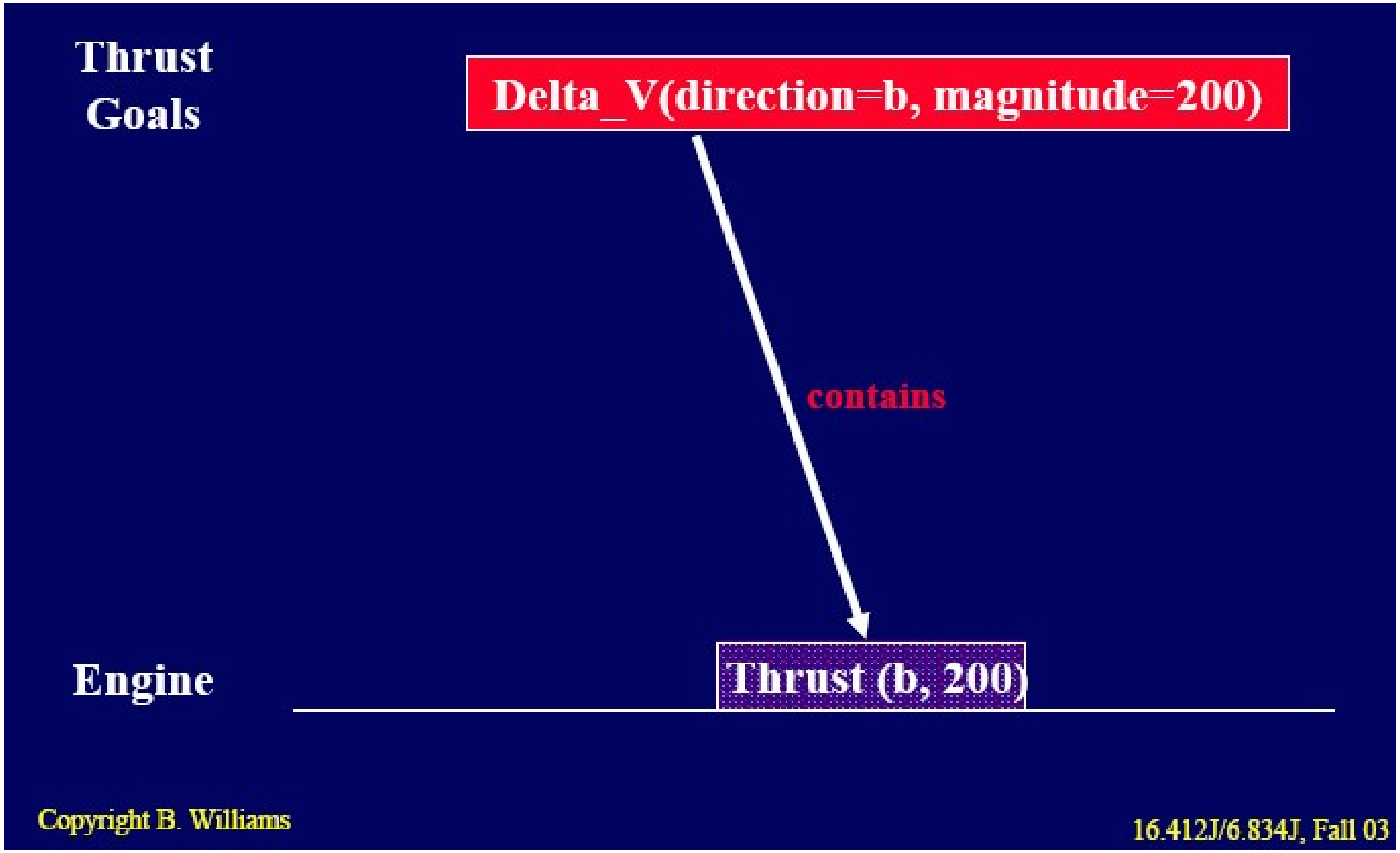
Remote Agent

- Mission Manager



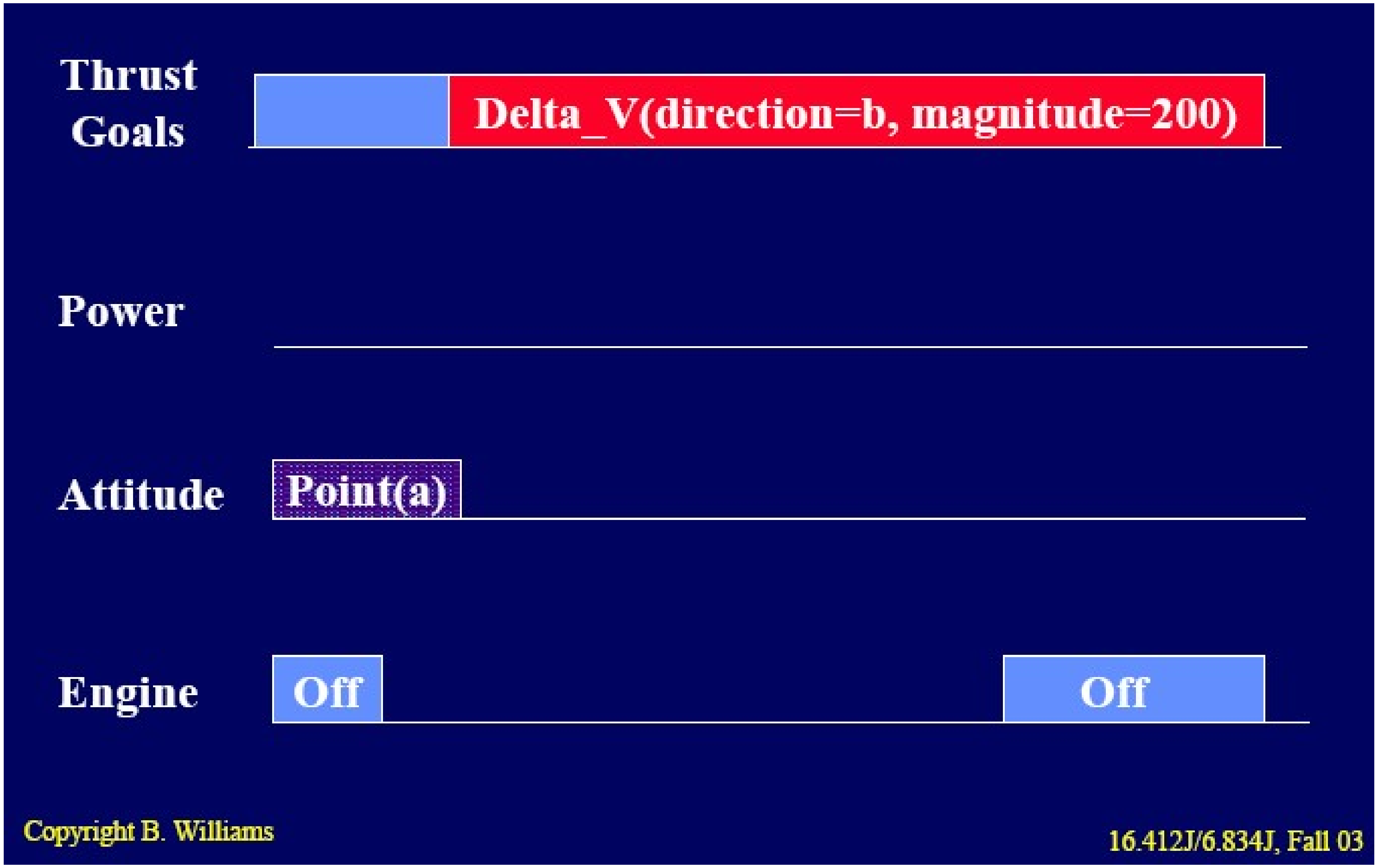
Remote Agent

- Constraints:



