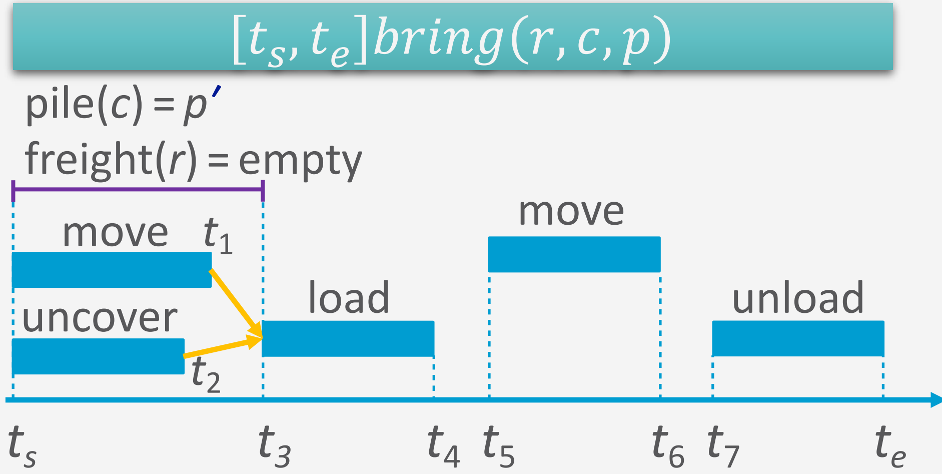
Automated Planning and Acting

Temporal Models



Tanya Braun

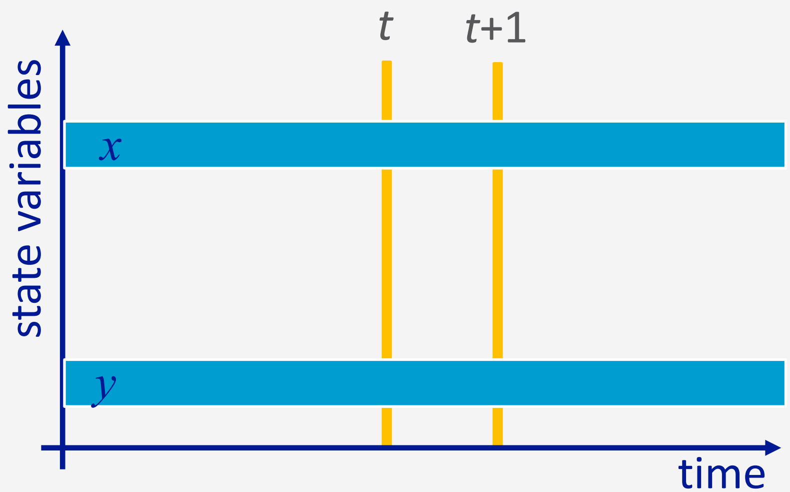
Content

Temporal Models

- Durations of actions
- Delayed effects and preconditions
  - E.g., resources borrowed or consumed during an action
- Time constraints on goals
  - Relative or absolute
- Exogenous events expected to occur in the future
  - When?
- Maintenance actions:
  - Maintain a property (≠ changing a value)
  - E.g., track a moving target, keep a spring latch in position
- Concurrent actions
  - Interacting effects, joint effects
- Delayed commitment
  - Instantiation at acting time

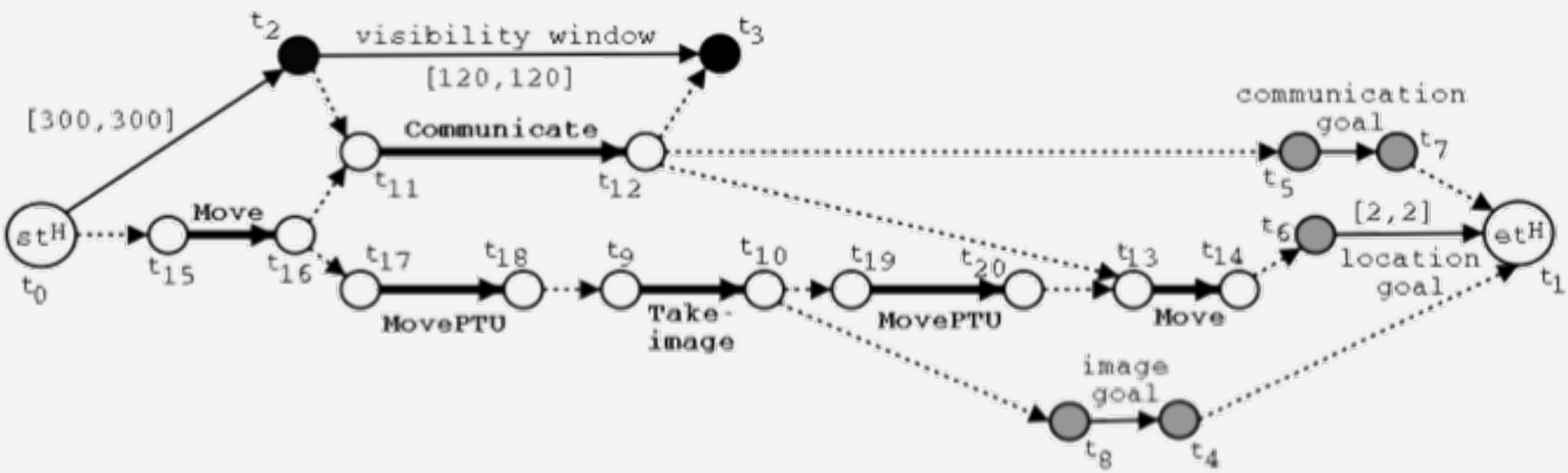
Timelines

- Up to now, “state-oriented view”
  - Time is a sequence of states s_0, s_1, s_2
  - Instantaneous actions transform each state into the next one
  - No overlapping actions
- Switch to a “time-oriented view”
  - Sequence of integer time points
    - $t = 1, 2, 3, \ldots$
  - For each state variable x, a timeline
    - Values during different time intervals
  - State at time $t = \{\text{state}-\text{variable values at time } t\}$



Timelines

- Sets of constraints on state variables and events
  - Reflect predicted actions and events
- Planning is constraint-based



Outline per the Book

4.2 Representation
- Timelines
- Actions and tasks
- Chronicles

4.3 Temporal Planning
- Resolvers and flaws
- Search space

4.4 Constraint Management
- Consistency of object constraints and time constraints
- Controlling the actions when we do not know how long they will take

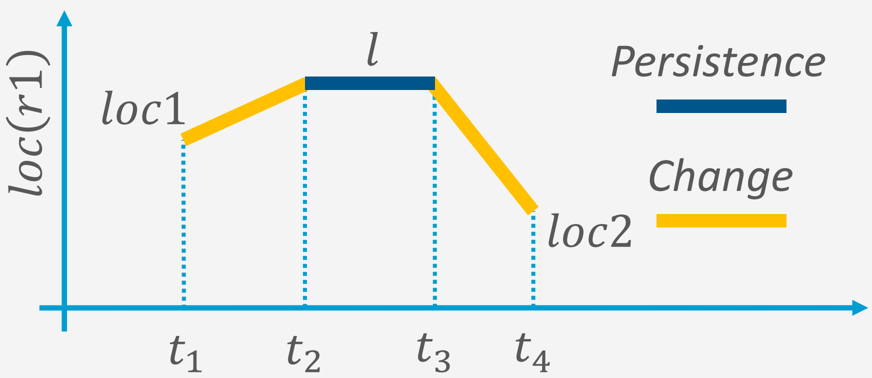
4.5 Acting with Temporal Models
- Acting with atemporal refinement
- Dispatching
- Observation actions

Representation

- Quantitative model of time
  - Discrete: time points are integers
- Expressions:
  - time-point variables
    - $t, \; t', \; t_2, \; t_j, \; \ldots$
  - simple constraints
    - $d \leq t' - t \leq d'$
- Temporal assertion:
  - Value of a state variable during a time interval
  - Persistence: $[t_1, t_2]x = v$ entails $t_1 < t_2$
  - Change: $[t_1, t_2]x : (v_1, v_2)$ entails $v_1 \neq v_2$

Timeline

- Timeline: pair $(\mathcal{T}, \mathcal{C})$, partially predicted evolution of one state variable
  - $\mathcal{T}$: temporal assertions
    - $[t_1, t_2]loc(r1) : (loc1, l)$
    - $[t_2, t_3]loc(r1) = l$
    - $[t_3, t_4]loc(r1) : (l, loc2)$
  - $\mathcal{C}$: constraints
    - $t_1 < t_2 < t_3 < t_4$
    - $l \neq loc1$
    - $l \neq loc2$
    - If we want to restrict $loc(r1)$ during $[t_1, t_2]$
      - $[t_1, t_1 + 1]loc(r1) : (loc1, route)$
      - $[t_2 - 1, t_2]loc(r1) : (route, l)$
      - $[t_1 + 1, t_2 - 1]loc(r1) = route$



- Instance of $(\mathcal{T}, \mathcal{C})$ = temporal and object variables instantiated
- An instance is consistent if it satisfies all constraints in $\mathcal{C}$ and does not specify two different values for a state variable at the same time
- A timeline is secure if its set of consistent instances is not empty

Actions

- Preliminaries:
  - Timelines $(\mathcal{T}_1, \mathcal{C}_1), \ldots, (\mathcal{T}_k, \mathcal{C}_k)$ for k different state variables
  - Their union:
    - $(\mathcal{T}_1, \mathcal{C}_1) \cup \cdots \cup (\mathcal{T}_k, \mathcal{C}_k) = (\mathcal{T}_1 \cup \cdots \cup \mathcal{T}_k, \mathcal{C}_1 \cup \cdots \cup \mathcal{C}_k)$
  - If
    - every $(\mathcal{T}_i, \mathcal{C}_i)$ is secure, and
    - no pair of timelines $(\mathcal{T}_i, \mathcal{C}_i)$ and $(\mathcal{T}_j, \mathcal{C}_j)$ has any unground variables in common
  - then
    - $(\mathcal{T}_1 \cup \cdots \cup \mathcal{T}_k, \mathcal{C}_1 \cup \cdots \cup \mathcal{C}_k)$ is also secure
- Action or primitive task (or just *primitive*):
  - a triple $(head, \mathcal{T}, \mathcal{C})$
    - $head$ is the name and arguments
    - $(\mathcal{T}, \mathcal{C})$ is the union of a set of timelines

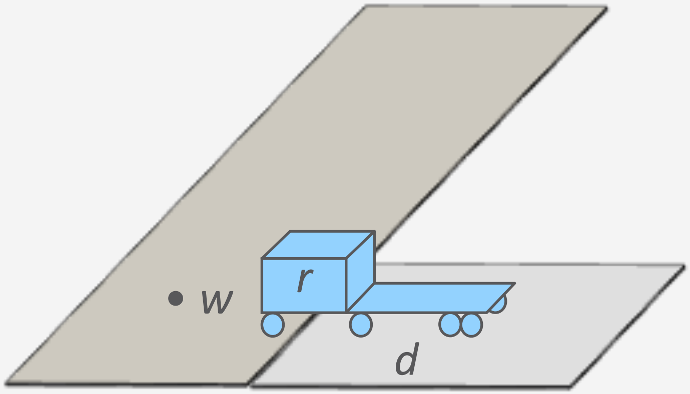
Actions

- $leave(r, d, w)$
  - Robot r leaves dock d, goes to adjacent waypoint w

leave(r,d,w)
  assertions:
    $[t_s,t_e]$ loc(r): (d,w)
    $[t_s,t_e]$ occupant(d): (r,empty)
  constraints:
    $t_e \leq t_s + \delta_1$
    adj(d,w)

- $loc(r)$ changes to w with delay $\leq \delta_1$
- Dock d becomes empty

- Two additional parameters
  - Starting time t_s
  - Ending time t_e
- No separate preconditions and effects
  - Preconditions ⇔ need for causal support



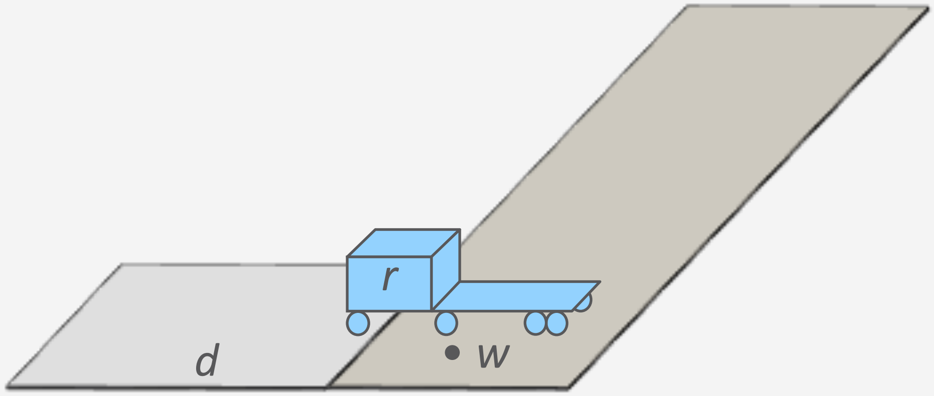
Actions

- $enter(r, d, w)$
  - r enters d from an adjacent waypoint w

```
enter(r,d,w)
    assertions:
        [ts,te] loc(r): (w,d)
        [ts,te] occupant(d): (empty,r)
    constraints:
        te ≤ ts + δ2
        adj(d,w)
```

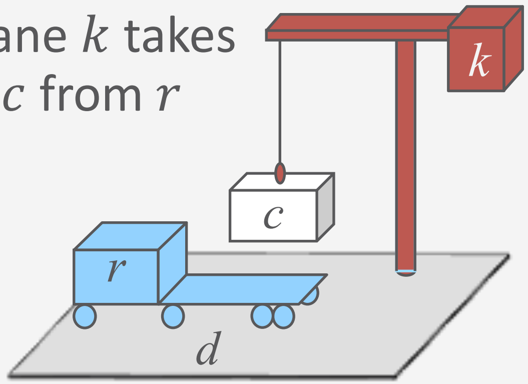
- $loc(r)$ changes to d with delay $\leq \delta_2$
- Dock d becomes occupied by r

- Two additional parameters
  - Starting time t_s
  - Ending time t_e
- No separate preconditions and effects
  - Preconditions ⇔ need for causal support



Actions

- $take(k, c, r, d)$
  - Action: crane k takes container c from r on dock d



- Two additional parameters
  - Starting time t_s
  - Ending time t_e
- No separate preconditions and effects
  - Preconditions ⇔ need for causal support

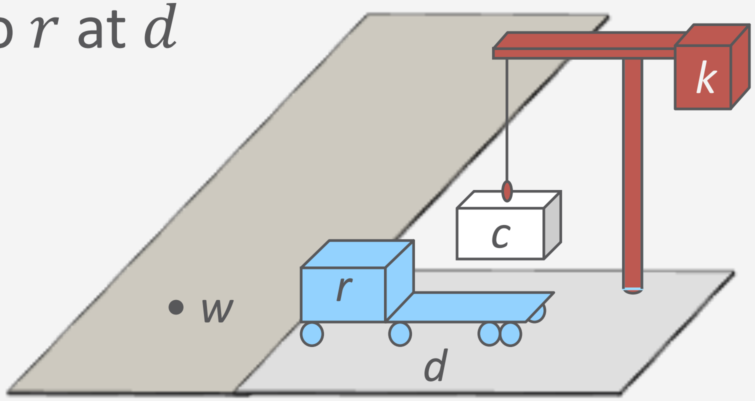
book omits *d*

take(*k*,*c*,*r*,*d*)
  assertions:
    [t_s,t_e] pos(*c*): (*r*, *k*) // where container *c* is
    [t_s,t_e] grip(*k*): (empty, *c*) // what crane *k*'s gripper is holding
    [t_s,t_e] freight(*r*): (*c*,empty) // what *r* is carrying
    [t_s,t_e] loc(*r*) = *d* // where *r* is
  constraints:
    attached(*k*,*d*)

Actions

- $leave(r, d, w)$ — robot r leaves dock d to an adjacent waypoint w
- $enter(r, d, w)$ — r enters d from an adjacent w
- $take(k, c, r, d)$ — crane k takes cont. c from r at d
- $navigate(r, w, w')$ — r navigates from w to w'
- $stack(k, c, p)$ — k stacks c on top of pile p
- $unstack(k, c, p)$ — k takes c from top of p
- $put(k, c, r, d)$ — k puts c onto r at d

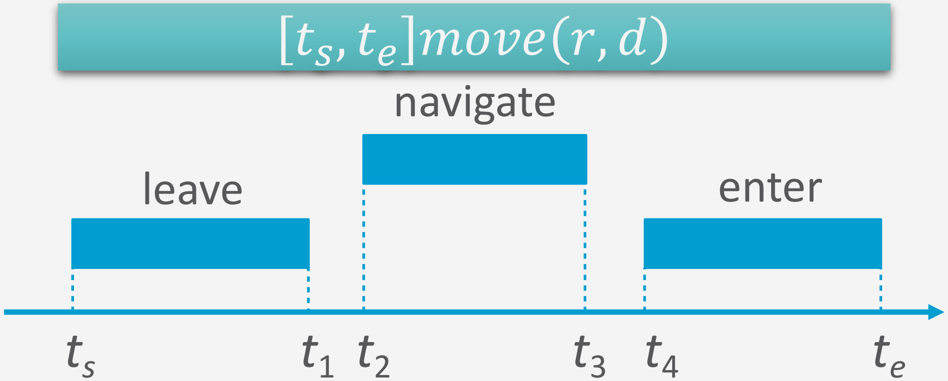
book omits *d*



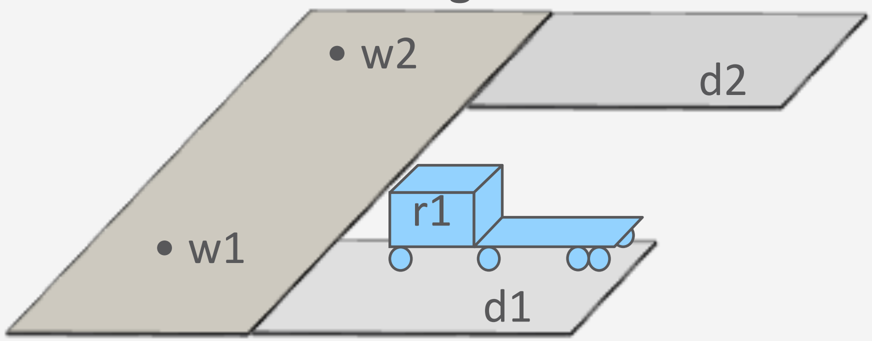
Tasks and Methods

- Task: move robot *r* to dock *d*
  - $[t_s, t_e] move(r, d)$
- Method:

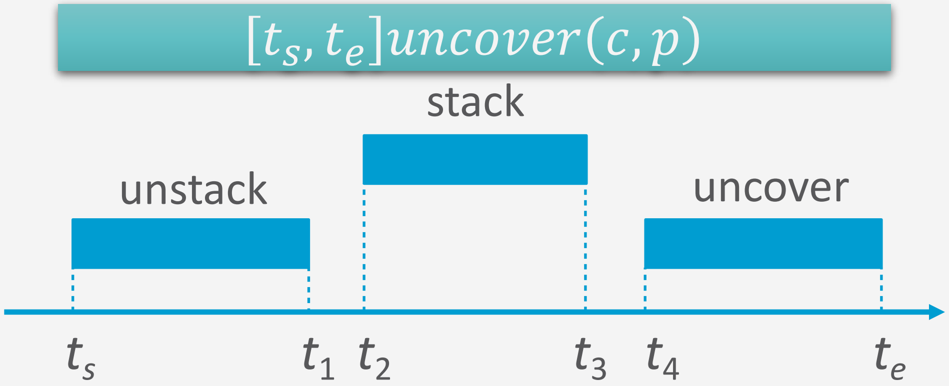
m-move1(*r*,*d*,*d′*,*w*,*w′*)
    task: move(*r*,*d*)
    refinement:
        $[t_s, t_1]$ leave(*r*,*d′*,*w′*)
        $[t_2, t_3]$ navigate(*r*,*w′*,*w*)
        $[t_4, t_e]$ enter(*r*,*d*,*w*)
    assertions:
        $[t_s, t_s+1]$ loc(*r*) = *d′*
    constraints:
        adj(*d*,*w*),
        adj(*d′*,*w′*), *d* ≠ *d′*,
        connected(*w*,*w′*),
        $t_1 \le t_2$, $t_3 \le t_4$



- d' becomes empty during $[t_s, t_1]$
  - another robot may enter it after t_1
- d doesn't need to be empty until t_4
  - when r starts entering it

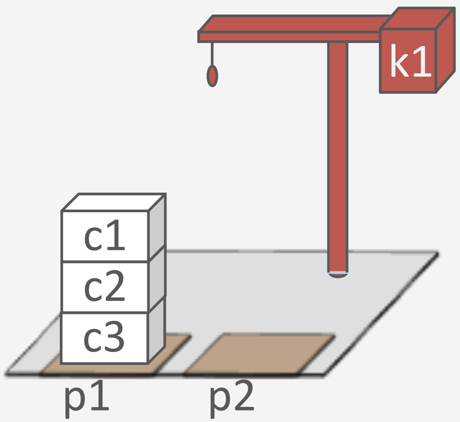


Tasks and Methods



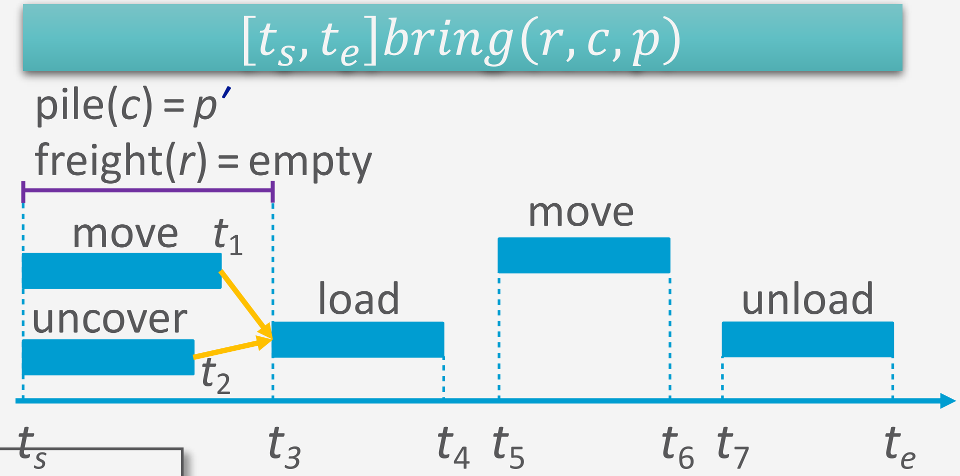
- Task: remove everything above container c in pile p
  - $[t_s, t_e]uncover(c, p)$
- Method:

m-uncover(*c*,*p*,*k*,*d*,*p'*)
task: uncover(*c*,*p*)
refinement: $[t_s,t_1]$ unstack(*k*,*c'*,*p*) // action
$[t_2,t_3]$ stack(*k*,*c'*,*p'*) // action
$[t_4,t_e]$ uncover(*c*,*p*) // recursive uncover
assertions: $[t_s,t_s+1]$ pile(*c*) = *p*
$[t_s,t_s+1]$ top(*p*) = *c'*
$[t_s, t_s+1]$ grip(*k*) = empty
constraints: attached(*k*,*d*), attached(*p*,*d*),
attached(*p'*,*d*),
$p \neq p'$, $c' \neq c$,
$t_1 \leq t_2$, $t_3 \leq t_4$



Tasks and Methods

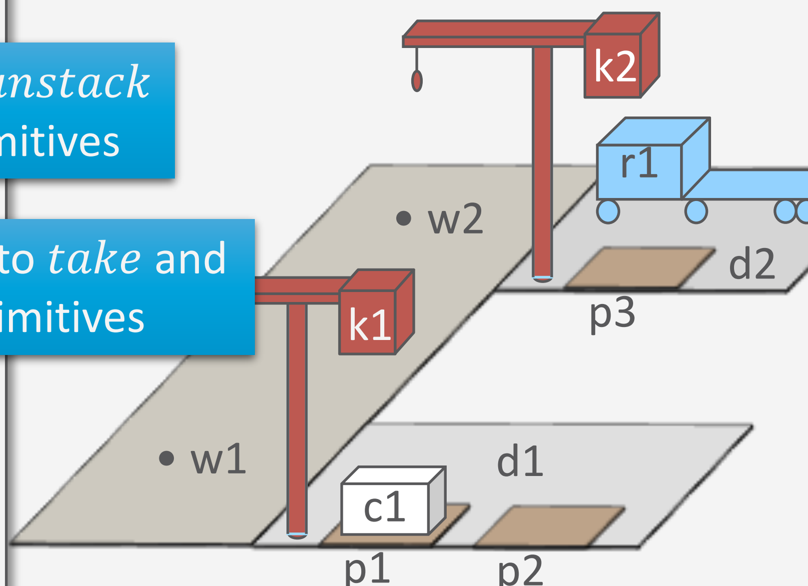
- Task: robot r brings container c to pile p
  - $[t_s, t_e]bring(r, c, p)$
- Method:



m-bring(r,c,p,p',d,d')
task: bring(r,c,p)
refinement: $[t_s,t_1]$ move(r,d')
$[t_s,t_2]$ uncover(c,p')
$[t_3,t_4]$ load(k',r,c,p')
$[t_5,t_6]$ move(r,d)
$[t_7,t_e]$ unload(k,r,c,p)
assertions: $[t_s,t_3]$ pile(c) = p'
$[t_s,t_3]$ freight(r) = empty
constraints: attached(p',d'), attached(p,d), $d \neq d'$
attached(k',d'), attached(k,d), $k \neq k'$
$t_1 \leq t_3$, $t_2 \leq t_3$, $t_4 \leq t_5$, $t_6 \leq t_7$

Refine into *unstack* and *put* primitives

Refine into *take* and *stack* primitives



Chronicles: Unions of Timelines

- Chronicle $\phi = (\mathcal{A}, \mathcal{S}, \mathcal{T}, \mathcal{C})$
  - $\mathcal{A}$: temporally qualified actions and tasks
  - $\mathcal{S}$: *a priori* supported assertions
  - $\mathcal{T}$: temporally qualified assertions
  - $\mathcal{C}$: constraints
- ϕ can include
  - Current state, future predicted events
  - Tasks to perform
  - Assertions and constraints to satisfy
- Can represent
  - Planning problem
  - Plan or partial plan

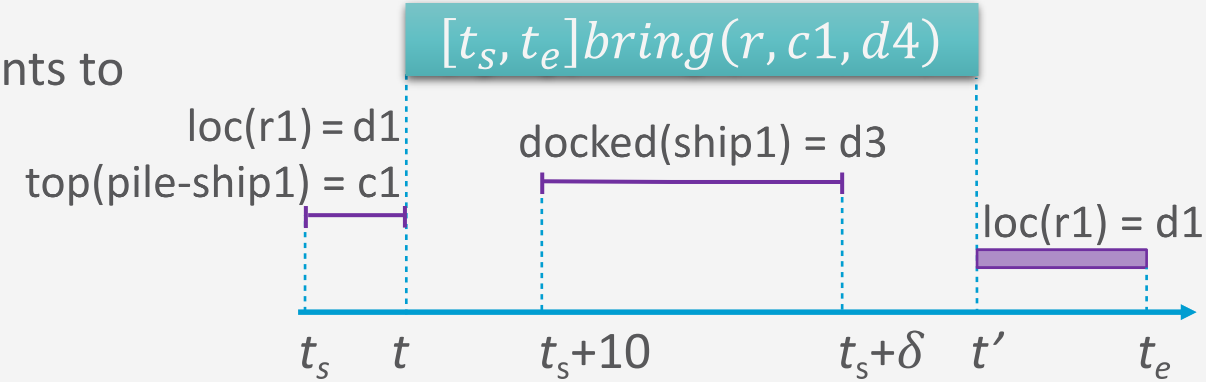
ϕ_0:

tasks: $[t,t']$ bring(r,c1,d4)

supported: $[t_s]$ loc(r1)=d1
$[t_s]$ loc(r2)=d2
$[t_s+10, t_s+\delta]$ docked(ship1)=d3
$[t_s]$ top(pile-ship1)=c1
$[t_s]$ pos(c1)=pallet

assertions: $[t_e]$ loc(r1)=d1
$[t_e]$ loc(r2)=d2

constraints: $t_s = 0 < t < t' < t_e$, $20 \leq \delta \leq 30$



Intermediate Summary

- Timelines
  - Temporal assertions (change, persistence), constraints
  - Conflicts, consistency, security, causal support
- Chronicle: union of several timelines
  - Consistency, security, causal support
- Actions represented by chronicles
  - No separate preconditions and effects
    - Preconditions $\Leftrightarrow$ need for causal support