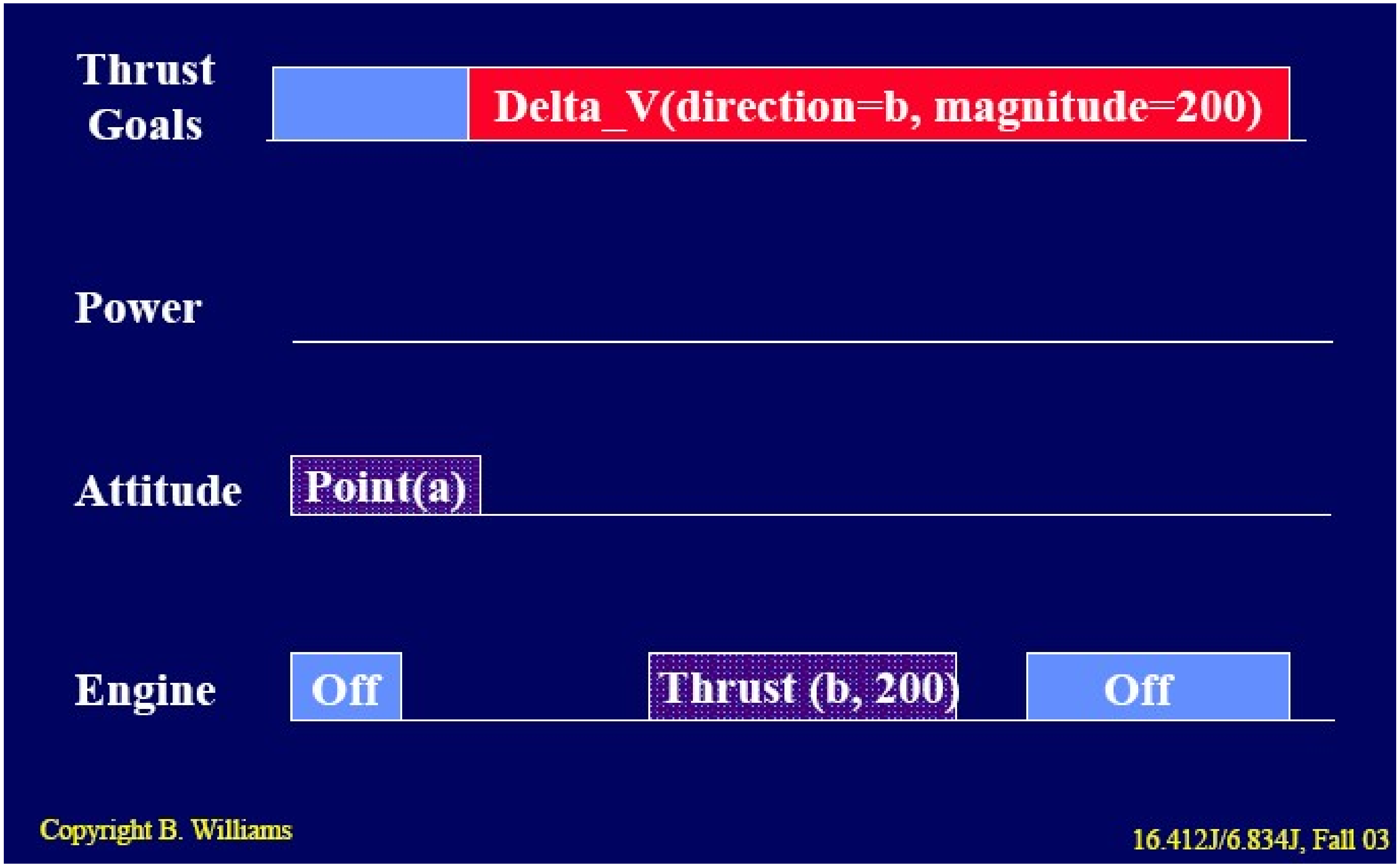
Remote Agent

- Planner starts



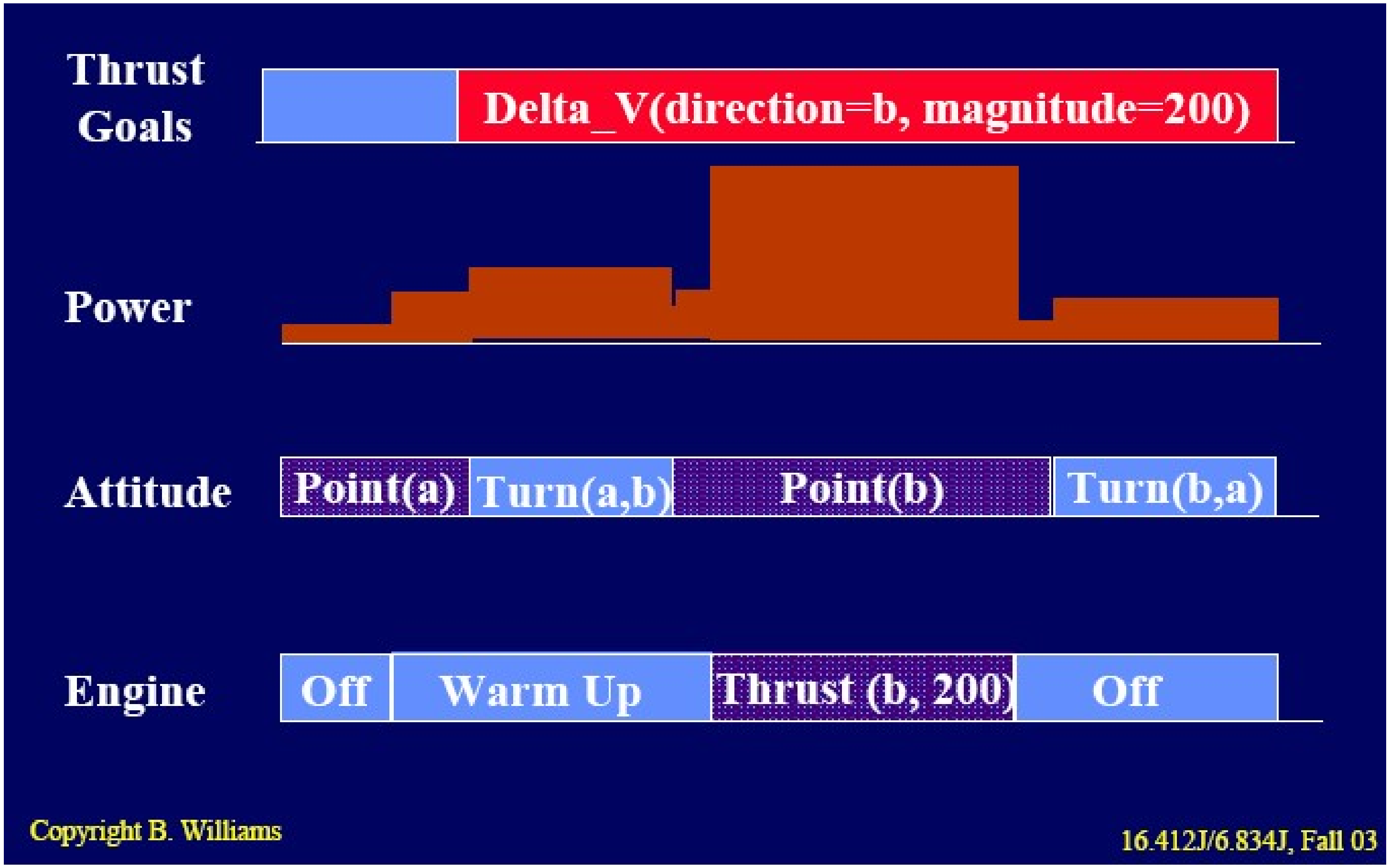
Remote Agent

- Planning



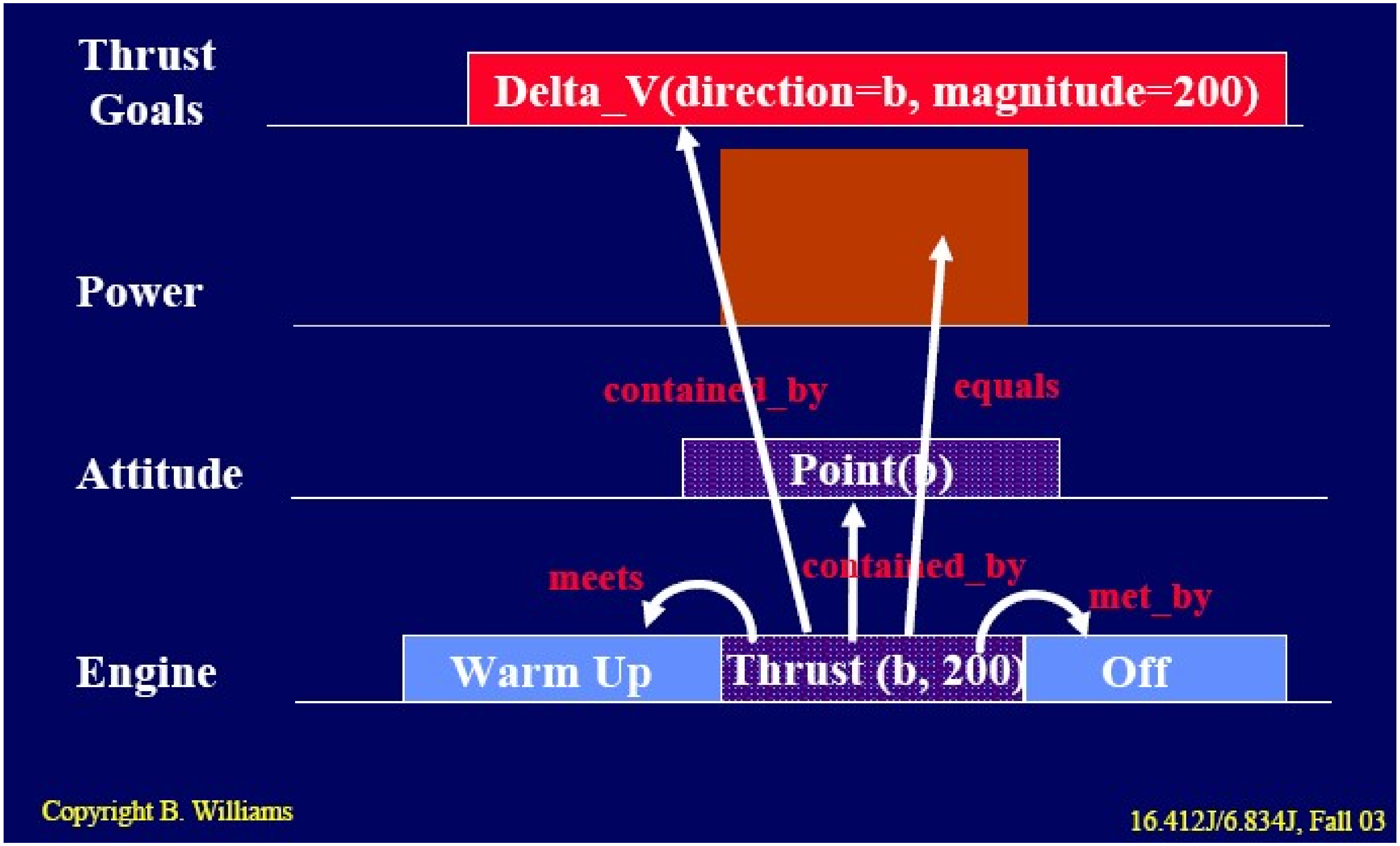
Remote Agent

- Final Plan



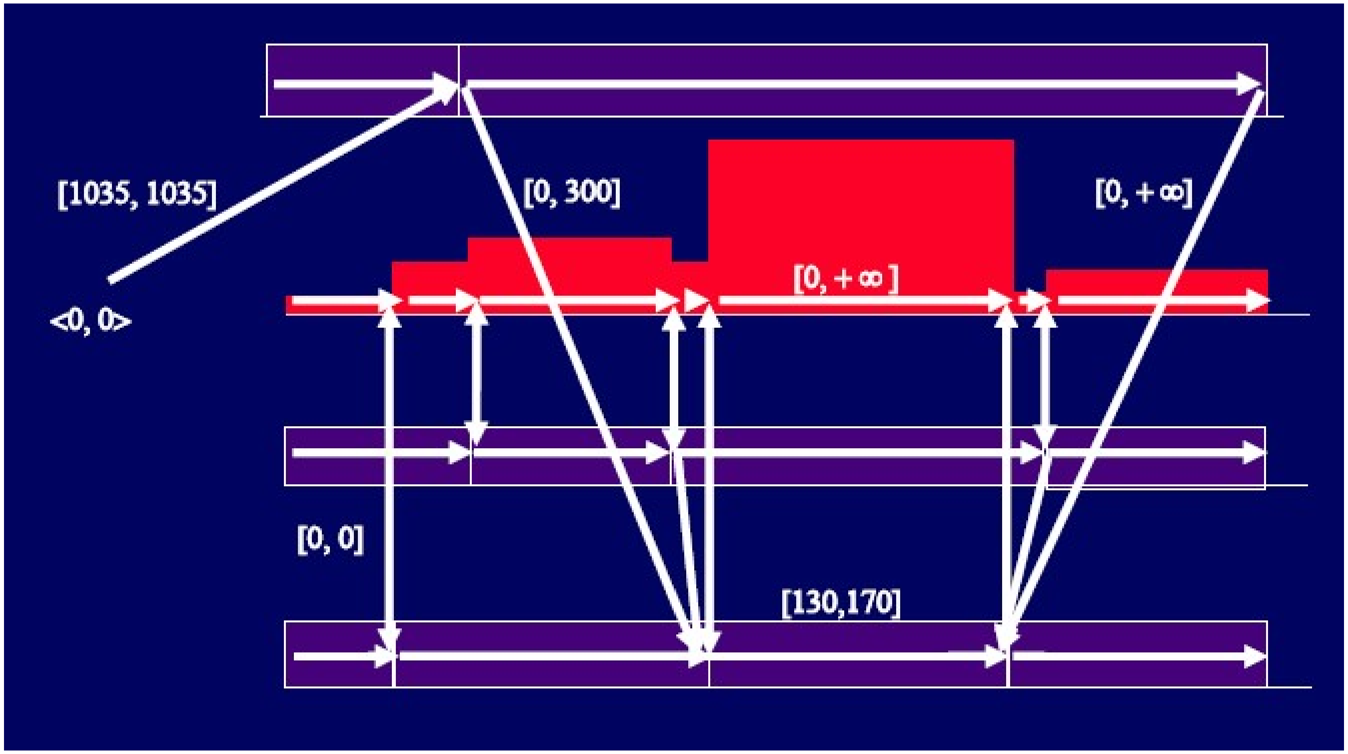
Remote Agent

- Constraints



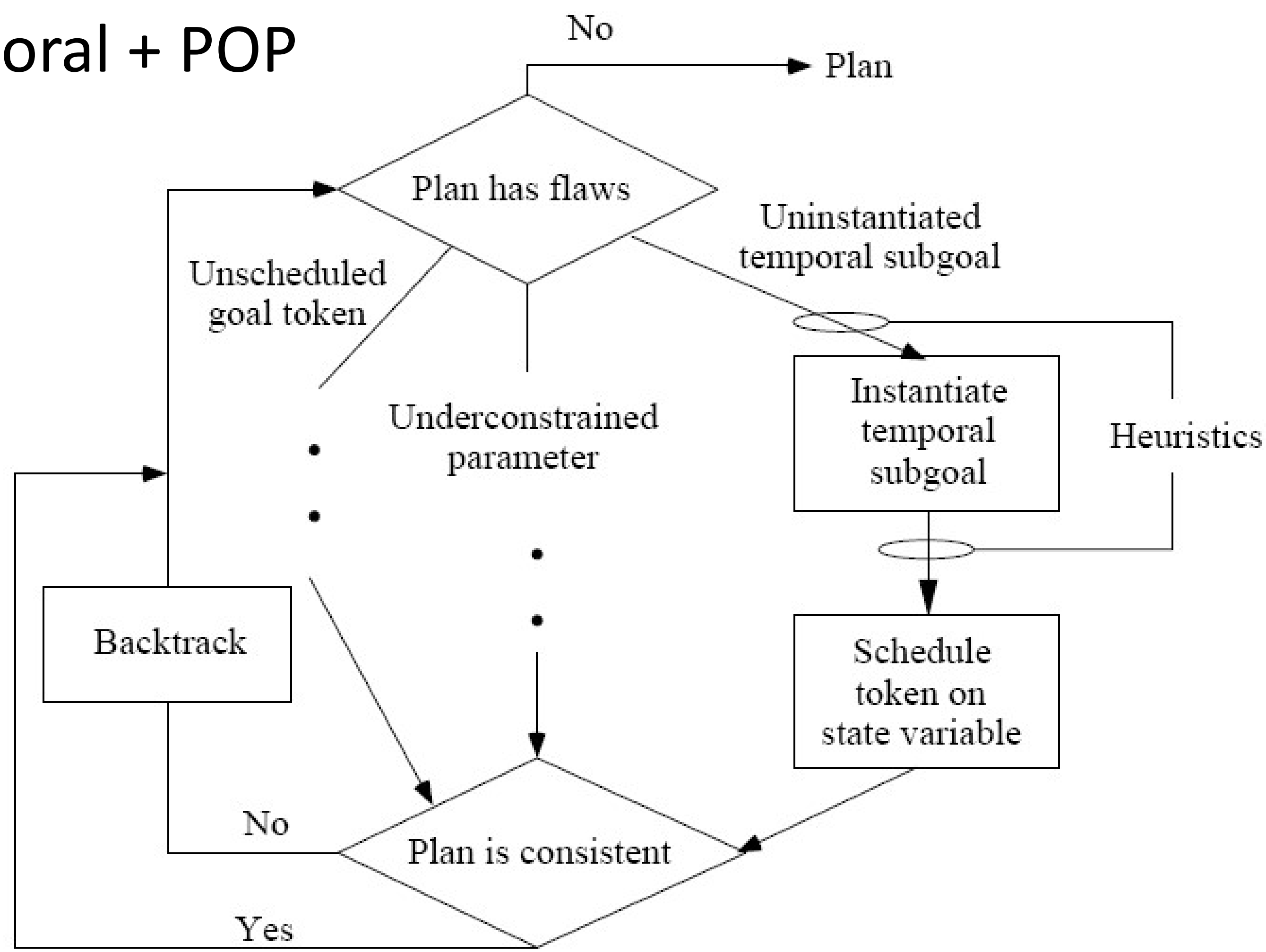
Remote Agent

- Flexible Temporal Plan through least commitment



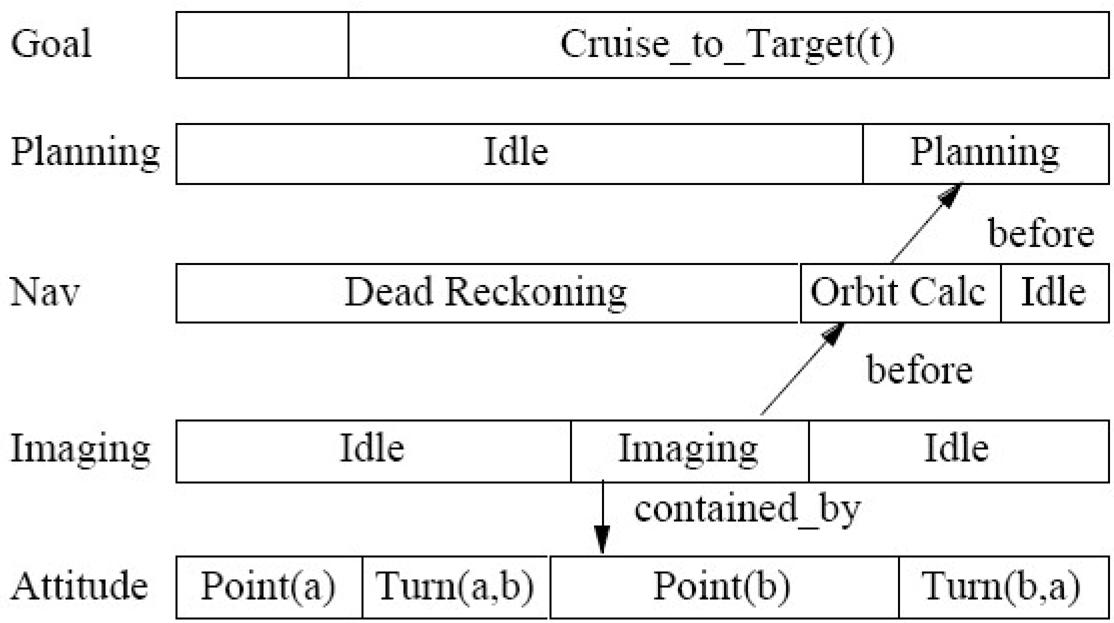
Remote Agent

- Planning
  - Temporal + POP



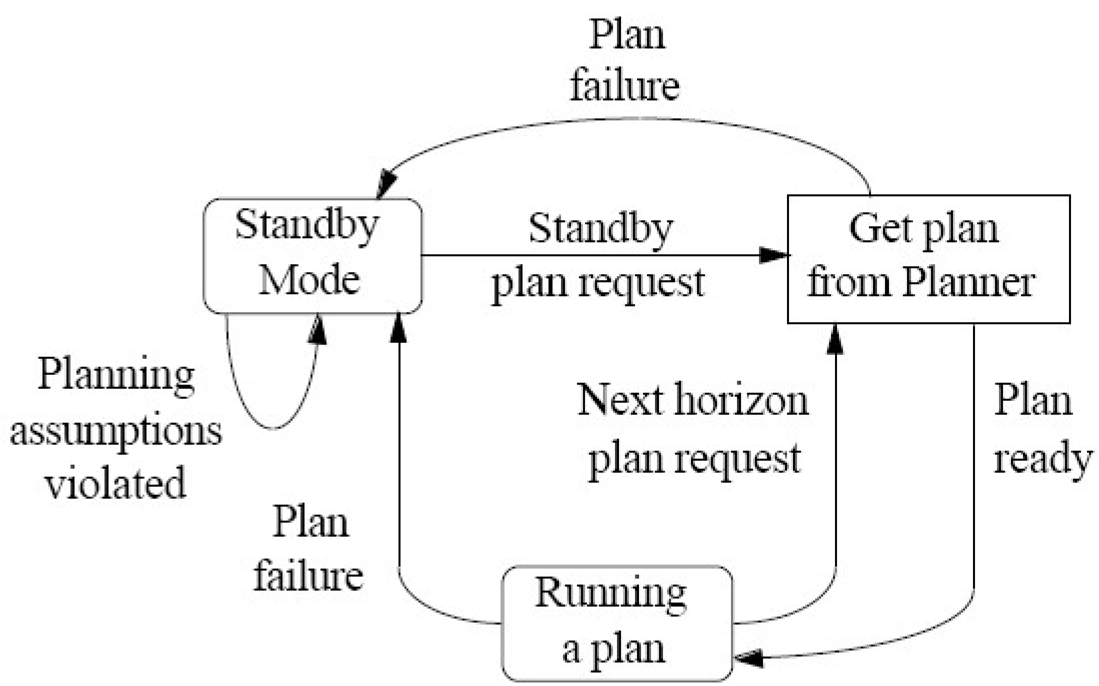
Remote Agent

- Planning to plan



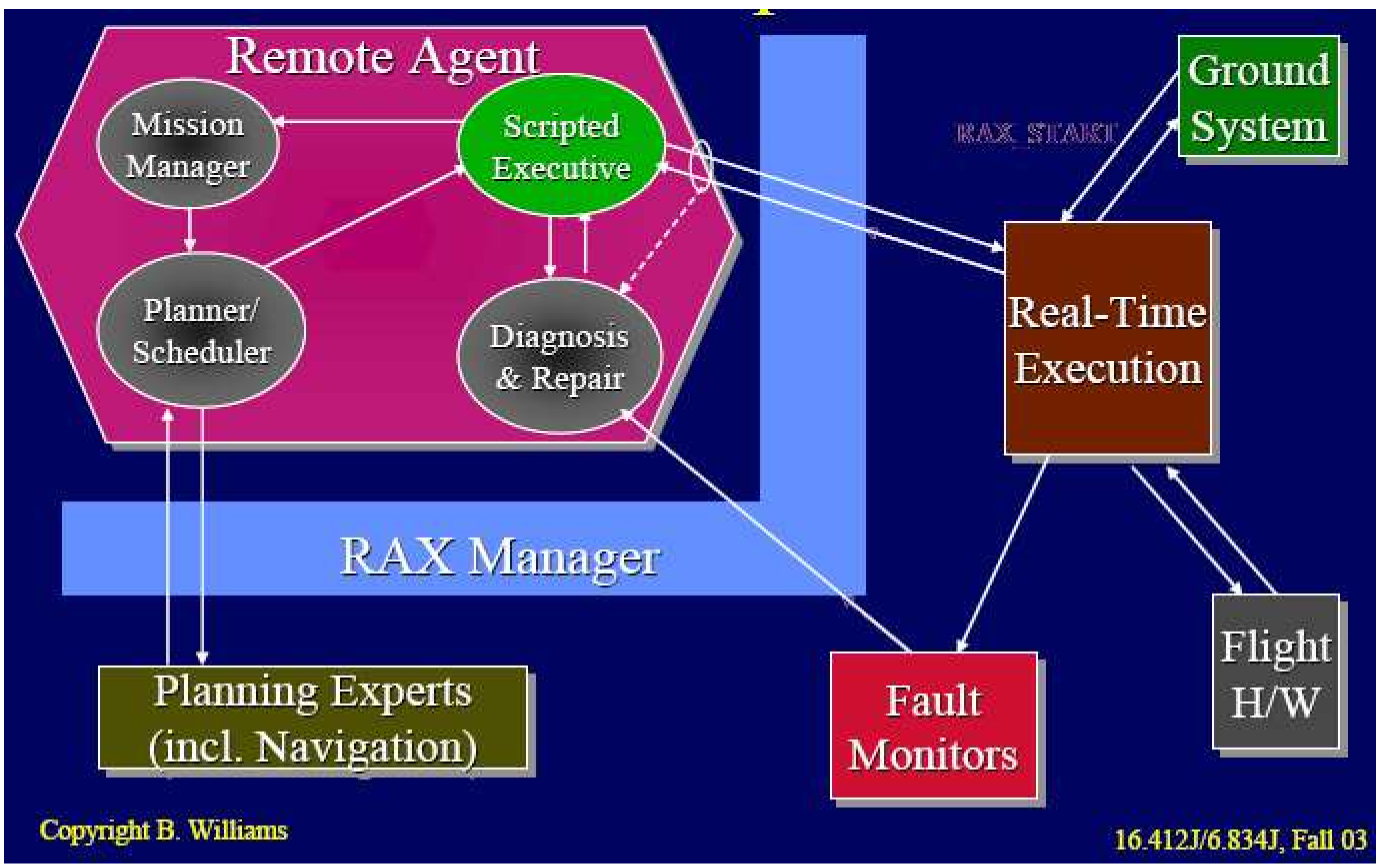