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4.5 Acting with Temporal Models
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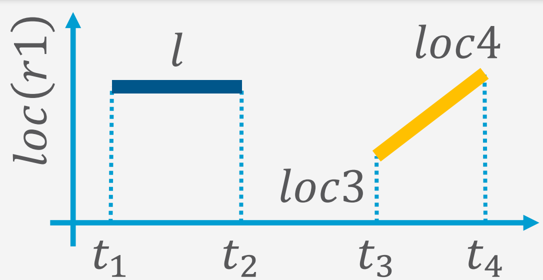
Planning

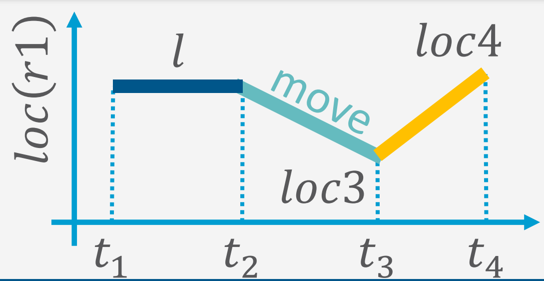
- Planning problem:
  - Chronicle ϕ_0 that has some flaws
    - Analogous to flaws in PSP

ϕ_0: tasks: *(none)*	
supported: *(none)*	
assertions:	$[t_1,t_2]$ loc(r1) = l
	$[t_3,t_4]$ loc(r1) : (loc3,loc4)
constraints:	adj(loc3,w1)
	adj(w1,loc3)
	adj(loc4,w2)
	adj(w2,loc4)
	connected(w1,w2)



- Add new assertions, constraints, actions to resolve the flaws

ϕ_0: tasks: $[t_2,t_3]$ move(r1,loc3)	
supported: *(none)*	
assertions:	$[t_1,t_2]$ loc(r1) = l
	$[t_3,t_4]$ loc(r1) : (loc3,loc4)
constraints:	adj(loc3,w1)
	adj(w1,loc3)
	adj(loc4,w2)
	adj(w2,loc4)
	connected(w1,w2)

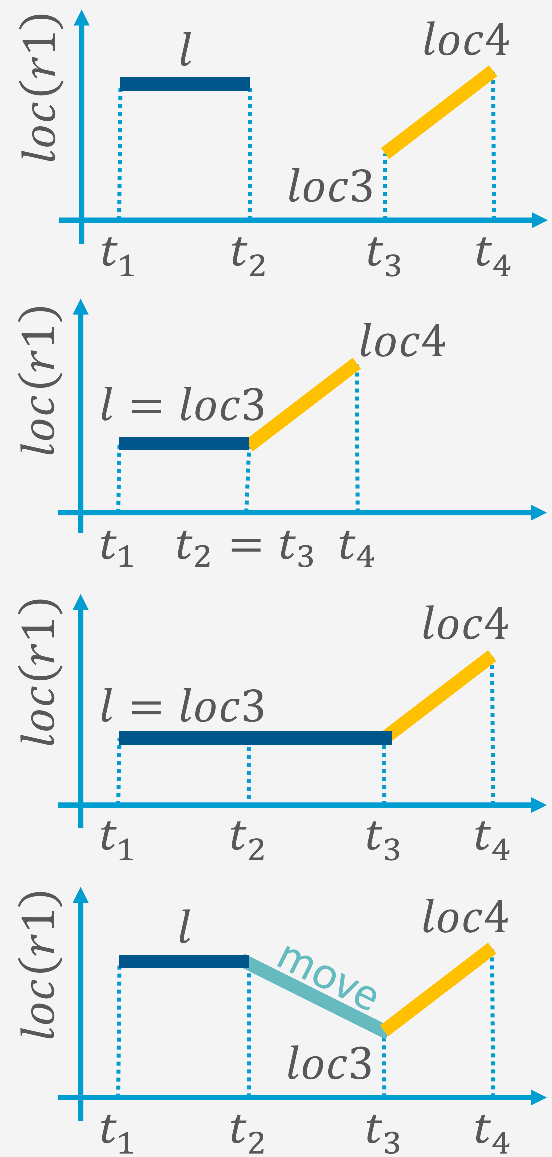


Flaws (1)

Like an open goal in PSP

1. Temporal assertion α that is not *causally supported*
    - What causes $r1$ to be at $loc3$ at time t_3?

- *Resolvers*:
    - Add constraints to support α from an assertion in ϕ
        - $l = loc3,\ t_2 = t_3$
    - Add a new persistence assertion to support α
        - $l = loc3, [t_2, t_3]loc(r1) = loc3$
    - Add a new task or action to support α
        - $[t_2, t_3]move(r1, loc3)$
            - Refining it will produce support for α

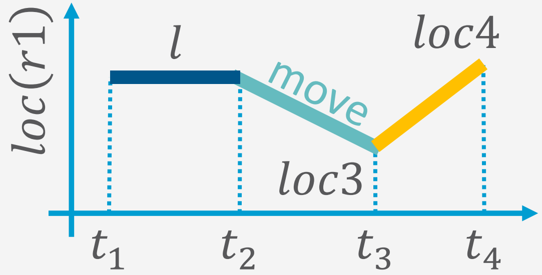


Flaws (2)

Like a task in SeRPE

2. Non-refined task

- *Resolver*: refinement method m
  - Applicable if it matches the task and its constraints are consistent with ϕ's
- Applying the resolver:
  - Modify ϕ by replacing the task with m
- Example: $[t_2, t_3]move(r1, loc3)$
  - Refinement will replace it with something like
    - $[t_2, t_5]leave(r1, l, w)$
    - $[t_5, t_6]navigate(r1, w, w')$
    - $[t_6, t_3]enter(r1, loc3, w')$
    - plus constraints

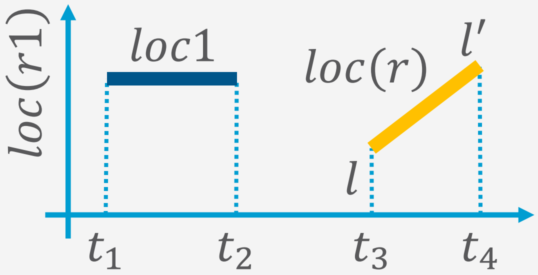


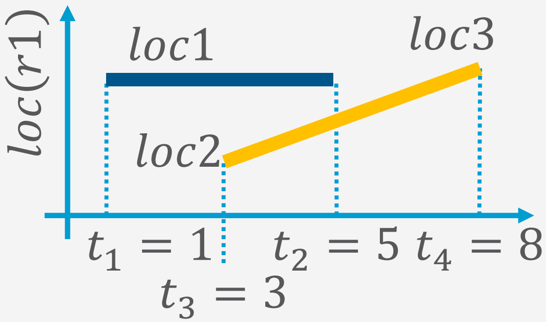
Flaws (3)

Like a threat in PSP

3. A pair of possibly-conflicting temporal assertions
   - Temporal assertions α and β possibly conflict if they can have inconsistent instances
   - Example
     - $[t_1, t_2]loc(r1) = loc1,\ [t_3, t_4]loc(r) : (l, l')$

       ↓ ↓ ↓ ↓ ↓ ↓ ↘
     - $[1, 5]loc(r1) = loc1,\quad [3, 8]loc(r1) : (loc2, loc3)$





- *Resolvers*: separation constraints
  - $r \neq r1$
  - $t_2 < t_3$
  - $t_4 < t_1$
  - $t_2 = t_3, r = r1, l = loc1$
    - Also provides causal support for $[t_3, t_4]loc(r) :\ (l, l')$
  - $t_4 = t_1, r = r1, l' = loc1$
    - Also provides causal support for $[t_1, t_2]loc(r1) = loc1$

Planning Algorithm

- Like PSP
  - Repeatedly selects flaws and chooses resolvers
- If resolving all flaws possible, at least one nondeterministic execution trace will do so
- In a deterministic implementation
  - Selecting a resolver ρ is a backtracking point
  - Selecting a flaw is not
  - (As in PSP)

```
TemPlan(ϕ)          // recursive version (book)
    Flaws ← set of flaws of ϕ
    if Flaws = ∅ then
        return ϕ
    arbitrarily select f ∈ Flaws
    Resolvers ← set of resolvers of f
    if Resolvers = ∅ then
        return failure
    nondeterministically choose ρ ∈ Resolvers
    ϕ ← Transform(ϕ, ρ)
    TemPlan(ϕ,Σ)
```

```
TemPlan(ϕ)          // iterative version
    loop
        Flaws ← set of flaws of ϕ
        if Flaws = ∅ then
            return ϕ
        arbitrarily select f ∈ Flaws
        Resolvers ← set of resolvers of f
        if Resolvers = ∅ then
            return failure
        nondeterministically choose ρ ∈ Resolvers
        ϕ ← Transform(ϕ, ρ)
```

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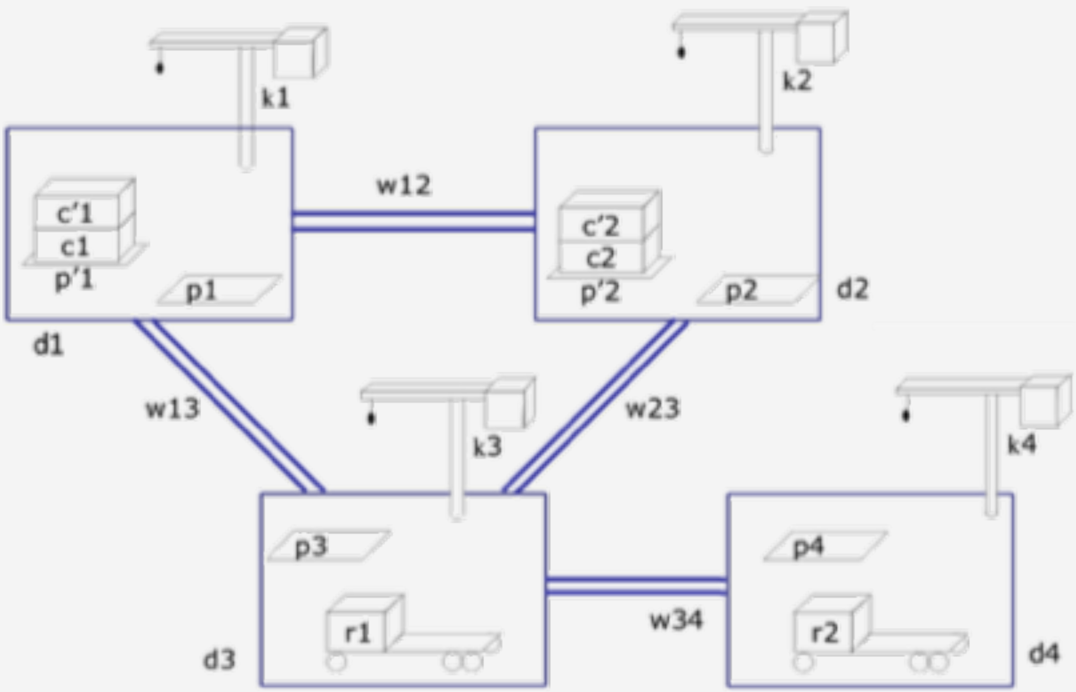
Example

- $\phi = (\mathcal{A}, \mathcal{S}, \mathcal{T}, \mathcal{C})$
  - Establishes state-variable values at time $t = 0$
  - Flaws: two unrefined tasks
    - bring(r,c1,p3), bring(r',c2,p4)



ϕ_0: tasks: bring(r,c1,p3)
bring(r',c2,p4)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p′1
[0] pile(c′1)=p′1
[0] pos(c1)=pallet
[0] pos(c′1)=c1
. . .

assertions: *(none)*

constraints:
adj(d1,w12)
adj(d1,w13)
. . .

Example

- Flaws: two unrefined tasks
  - bring(r,c1,p3), bring(r',c2,p4)
- Refinement for both:

m-bring(r,c,p,p',d,d',k,k')

task: bring(r,c,p)

refinement: $[t_s,t_1]$ move(r,d')
$[t_s,t_2]$ uncover(c,p')
$[t_3,t_4]$ load(k',r,c,p')
$[t_5,t_6]$ move(r,d)
$[t_7,t_e]$ unload(k,r,c,p)

assertions: $[t_s,t_3]$ pile(c) = p'
$[t_s,t_3]$ freight(r) = empty

constraints: attached(p',d'),
attached(p,d), $d \neq d'$
attached(k',d'),
attached(k,d), $k \neq k'$
$t_1 \leq t_3,\ t_2 \leq t_3,\ t_4 \leq t_5,\ t_6 \leq t_7$

ϕ_0: tasks: bring(r,c1,p3)
bring(r',c2,p4)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p'1
[0] pile(c'1)=p'1
[0] pos(c1)=pallet
[0] pos(c'1)=c1

)

1,w12)
1,w13)
. . .

Method Instance

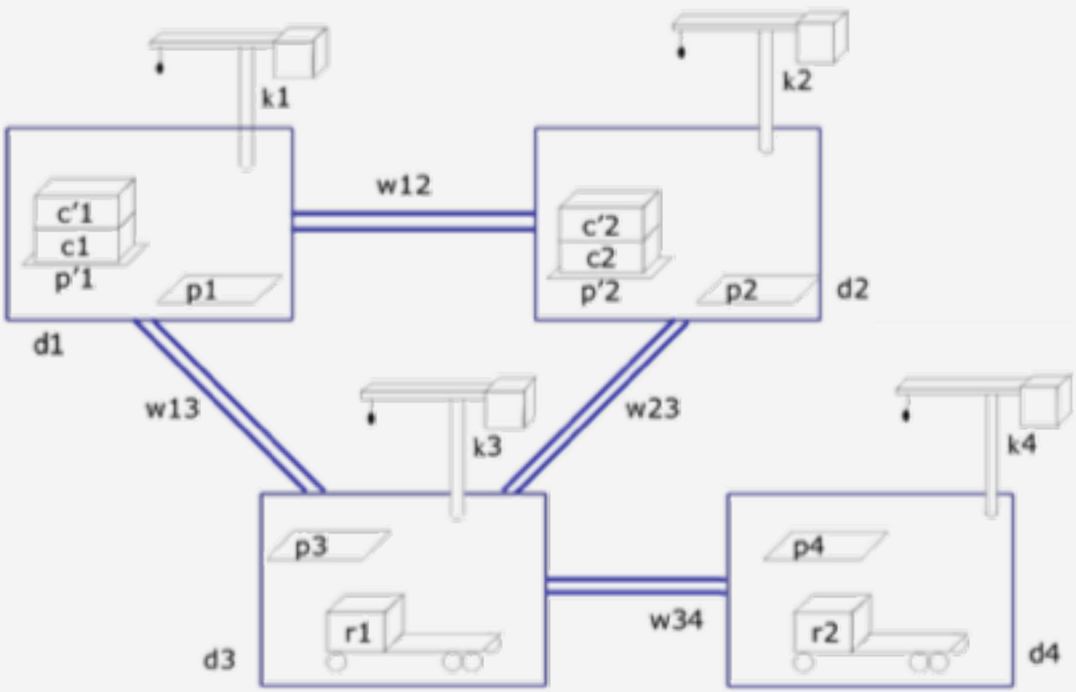
- Instantiate $c = c1$ and $p = p3$ to match $bring(r, c1, p3)$
  - p', d, d', k, k' instantiated to match book
  - Needed later to satisfy action preconditions

ϕ_0: tasks: bring(r,c1,p3)
bring(r',c2,p4)
supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p′1
[0] pile(c′1)=p′1
[0] pos(c1)=pallet
[0] pos(c′1)=c1
e)
1,w12)
1,w13)
. . .

m-bring(r,c1,p3,p′1,d3,d1,k3,k1)
task: bring(r,c1,p3)
refinement: [t_s,t_1] move(r,d1)
[t_s,t_2] uncover(c1,p′1)
[t_3,t_4] load(k1,r,c1,p′1)
[t_5,t_6] move(r, d3)
[t_7,t_e] unload(k3,r,c1,p3)
assertions: [t_s,t_3] pile(c1) = p′1
[t_s,t_3] freight(r) = empty
constraints: attached(p′1,d1),
attached(p3,d3), d3 ≠ d1
attached(k1,d1),
attached(k3,d3), k3 ≠ k1
$t_1 \leq t_3$, $t_2 \leq t_3$, $t_4 \leq t_5$, $t_6 \leq t_7$

Modified Chronicle

- Changes to ϕ_0
  - Removed $bring(r, c1, p3)$
  - Added 5 tasks, 2 assertions, 10 constraints
- Flaws
  - 6 unrefined tasks, 2 unsupported assertions



ϕ_1: tasks: $[t_s,t_1]$ move(r,d1)
$[t_s,t_2]$ uncover(c1,p'1)
$[t_3,t_4]$ load(k1,r,c1,p'1)
$[t_5,t_6]$ move(r,d3)
$[t_7,t_e]$ unload(k3,r,c1,p3)
bring(r',c2,p4)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p'1
[0] pile(c'1)=p'1
[0] pos(c1)=pallet
[0] pos(c'1)=c1
. . .

assertions: $[t_s,t_3]$ pile(c1) = p'1
$[t_s,t_3]$ freight(r) = empty

constraints: $t_s{<}t_1{\le}t_3$, $t_s{<}t_2{\le}t_3$, $t_4{\le}t_5$, $t_6{\le}t_7$,
adj(d1,w12),
adj(d1,w13),
. . .

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Method Instance

- Instantiate $r = r', c = c2, p = p4$ to match $bring(r', c2, p4)$
  - p', d, d', k, k' instantiated to match book again

ϕ_1: tasks: $[t_s,t_1]$ move(r,d1)
$[t_s,t_2]$ uncover(c1,p′1)
$[t_3,t_4]$ load(k1,r,c1,p′1)
$[t_5,t_6]$ move(r,d3)
$[t_7,t_e]$ unload(k3,r,c1,p3)
bring($r′$,c2,p4)
supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p′1
(c′1)=p′1
(c1)=pallet
(c′1)=c1
ile(c1) = p′1
eight(r) = empty
t_3, $t_s<t_2\leq t_3$, $t_4\leq t_5$, $t_6\leq t_7$,
w12),
w13),
. . .

m-bring($r′$,c2,p4,p′2,d4,d2,k4,k2)
task: bring($r′$,c2,p4)
refinement: $[t_s,t_1]$ move($r′$,d2)
$[t_s,t_2]$ uncover(c2,p′2)
$[t_3,t_4]$ load(k2,$r′$,c2,p′2)
$[t_5,t_6]$ move($r′$, d4)
$[t_7,t_e]$ unload(k4,$r′$,c2,p4)
assertions: $[t_s,t_3]$ pile(c2) = p′2
$[t_s,t_3]$ freight($r′$) = empty
constraints: attached(p′2,d2),
attached(p4,d4), d4 ≠ d2
attached(k2,d2),
attached(k4,d4), k4 ≠ k2
$t_1 \leq t_3$, $t_2 \leq t_3$, $t_4 \leq t_5$, $t_6 \leq t_7$