Remote Agent

- Periodic planning and replanning



RAX: Remote Agent

- Executive system dispatch tasks

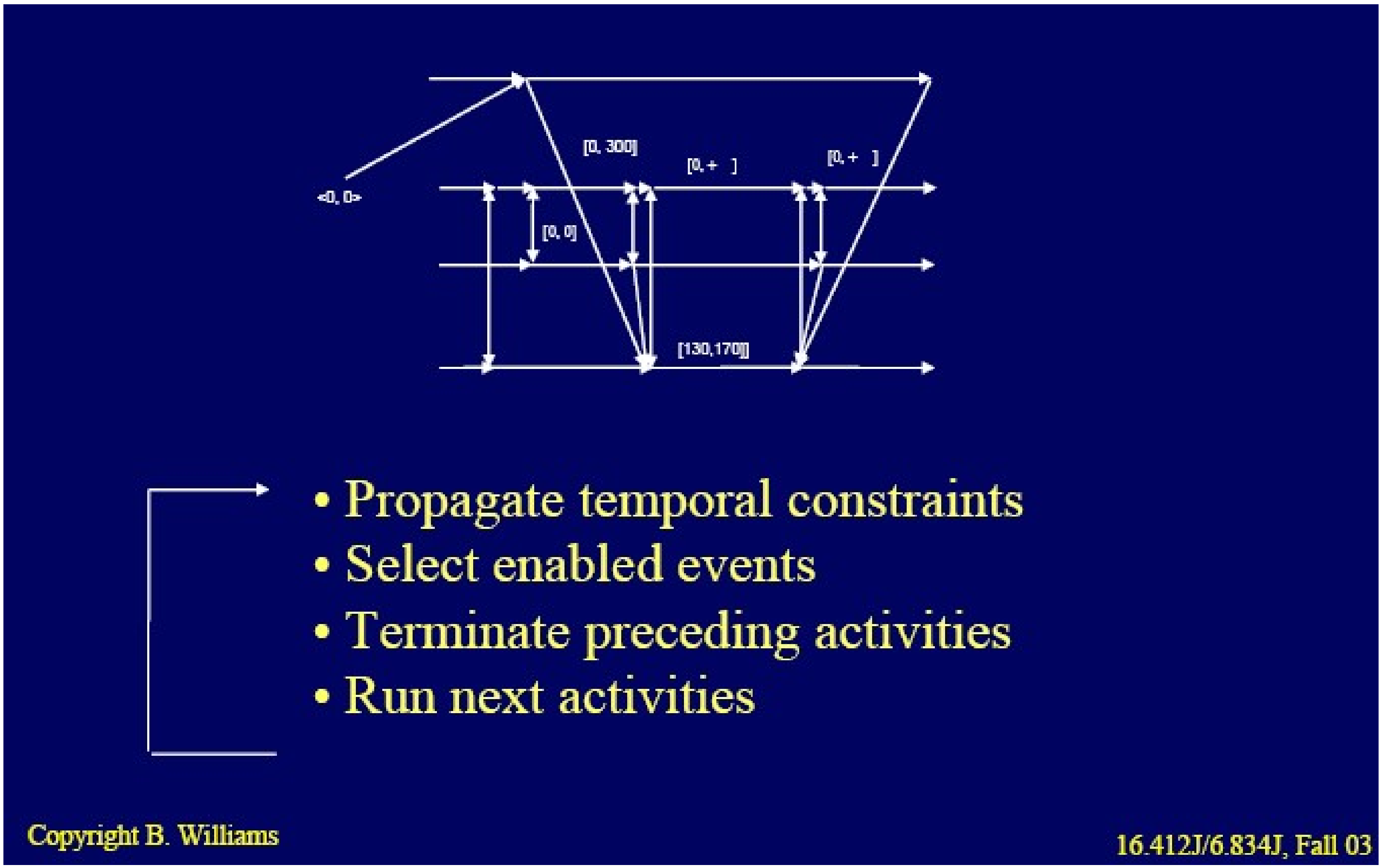


Remote Agent

- The Plan Executor has two duties:
  - Select and Schedule activities for execution
  - Update the network (constraint propagation) after the action execution or execution step (latency)
- Executor Cycle:
  - Activity Graph (STN) from Planner
  - Propagate with latency
  - Enabled time points = scheduled parents (fixed time points)
  - Select and Schedule enabled time points
  - Propagate constraint network given the new binds