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Modified Chronicle

- Changes
  - Removed $bring(r', c2, p4)$
  - Added 5 tasks, 2 assertions, 10 constraints
- Flaws
  - 10 unrefined tasks, 4 unsupported assertions
- Next, work on these two assertions

ϕ_2: tasks: $[t_s,t_1]$ move(r,d1)
$[t_s,t_2]$ uncover(c1,p'1)
$[t_3,t_4]$ load(k1,r,c1,p'1)
$[t_5,t_6]$ move(r,d3)
$[t_7,t_e]$ unload(k3,r,c1,p3)
$[t'_s,t'_1]$ move(r',d2)
$[t'_s,t'_2]$ uncover(c2,p'2)
$[t'_3,t'_4]$ load(k4,r',c2,p'2)
$[t'_5,t'_6]$ move(r',d4)
$[t'_7,t'_e]$ unload(k2,r',c2,p'2)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p'1
. . .

assertions: $[t_s,t_3]$ pile(c1) = p'1
$[t_s,t_3]$ freight(r) = empty
$[t'_s,t'_3]$ pile(c2) = p'2
$[t'_s,t'_1]$ freight(r') = empty

constraints: $t_s<t_1\leq t_3$, $t_s<t_2\leq t_3$, $t_4\leq t_5$, $t_6\leq t_7$,
$t'_s<t'_1\leq t'_3$, $t'_s<t'_2\leq t'_3$, $t'_4\leq t'_5$, $t'_6\leq t'_7$,
adj(d1,w12),
adj(d1,w13), . . .

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Supporting the Assertions

- 3 ways to support

$$[t_s, t_3]pile(c1) = p'1$$

1. $\boxed{\text{Constrain } t_s = 0}$, use $[0]pile(c1) = p'1$
2. Add persistence $[0, t_s]pile(c1) = p'1$
3. Add new action $[t_8, t_s]stack(k1, c1, p'1)$

Will any of them also provide support for $[t_s, t_3]$ freight(r) = empty ?

ϕ_2: tasks: $[t_s, t_1]$ move(r,d1)
$[t_s, t_2]$ uncover(c1,p′1)
$[t_3, t_4]$ load(k1,r,c1,p′1)
$[t_5, t_6]$ move(r,d3)
$[t_7, t_e]$ unload(k3,r,c1,p3)
$[t'_s, t'_1]$ move(r',d2)
$[t'_s, t'_2]$ uncover(c2,p′2)
$[t'_3, t'_4]$ load(k4,r',c2,p′2)
$[t'_5, t'_6]$ move(r',d4)
$[t'_7, t'_e]$ unload(k2,r',c2,p′2)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p′1
. . .

assertions: $[t_s, t_3]$ pile(c1) = p′1
$[t_s, t_3]$ freight(r) = empty
$[t'_s, t'_3]$ pile(c2) = p′2
$[t'_s, t'_1]$ freight(r') = empty

constraints: $t_s < t_1 \le t_3$, $t_s < t_2 \le t_3$, $t_4 \le t_5$, $t_6 \le t_7$,
$t'_s < t'_1 \le t'_3$, $t'_s < t'_2 \le t'_3$, $t'_4 \le t'_5$, $t'_6 \le t'_7$,
adj(d1,w12),
adj(d1,w13), . . .

Supporting the Assertions

- 3 ways to support

$$[t_s, t_3]pile(c1) = p'1$$

1. $\boxed{\text{Constrain } t_s = 0}$, use $[0]pile(c1) = p'1$

- To support

$$[0, t_3]freight(r) = empty$$

1. $\boxed{\text{Constrain } r = r1}$, use $[0]freight(r1) = empty$

ϕ_2: tasks: $[\boxed{0}, t_1]$ move(r,d1)
$[\boxed{0}, t_2]$ uncover(c1,p'1)
$[t_3, t_4]$ load(k1,r,c1,p'1)
$[t_5, t_6]$ move(r,d3)
$[t_7, t_e]$ unload(k3,r,c1,p3)
$[t'_s, t'_1]$ move(r',d2)
$[t'_s, t'_2]$ uncover(c2,p'2)
$[t'_3, t'_4]$ load(k4,r',c2,p'2)
$[t'_5, t'_6]$ move(r',d4)
$[t'_7, t'_e]$ unload(k2,r',c2,p'2)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p'1
. . .

assertions: $[\boxed{0}, t_3]$ pile(c1) = p'1
$[\boxed{0}, t_3]$ freight(r) = empty
$[t'_s, t'_3]$ pile(c2) = p'2
$[t'_s, t'_1]$ freight(r') = empty

constraints: $\boxed{0} < t_1 \leq t_3$, $\boxed{0} < t_2 \leq t_3$, $t_4 \leq t_5$, $t_6 \leq t_7$,
$t'_s < t'_1 \leq t'_3$, $t'_s < t'_2 \leq t'_3$, $t'_4 \leq t'_5$, $t'_6 \leq t'_7$,
adj(d1,w12),
adj(d1,w13), . . .

Supporting the Assertions

- 3 ways to support

$$[t_s, t_3]pile(c1) = p'1$$

1. Constrain $t_s = 0$,
   use $[0]pile(c1) = p'1$

- To support

$$[0, t_3]freight(r) = empty$$

1. $\boxed{\text{Constrain } r = r1}$,
   use $[0]freight(r1) = empty$

ϕ_2: tasks: $[0,t_1]$ move($\boxed{\text{r1}}$,d1)
$[0,t_2]$ uncover(c1,p'1)
$[t_3,t_4]$ load(k1,$\boxed{\text{r1}}$,c1,p'1)
$[t_5,t_6]$ move($\boxed{\text{r1}}$,d3)
$[t_7,t_e]$ unload(k3,$\boxed{\text{r1}}$,c1,p3)
$[t'_s,t'_1]$ move(r',d2)
$[t'_s,t'_2]$ uncover(c2,p'2)
$[t'_3,t'_4]$ load(k4,r',c2,p'2)
$[t'_5,t'_6]$ move(r',d4)
$[t'_7,t'_e]$ unload(k2,r',c2,p'2)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p'1
. . .
$[0,t_3]$ pile(c1) = p'1
$[0,t_3]$ freight($\boxed{\text{r1}}$) = empty

assertions: $[t'_s,t'_3]$ pile(c2) = p'2
$[t'_s,t'_1]$ freight(r') = empty

constraints: $0<t_1\leq t_3$, $0<t_2\leq t_3$, $t_4\leq t_5$, $t_6\leq t_7$,
$t'_s<t'_1\leq t'_3$, $t'_s<t'_2\leq t'_3$, $t'_4\leq t'_5$, $t'_6\leq t'_7$,
adj(d1,w12),
adj(d1,w13), . . .

Supporting the Assertions

- To support

$$[t'_s, t'_3]pile(c2) = p'2$$

1. Add persistence condition $\boxed{[0, t'_s]pile(c2) = p'2}$
2. Constrain $t'_s = 0$
3. Add new action $stack(k2, c2, p'2)$

ϕ_2: tasks: $[0,t_1]$ move(r1,d1)
$[0,t_2]$ uncover(c1,p'1)
$[t_3,t_4]$ load(k1,r1,c1,p'1)
$[t_5,t_6]$ move(r1,d3)
$[t_7,t_e]$ unload(k3,r1,c1,p3)
$[t'_s,t'_1]$ move(r',d2)
$[t'_s,t'_2]$ uncover(c2,p'2)
$[t'_3,t'_4]$ load(k4,r',c2,p'2)
$[t'_5,t'_6]$ move(r',d4)
$[t'_7,t'_e]$ unload(k2,r',c2,p'2)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p'1
. . .
$[0,t_3]$ pile(c1) = p'1
$[0,t_3]$ freight(r1) = empty

assertions: $[t'_s,t'_3]$ pile(c2) = p'2
$[t'_s,t'_1]$ freight(r') = empty

constraints: $0<t_1\leq t_3$, $0<t_2\leq t_3$, $t_4\leq t_5$, $t_6\leq t_7$,
$t'_s<t'_1\leq t'_3$, $t'_s<t'_2\leq t'_3$, $t'_4\leq t'_5$, $t'_6\leq t'_7$,
adj(d1,w12),
adj(d1,w13), . . .

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Supporting the Assertions

- To support
  $$[t'_s, t'_3]pile(c2) = p'2$$
  1. Add persistence condition $\boxed{[0, t'_s]pile(c2) = p'2}$
- To support
  $$[t'_s, t'_1]freight(r') = empty$$
  1. Constrain $\boxed{r' = r2,}$ add persistence condition $\boxed{[0, t'_s]freight(r2) = empty}$

ϕ_2: tasks: $[0,t_1]$ move(r1,d1)
$[0,t_2]$ uncover(c1,p'1)
$[t_3,t_4]$ load(k1,r1,c1,p'1)
$[t_5,t_6]$ move(r1,d3)
$[t_7,t_e]$ unload(k3,r1,c1,p3)
$[t'_s,t'_1]$ move(r',d2)
$[t'_s,t'_2]$ uncover(c2,p'2)
$[t'_3,t'_4]$ load(k4,r',c2,p'2)
$[t'_5,t'_6]$ move(r',d4)
$[t'_7,t'_e]$ unload(k2,r',c2,p'2)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p'1 . . .
$[0,t_3]$ pile(c1) = p'1
$[0,t_3]$ freight(r1) = empty
$\boxed{[0,t'_s] \text{ pile(c2)=p'2}}$
$[t'_s,t'_3]$ pile(c2) = p'2

assertions: $[t'_s,t'_1]$ freight(r') = empty

constraints: $0<t_1\leq t_3$, $0<t_2\leq t_3$, $t_4\leq t_5$, $t_6\leq t_7$,
$t'_s<t'_1\leq t'_3$, $t'_s<t'_2\leq t'_3$, $t'_4\leq t'_5$, $t'_6\leq t'_7$,
adj(d1,w12),
adj(d1,w13), . . .