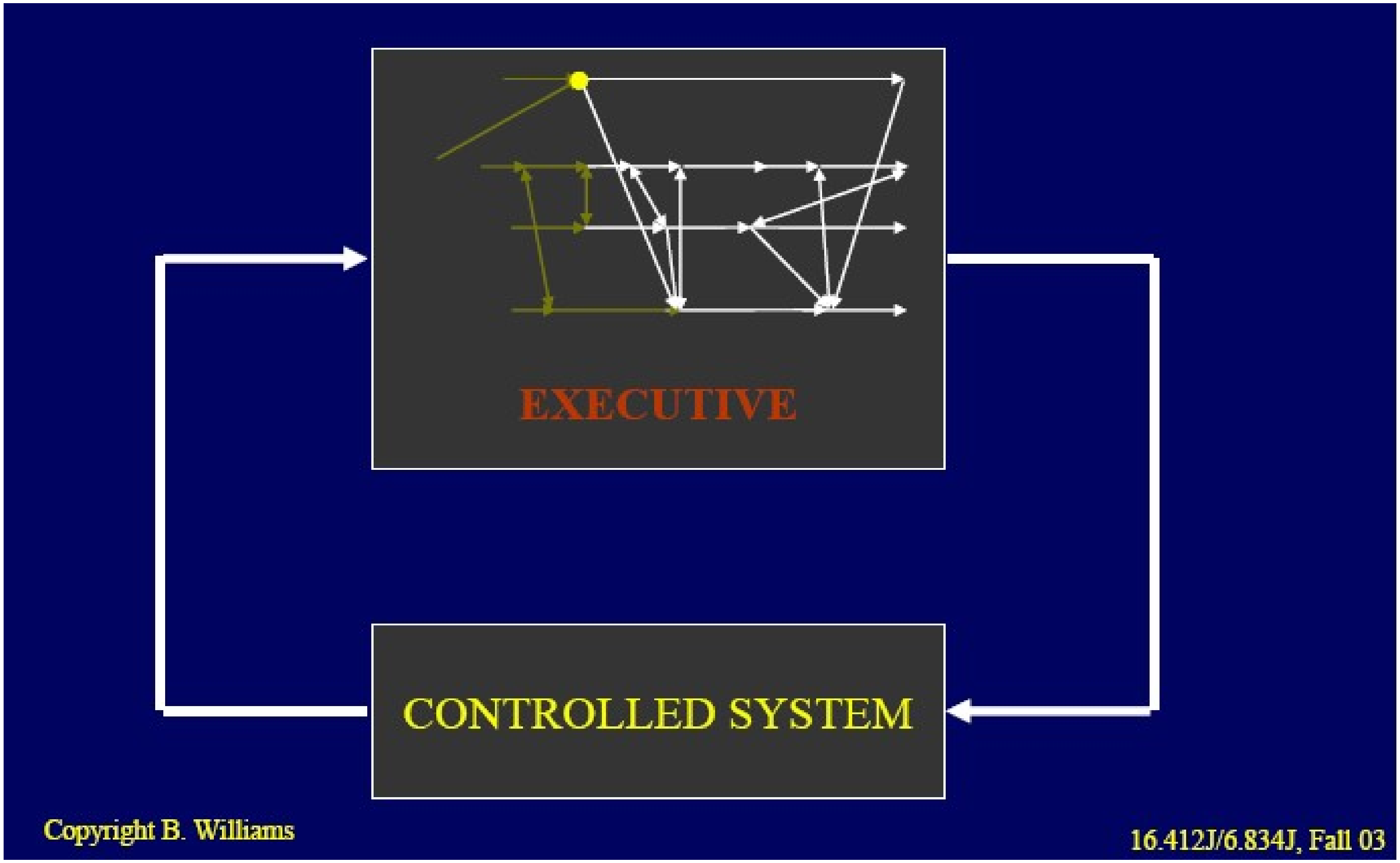
Remote Agent

- Executing Flexible Plans



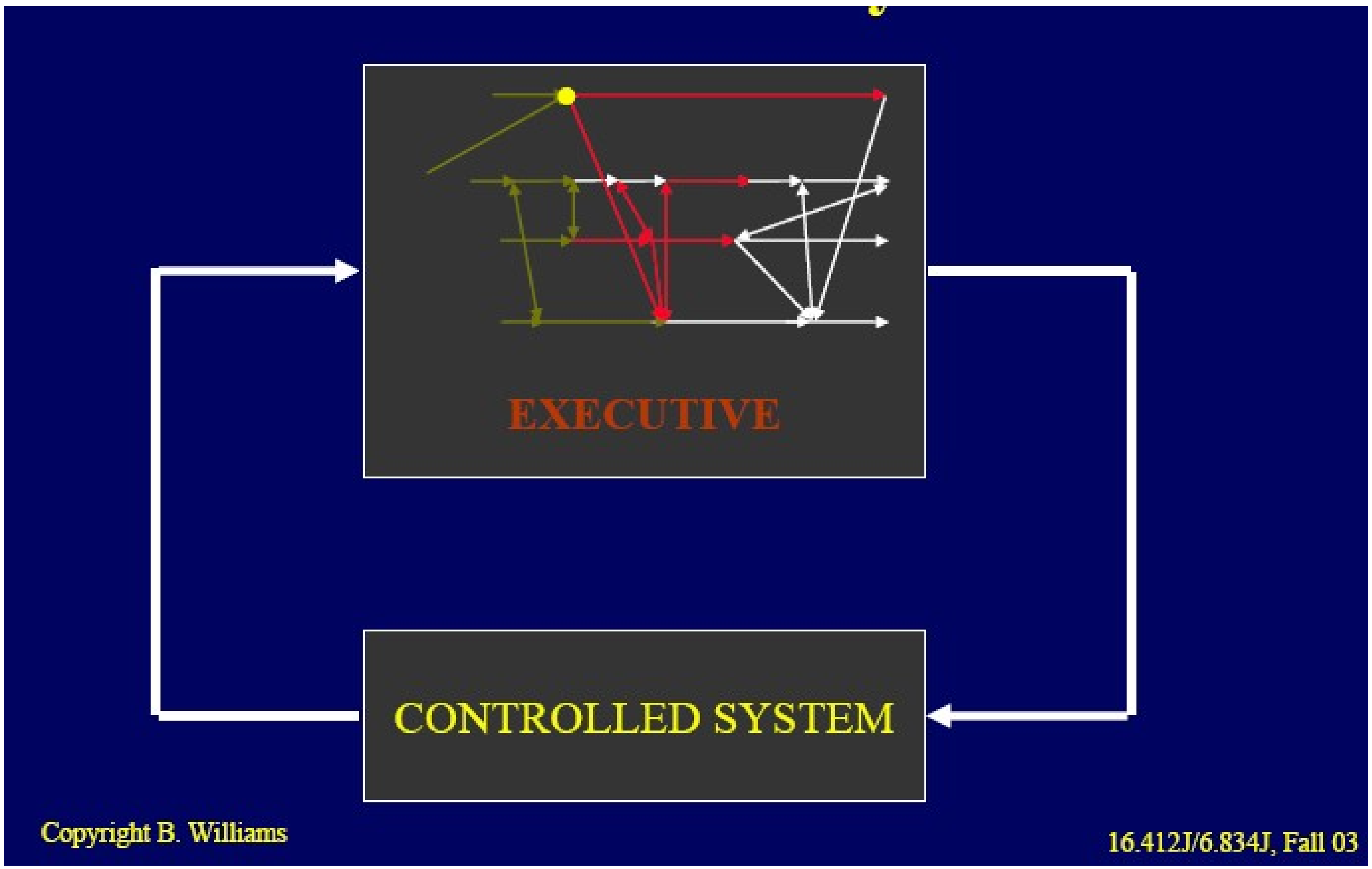
Remote Agent

- Constraint propagation can be costly



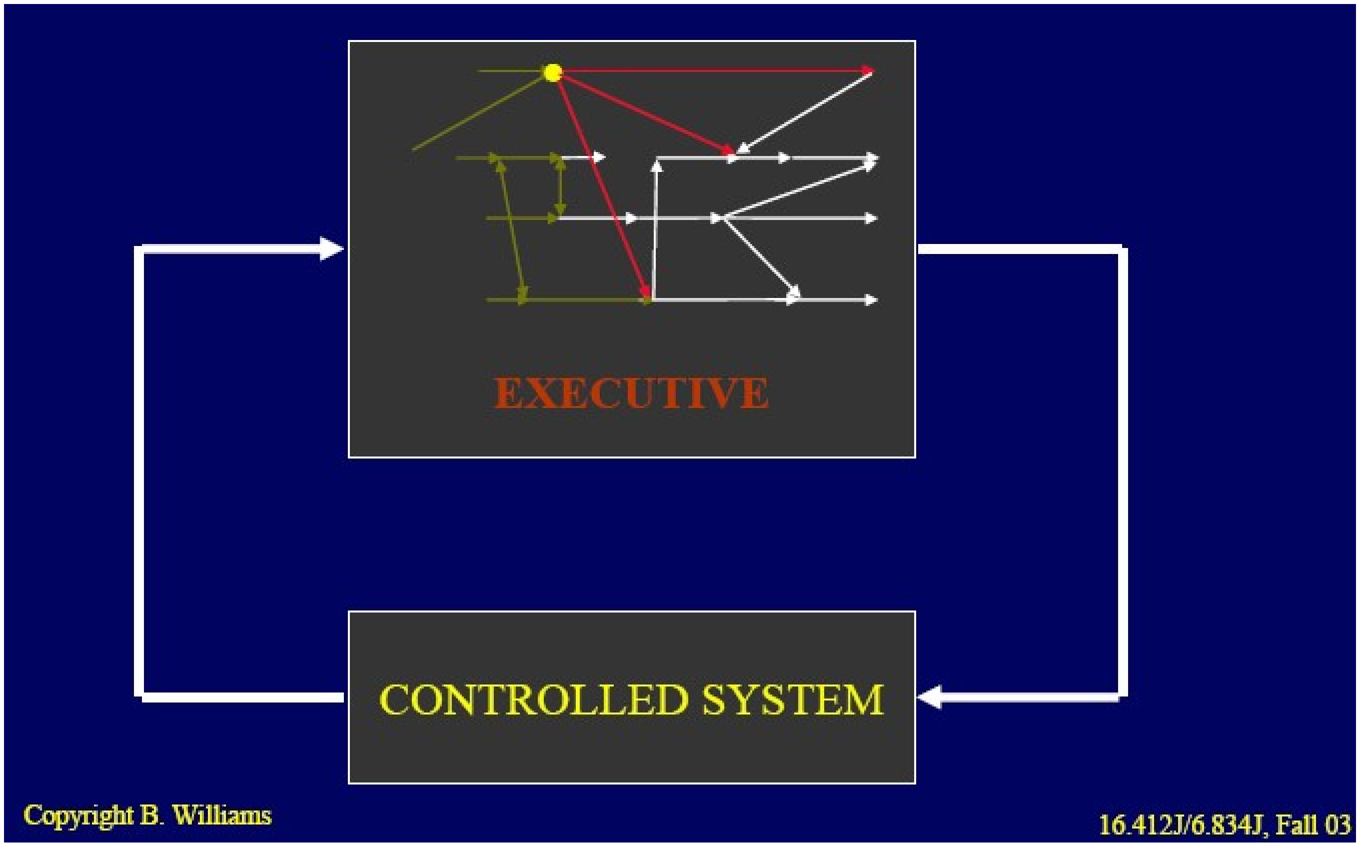
Remote Agent

- Constraint propagation can be costly



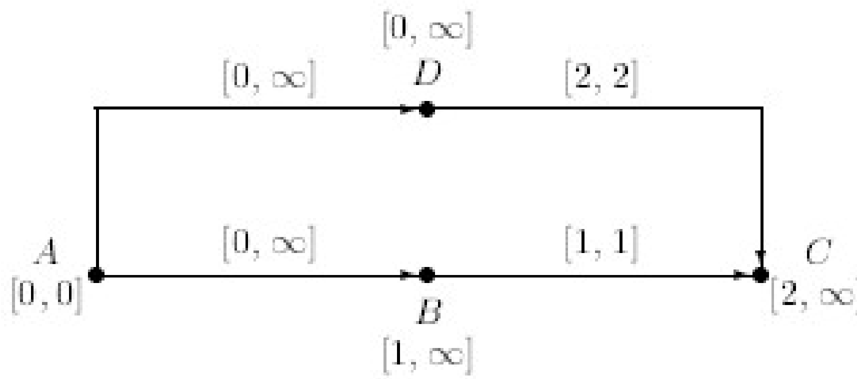
Remote Agent

- Solution: compile temporal constraints to an efficient network

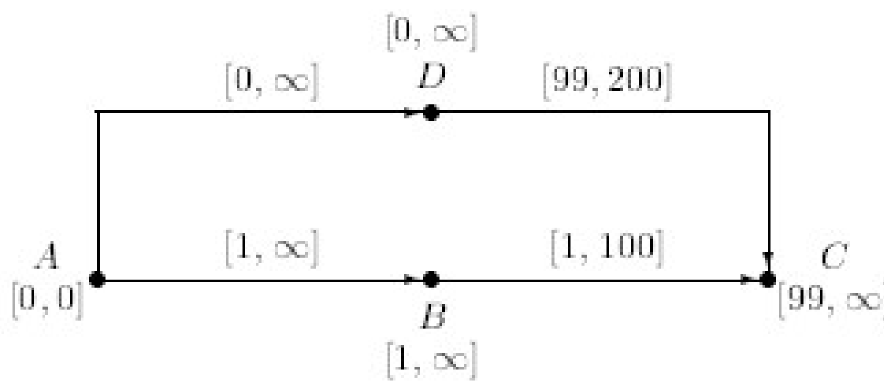


Remote Agent

- Dispatchability
  - Alcuni vincoli non visibili a tempo di esecuzione;

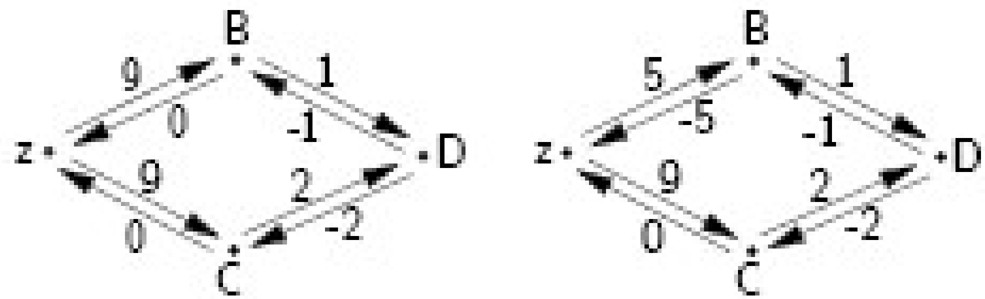


  - Occorre rendere la rete dispatchable aggiungendo vincoli impliciti (e.g. D prima di B)
  - Compilare la rete in forma dispatchable:
    - Introdotti vincoli impliciti
    - Tolti vincoli ridondanti



Dispatchability

A Sample Execution*



After executing B at time 5, it turns out that C must be executed at time 4 (which is already past).

* (Muscettola, Morris, & Tsamardinos 1998)

Dispatcher

Greedy Dispatcher*

While some time-points not yet executed:

- Wait until some time-point is executable.
- If more than one, pick one to execute.
- Propagate updates only to *neighboring* time-points (i.e., do not fully update $\mathcal{D}$).

* (Muscettola, Morris, & Tsamardinos 1998)

Dispatcher

```
TIME DISPATCHING ALGORITHM:
    1. Let
         A = {start_time_point}
         current_time = 0
         S = {}
    2. Arbitrarily pick a time point TP in A such
       that current_time belongs to TP's time bound;
    3. Set TP's execution time to current_time and add
       TP to S;
    4. Propagate the time of execution