Supporting the Assertions

- To support
$$[t'_s, t'_3]pile(c2) = p'2$$
  1. Add persistence condition $[0, t'_s]pile(c2) = p'2$
- To support
$$[t'_s, t'_1]freight(r') = empty$$
  1. Constrain $\boxed{r' = r2,}$ add persistence condition $\boxed{[0, t'_s]freight(r2) = empty}$

- All assertions currently supported
- Remaining flaws: unrefined tasks

ϕ_2: tasks: $[0,t_1]$ move(r1,d1)
$[0,t_2]$ uncover(c1,p'1)
$[t_3,t_4]$ load(k1,r1,c1,p'1)
$[t_5,t_6]$ move(r1,d3)
$[t_7,t_e]$ unload(k3,r1,c1,p3)
$[t'_s,t'_1]$ move($\boxed{r2}$,d2)
$[t'_s,t'_2]$ uncover(c2,p'2)
$[t'_3,t'_4]$ load(k4,$\boxed{r2}$,c2,p'2)
$[t'_5,t'_6]$ move($\boxed{r2}$,d4)
$[t'_7,t'_e]$ unload(k2,$\boxed{r2}$,c2,p'2)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p'1 . . .
$[0,t_3]$ pile(c1) = p'1
$[0,t_3]$ freight(r1) = empty
$[0,t'_s]$ pile(c2)=p'2
$[t'_s,t'_3]$ pile(c2) = p'2
$\boxed{[0,t'_s] \text{ freight(r2)=empty}}$
$[t'_s,t'_1]$ freight($\boxed{r2}$) = empty

assertions: *(none)*

constraints: $0<t_1\le t_3$, $0<t_2\le t_3$, $t_4\le t_5$, $t_6\le t_7$,
$t'_s<t'_1\le t'_3$, $t'_s<t'_2\le t'_3$, $t'_4\le t'_5$, $t'_6\le t'_7$,
adj(d1,w12),adj(d1,w13), . . .

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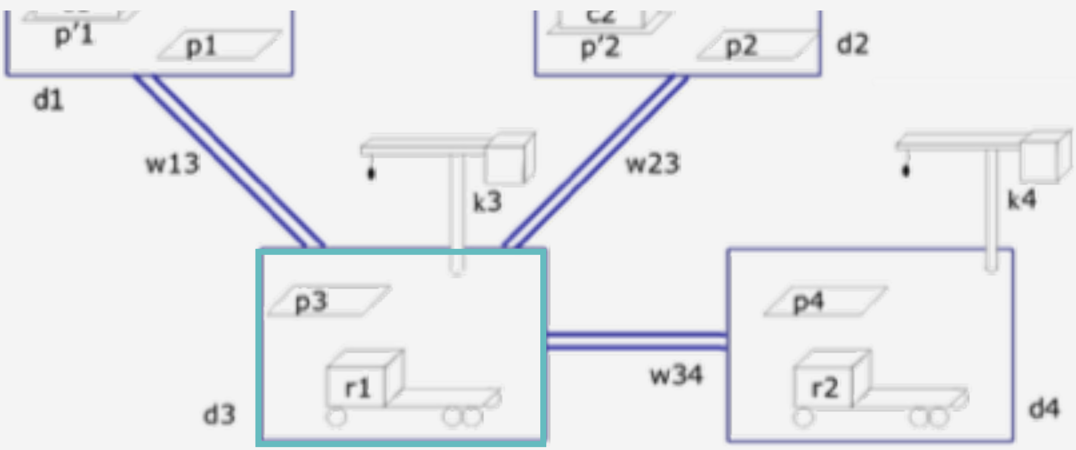
Example of Conflicts

- Refining tasks into actions will produce possibly-conflicting assertions
  - move(r2,d4) must go from d2 through d3
  - Conflict: occupant(d3)=r1, occupant(d3)=r2
- Resolvers:
  - Separation constraints to ensure r2 only goes through d3 while r1 away from d3
    - E.g., by ensuring move(r1,d3) has happened



ϕ_2: tasks: $[0,t_1]$ move(r1,d1)
$[0,t_2]$ uncover(c1,p'1)
$[t_3,t_4]$ load(k1,r1,c1,p'1)
$\boxed{[t_5,t_6]\ \text{move(r1,d3)}}$
$[t_7,t_e]$ unload(k3,r1,c1,p3)
$[t'_s,t'_1]$ move(r2,d2)
$[t'_s,t'_2]$ uncover(c2,p'2)
$[t'_3,t'_4]$ load(k4,r2,c2,p'2)
$\boxed{[t'_5,t'_6]\ \text{move(r2,d4)}}$
$[t'_7,t'_e]$ unload(k2,r2,c2,p'2)

supported: [0] loc(r1)=d3
[0] freight(r1)=empty
[0] pile(c1)=p'1 . . .
$[0,t_3]$ pile(c1) = p'1
$[0,t_3]$ freight(r1) = empty
$[0,t'_s]$ pile(c2)=p'2
$[t'_s,t'_3]$ pile(c2) = p'2
$[0,t'_s]$ freight(r2)=empty
$[t'_s,t'_1]$ freight(r2) = empty

assertions: *(none)*

constraints: $0<t_1\leq t_3$, $0<t_2\leq t_3$, $t_4\leq t_5$, $t_6\leq t_7$,
$t'_s<t'_1\leq t'_3$, $t'_s<t'_2\leq t'_3$, $t'_4\leq t'_5$, $t'_6\leq t'_7$,
adj(d1,w12),adj(d1,w13), . . .

Heuristics for Guiding TemPlan

- Flaw selection, resolver selection heuristics similar to those in PSP
  - Select the flaw with the smallest number of resolvers
  - Choose the resolver that rules out the fewest resolvers for the other flaws
- There is also a problem with constraint management
  - We ignored it when discussing PSP
  - We discuss it next

```
TemPlan(φ)
    Flaws ← set of flaws of φ
    if Flaws = ∅ then
        return φ
    arbitrarily select f ∈ Flaws
    Resolvers ← set of resolvers of f
    if Resolvers = ∅ then
        return failure
    nondeterministically choose ρ ∈ Resolvers
    φ ← Transform(φ, ρ)
    TemPlan(φ)
```

```
PSP(Σ,π)
    loop
        if Flaws(π) = ∅ then
            return π
        arbitrarily select f ∈ Flaws(π)
        R ←{all feasible resolvers for f}
        if R = ∅ then
            return failure
        nondeterministically choose ρ ∈ R
        π ← ρ(π)
    return π
```

Intermediate Summary

- Planning problems
  - Three kinds of flaws and their resolvers:
    - tasks (that need to be refined),
    - causal support (for assertions),
    - security (of instantiations)
  - Partial plans, solution plans
- Planning: TemPlan
  - Like PSP but with tasks, temporal assertions, temporal constraints

Outline per the Book

4.2 Representation

- Timelines
- Actions and tasks
- Chronicles

4.3 Temporal Planning

- Resolvers and flaws
- Search space

4.4 Constraint Management

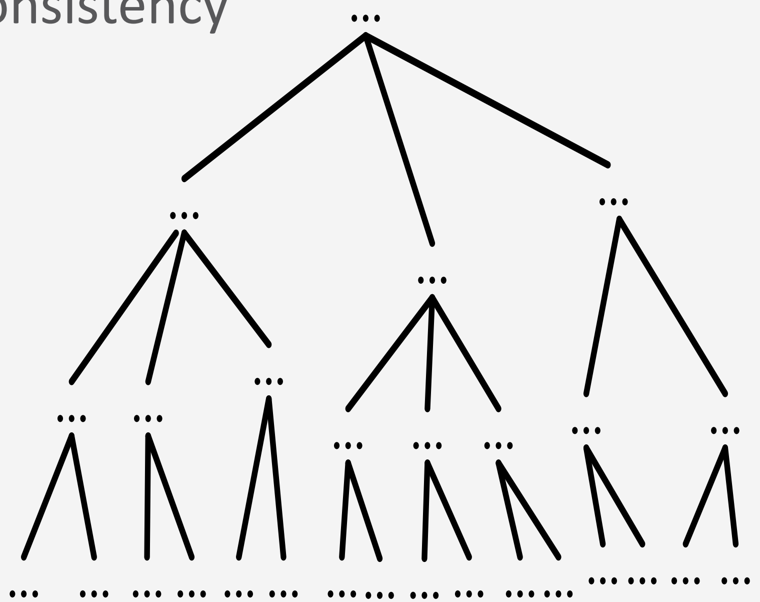
- Consistency of object constraints and time constraints
- Controlling the actions when we do not know how long they will take

4.5 Acting with Temporal Models

- Acting with atemporal refinement
- Dispatching
- Observation actions

Constraint Management

- Each time TemPlan applies a resolver, it modifies $(\mathcal{T}, \mathcal{C})$
  - Some resolvers will make $(\mathcal{T}, \mathcal{C})$ inconsistent
    - No solution in this part of the search space
    - Detect inconsistency → prune this part of the search space
    - Do not detect it → waste time looking for a solution
- Analogy: PSP checks simple cases of inconsistency
  - E.g., cannot create a constraint $a \prec b$ if there is already a constraint $b \prec a$
  - Ignores more complicated cases
  - Example:
    - $c_1, c_2, c_3 \in Containers = \{c1, c2\}$
    - Threats involving c_1, c_2, c_3
    - For resolvers, suppose PSP chooses
      - $c_1 \neq c_2, c_2 \neq c_3, c_1 \neq c_3$
    - No solutions in this part of the search space, but PSP searches it anyway