       to its IMMEDIATE NEIGHBORS in the distance
       graph;
    5. Put in A all time points TPx such that all
       negative edges starting from TPx have a
       destination that is already in S;
    6. Wait until current_time has advanced to
       some time between
          min{lower_bound(TP) : TP in A}
       and
          min{upper_bound(TP) : TP in A}
    7. Go to 2 until every time point is in S.
```

Dispatchability

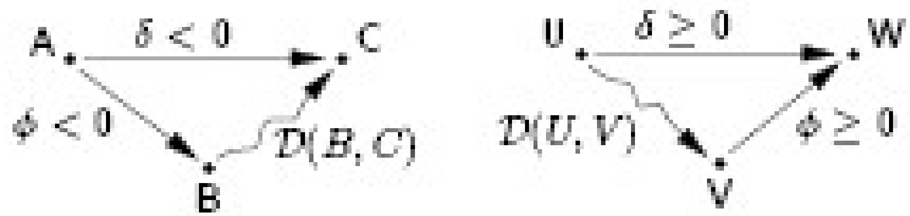
Dispatchability*

- An STN that is guaranteed to be satisfied by the Greedy Dispatcher is called *dispatchable*.
- Any *consistent* STN can be transformed into an equivalent *dispatchable* STN.
- Step I: The corresponding All-Pairs graph is equivalent and dispatchable.
- Step II: Remove *lower- and upper-dominated* edges (does not affect dispatchability).

* (Muscettola, Morris, & Tsamardinos 1998).

Dispatchability

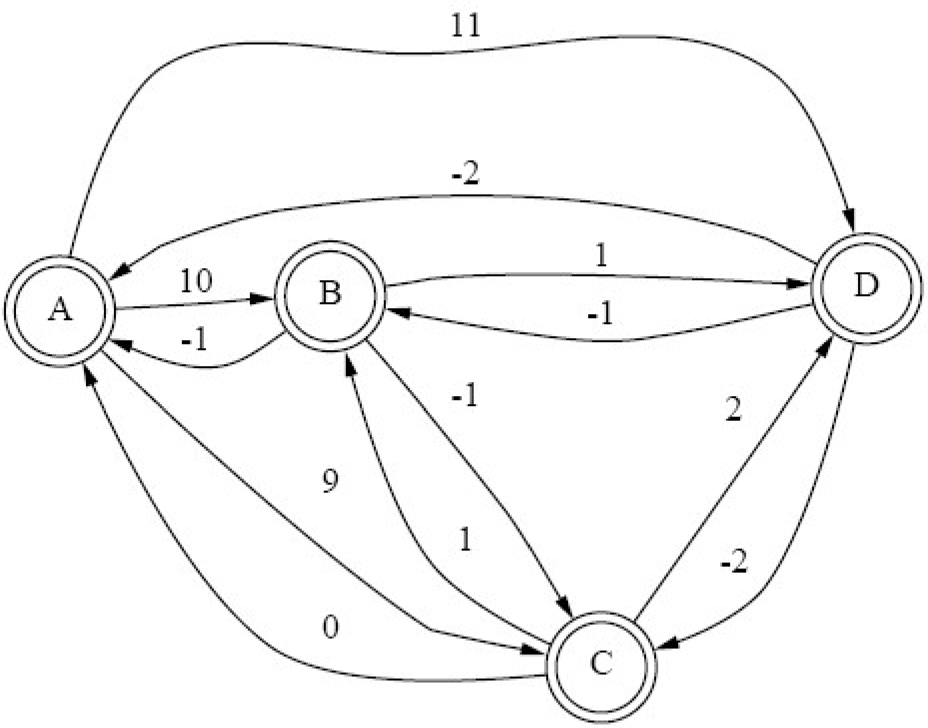
Lower and Upper Dominance*



- The *negative edge* AC is *lower-dominated* if:
  $\delta = \phi + \mathcal{D}(B,C)$.
- The *non-negative edge* UW is *upper-domin'd* if:
  $\delta = \mathcal{D}(U,V) + \phi$.

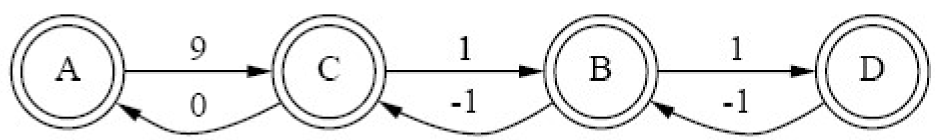
* (Muscettola, Morris, & Tsamardinos 1998)

Dispatchability



All pair graph

Filtered graph



Controllability

- Alcune attività non sono controllabili, ma solo osservabili
- E.g. after start_turn, end_turn ? Quando finisce?
- Il grafo delle attività STN contiene time point controllabili e non controllabili
- Le attività non controllabili non possono essere schedulate, ma solo osservate
- Propagazione?

Controllability

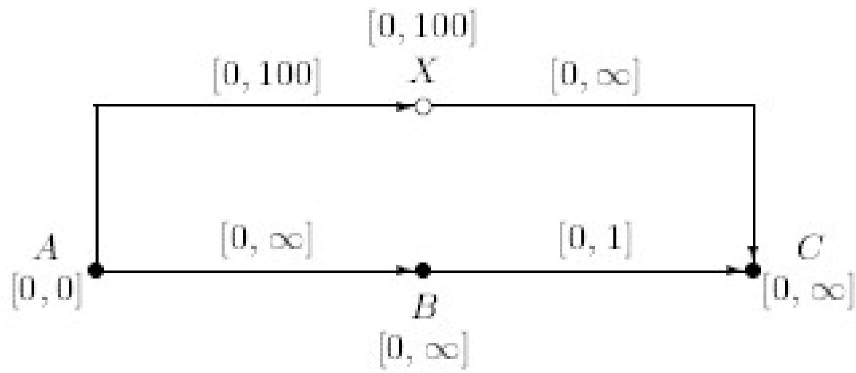
Controllability Issues*

- In real-world applications, an agent may only control some time-points directly; others may be controlled by other agents or Nature.
- Such a network is called *controllable* if there exists a strategy for the agent to execute the time-points under its direct control that will ensure the consistency of the network—no matter how the other agents or Nature execute their time-points.

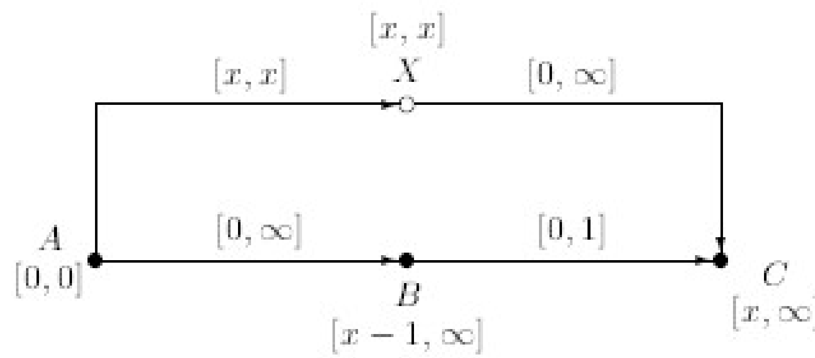
* (Vidal & Ghallab 1995; Vidal & Fargier)

Controllability

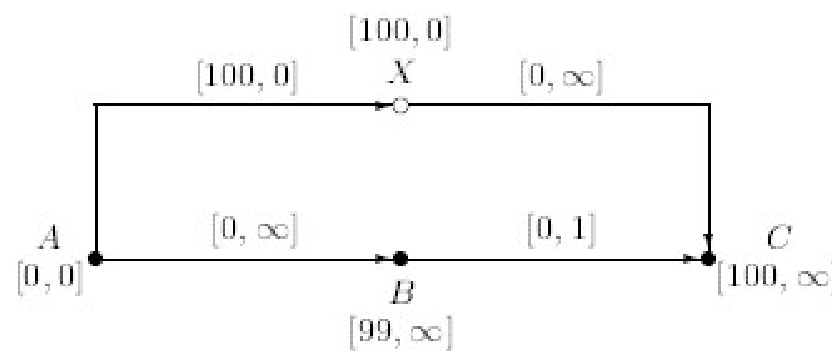
- Gestire eventi non controllabili
- Es. Se B schedulato prima di X, B vincola X



  - Soluzione Dinamica: B dopo X



  - Soluzione Forte: B a 99



Controllability

- **Weak Controllability**: per ogni evento incontrollabile esiste uno scheduling che permette l'esecuzione;
- **Strong Controllability**: esiste uno scheduling robusto qualunque siano gli eventi non controllabili;
- **Dynamic Controllability**: per ogni evento incontrollabile passato esiste uno scheduling che permette l'esecuzione.

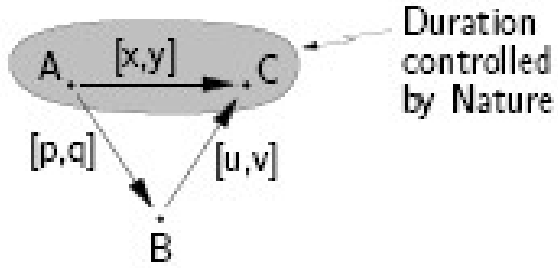
Controllability

Checking Dynamic Controllability*

Morris et al. (2001) present a sound and complete algorithm for checking dynamic controllability using:

- *Triangular Reductions*
- *Wait Propagation*

Triangular Reductions



- If v < 0, then B follows C – no reduction.
- If u ≥ 0, then B precedes C. Must tighten bounds on interval AB to: [y-v, x-u].

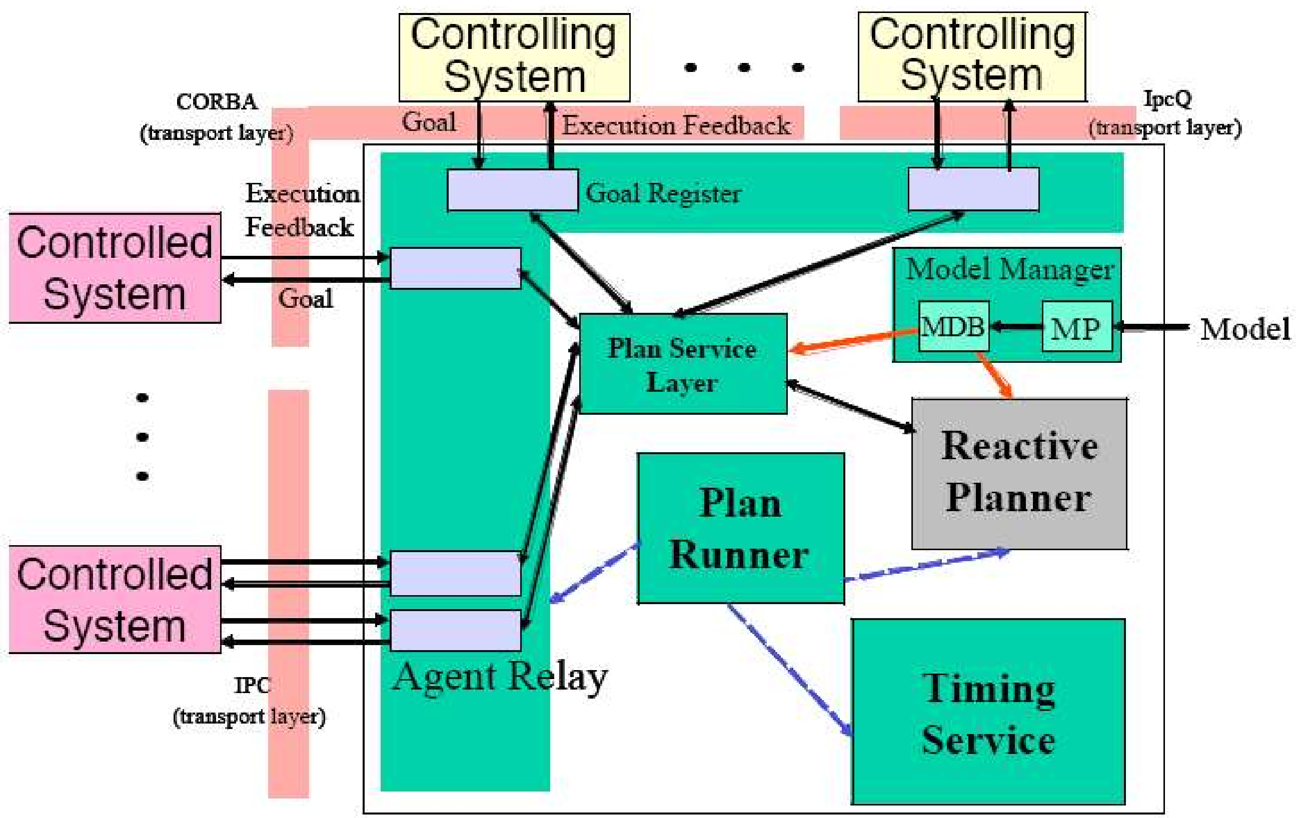
Triangular Reductions (ctd.)

- If u < 0 and v ≥ 0, then the order of B and C is not yet determined. Derive a *WAIT*: If C has not yet been executed, B must *wait* to be executed until (y-v) after A.

Waits can be propagated much like binary constraints.

IDEA Architecture

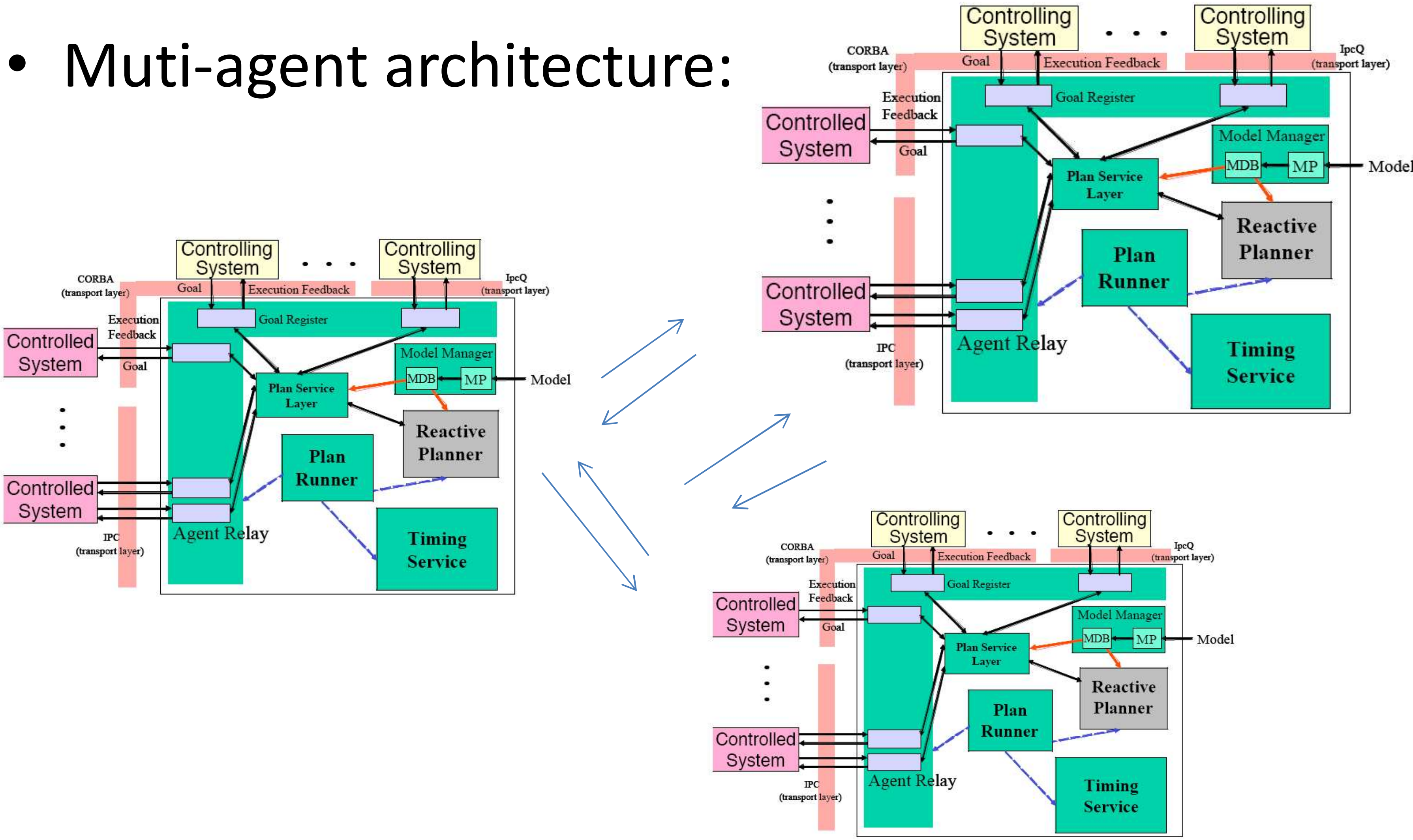
- Evoluzione del RA: reactive and deliberative planning



EUROPA Planner:
https://github.com/nasa/europa

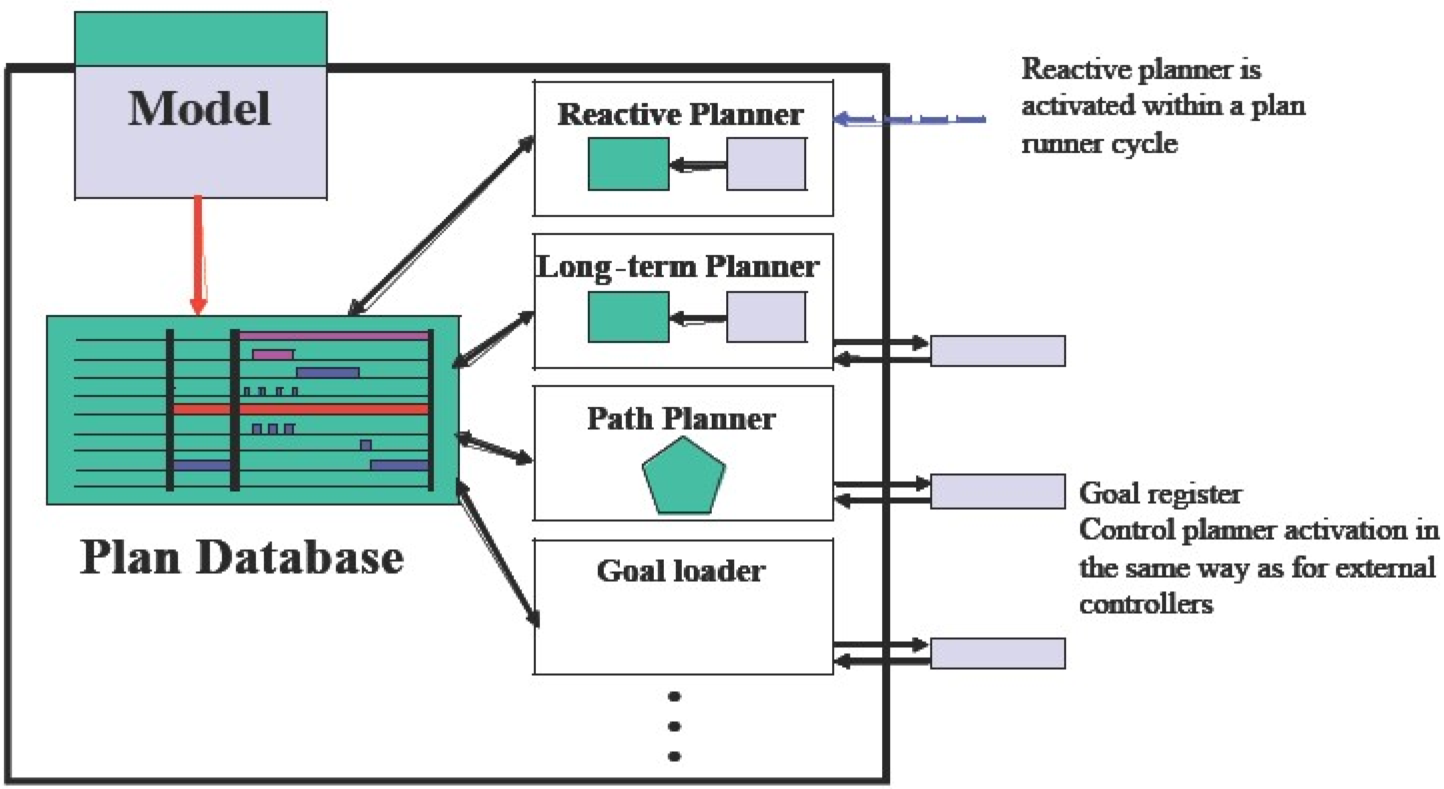
IDEA Architecture

- Muti-agent architecture:



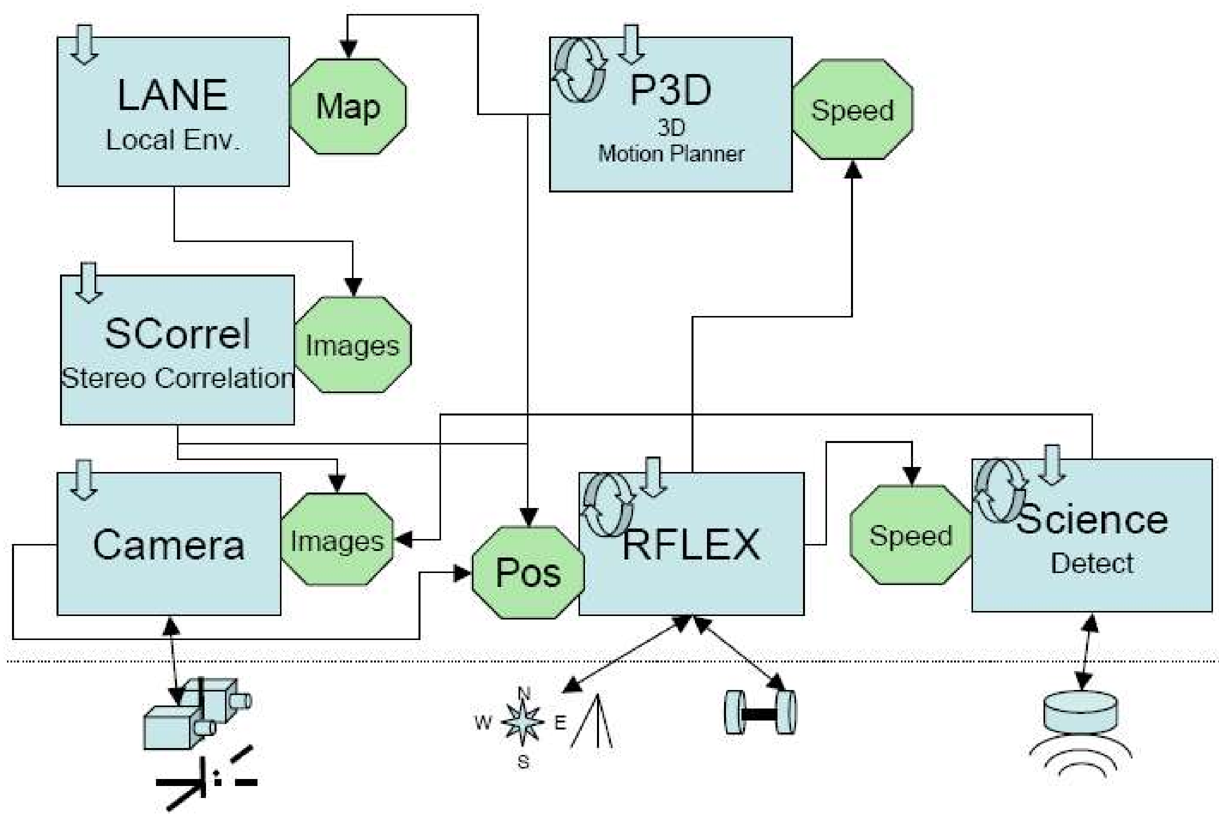
IDEA Architecture

- Reactive planning come controllo
- Interazione deliberative and reactive planning



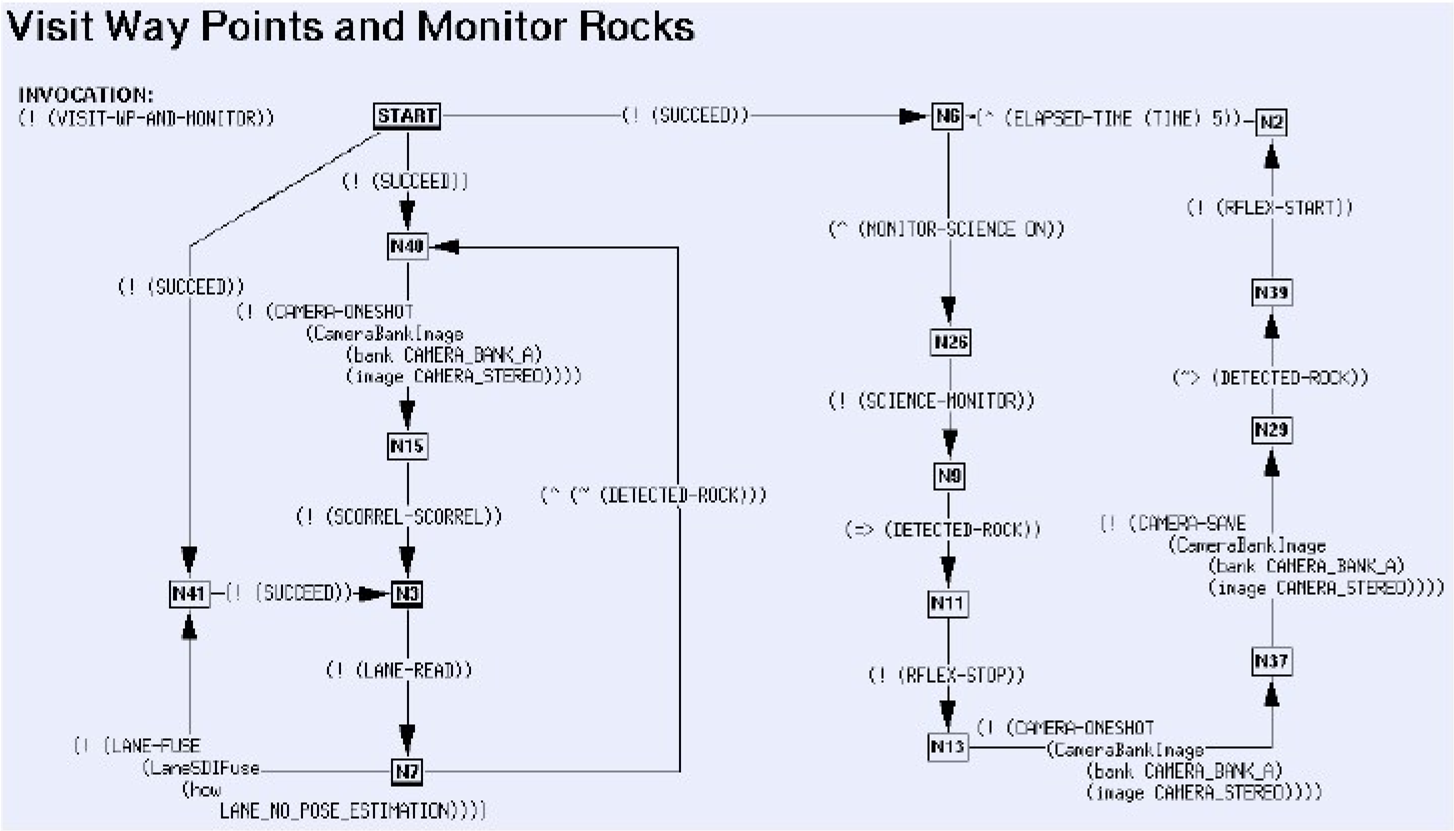
Functional Layer

- GenoM (LAAS)



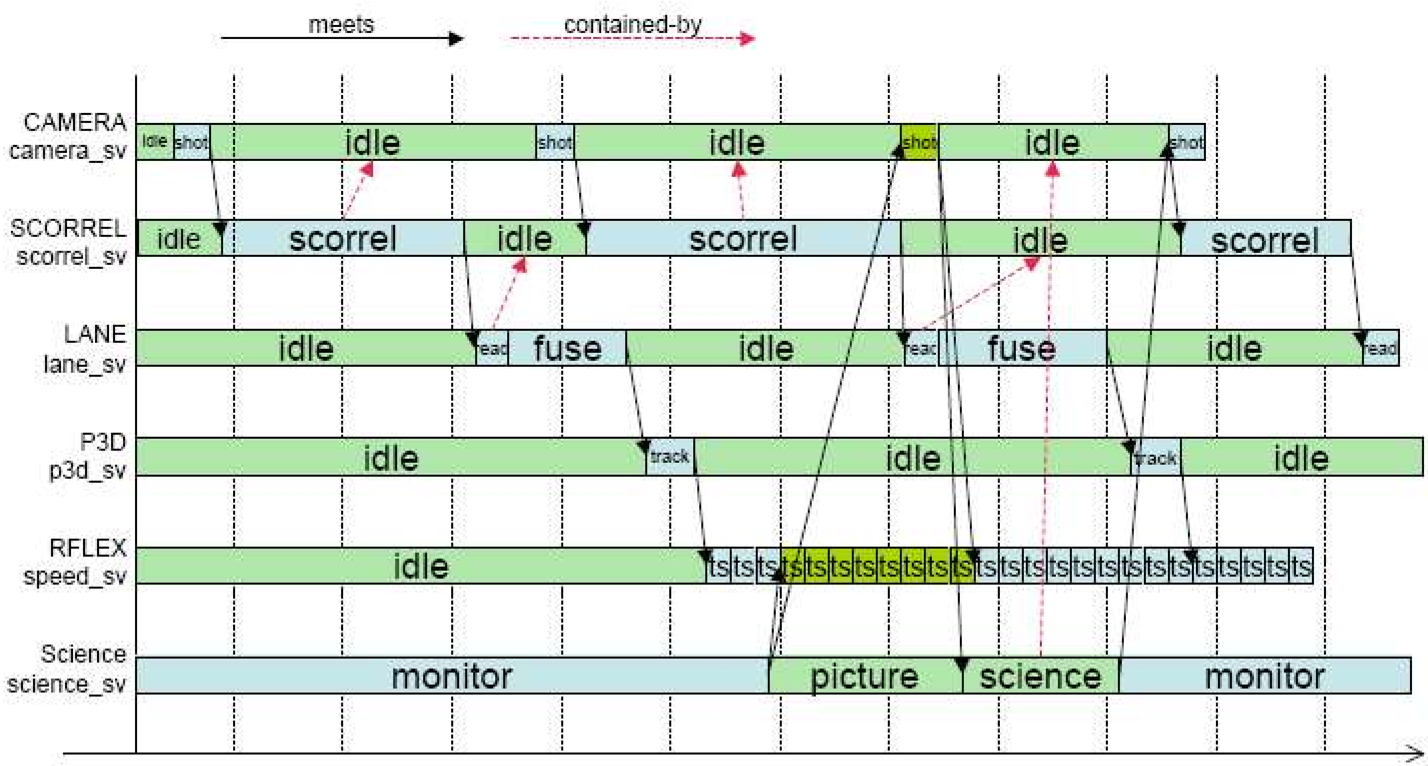
PRS Controller

- A procedural controller (vedi dopo …)



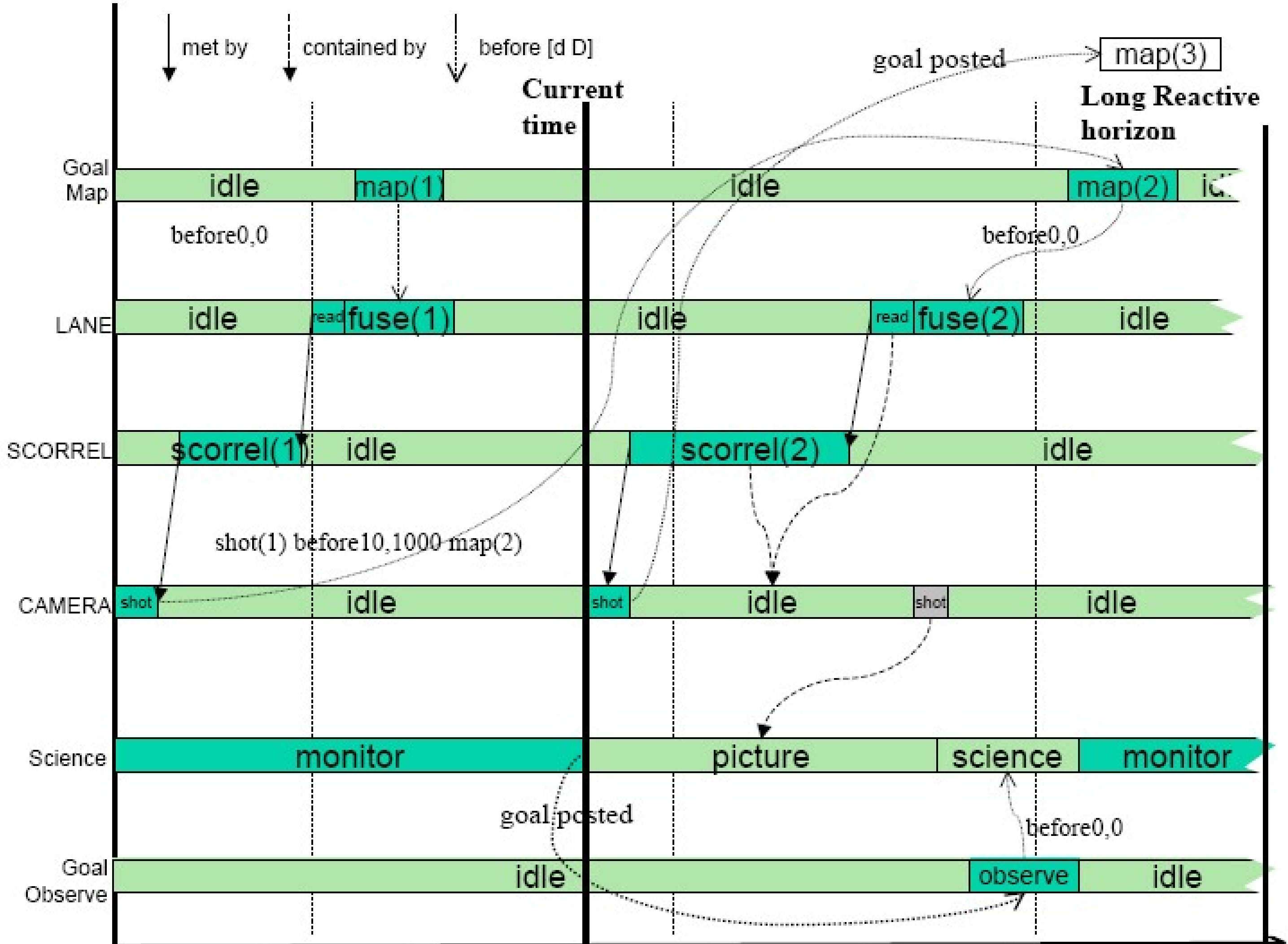
IDEA Architecture

- Attività pianificate e schedulate (plan database):



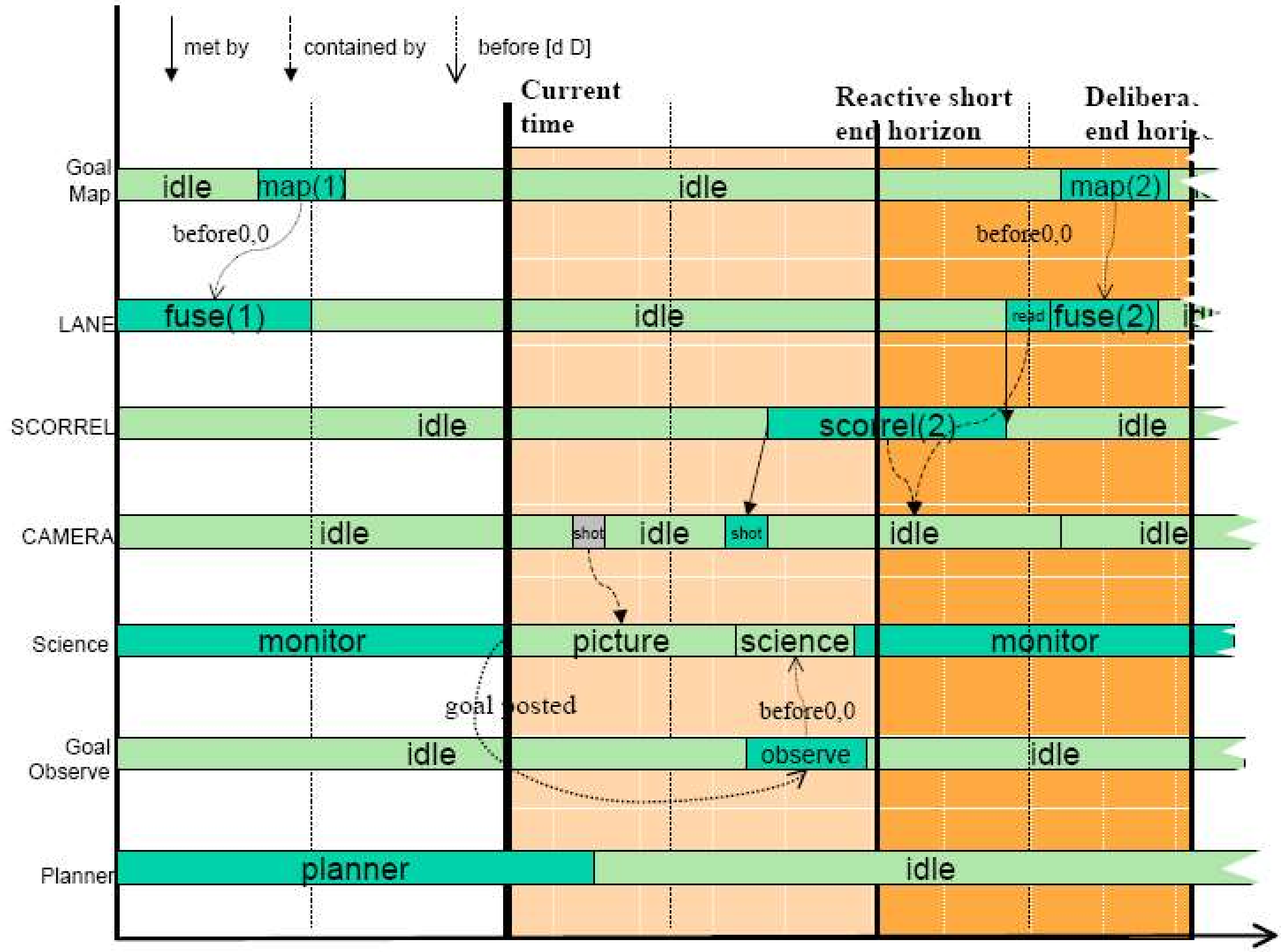
IDEA Architecture

- Reactive Planning



IDEA Architecture

- Reactive and Deliberative planning



Task Planners

- Classical planner
  - FF
    - https://fai.cs.uni-saarland.de/hoffmann/ff.html
- Hierarchical Planner
  - SHOP:
    - https://www.cs.umd.edu/projects/shop/
  - PANDA:
    - https://www.uniulm.de/en/in/ki/research/software/panda/
- Temporal Planner
  - EUROPA
    - https://github.com/nasa/europa
  - OPTIC
    - https://github.com/nasa/europa
- Collectors
  - ROSPLAN
    - https://kcl-planning.github.io/ROSPlan/documentation/

Planning Problems

- Path and Motion planning
  - Map/Configuration space
    - Methods: A*, PRM, RRT, etc.
    - Solution: path/trajectory
- Decision Theory Planning
  - Markovian Models
    - Methods: MDPs, POMDPs solvers (e.g., Dynamic Programming)
    - Solution: Policy
- Reinforcement Learning
  - Markovian Models
    - Methods: SARSA, Qlearning, etc.
    - Solution: Policy
- Task Planning (and Scheduling)
  - Planning Domains (symbolic representations)
    - Methods: Classical Planning, POP, HTNs, Temporal Planning, etc.
    - Solutions: sequence of actions, partial order plans, flexible plans, etc.