Constraint Management in TemPlan

- At various points, check consistency of $\mathcal{C}$
  - If $\mathcal{C}$ is inconsistent, then $(\mathcal{T}, \mathcal{C})$ is inconsistent
  - Can prune this part of the search space

- If $\mathcal{C}$ is consistent, then $(\mathcal{T}, \mathcal{C})$ may or may not be consistent
  - Example:
    - $\mathcal{T} = \{[t_1, t_2] loc(r1) = loc1, [t_3, t_4] loc(r1) = loc2\}$
    - $\mathcal{C} = (t_1 < t_3 < t_4 < t_2)$
    - Gives $loc(r1)$ two values during $[t_3, t_4]$

An instance is consistent if
- it satisfies all constraints in $\mathcal{C}$ and
- does not specify two different values for a state variable at the same time

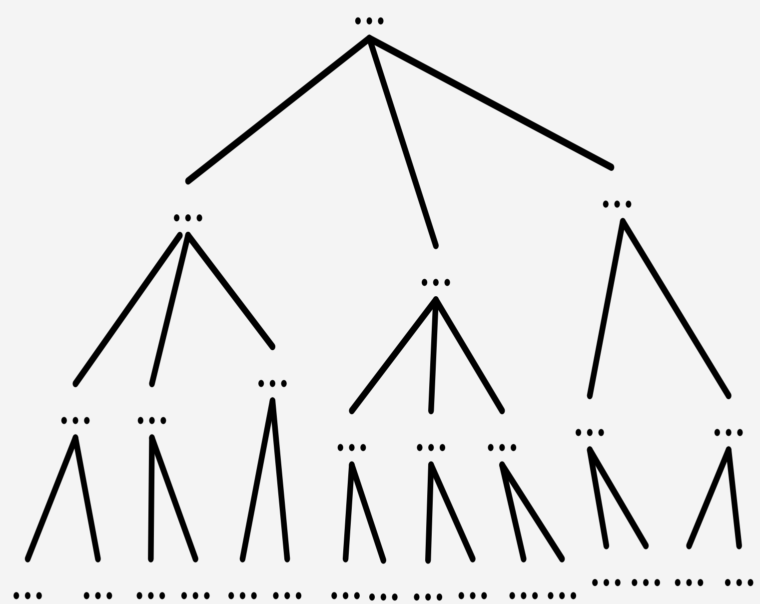
Consistency of $\mathcal{C}$

- $\mathcal{C}$ contains two kinds of constraints
  - Object constraints
    - $loc(r) \neq l_2, \quad l \in \{loc3, loc4\}, \quad r = r1, \; o \neq o'$
  - Temporal constraints
    - $t_1 < t_3, \quad a < t, \quad t < t', \quad a \leq t' - t \leq b$
  - Assume object constraints are independent of temporal constraints and vice versa
    - Exclude things like $t < f(l, r)$ with some function f

- Then two separate subproblems:
  1. Check consistency of object constraints
  2. Check consistency of temporal constraints
  - $\mathcal{C}$ is consistent iff both are consistent

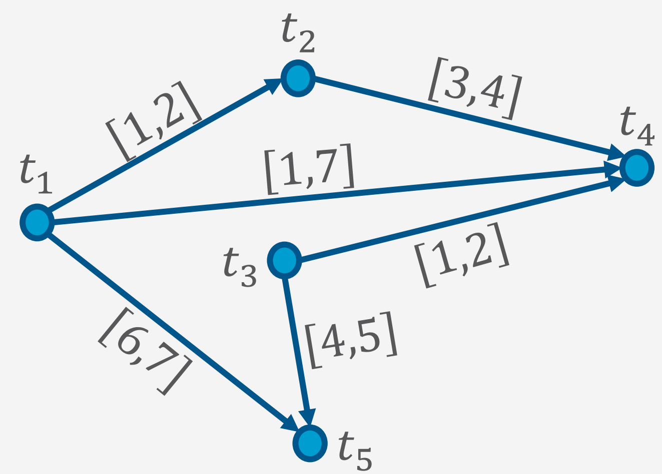
Object Constraints

- Constraint-satisfaction problem – NP-complete
- Can write an algorithm that is complete but runs in exponential time
  - If there is an inconsistency, always finds it
  - Might prune a lot, but spends lots of time at each node
- Instead, use a technique that is incomplete but takes polynomial time
  - Detects some inconsistencies but not others
    - Runs much faster, but prunes fewer nodes



Time Constraints: Representation

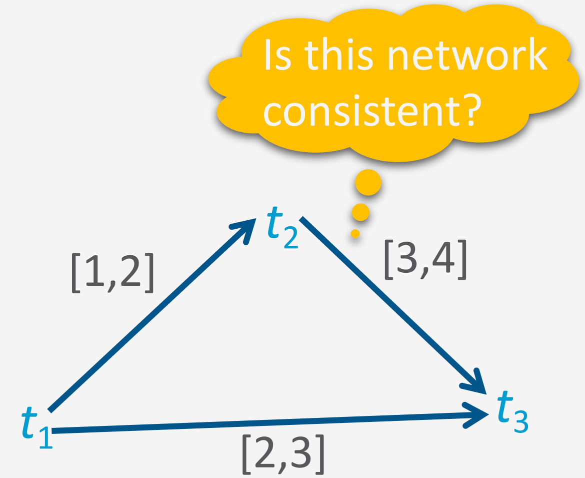
- Simple Temporal Networks (STNs)
  - Networks of constraints on time points
- Synthesise an STN incrementally starting from ϕ_0
  - TemPlan can check time constraints in time $O(n^3)$

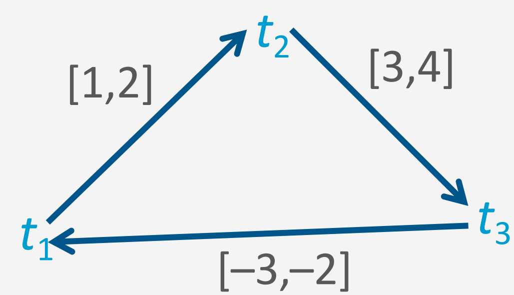


- Incrementally instantiated at acting time
- Kept consistent throughout planning and acting

Simple Temporal Networks

- STN: a pair $(\mathcal{V}, \mathcal{E})$, where
  - $\mathcal{V} = \{$a set of temporal variables $t_1, \dots, t_n\}$
  - $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is a set of edges
- Each edge (t_i, t_j) is labelled with an interval $[a, b]$
  - Shorthand: represents constraint $a \leq t_j - t_i \leq b$
  - Equivalently, $-b \leq t_i - t_j \leq -a$
- Representing unary constraints
  - Dummy variable $t_0 = 0$
  - Edge (t_0, t_i) labelled with $[a, b]$ represents $a \leq t_i - 0 \leq b$
- Solution to an STN
  - Integer value for each t_i
  - All constraints satisfied
- Consistent STN
  - Has a solution



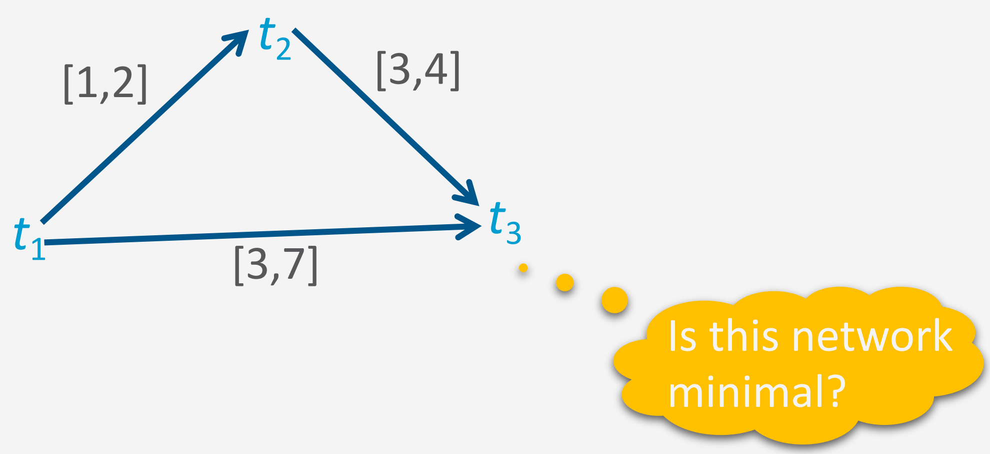


Book says:
- Solution
  - Integer value for each t_i
- Consistent:
  - Has a solution
  - *All constraints satisfied*

!

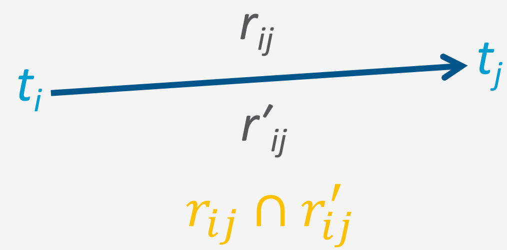
Time Constraints

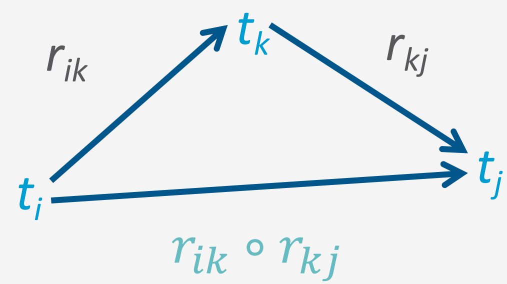
- Minimal STN:
  - For every edge (t_i, t_j) with label $[a, b]$
    - For every $t \in [a, b]$
      - There is at least one solution such that $t_j - t_i = t$
  - Cannot make any of the time intervals shorter without excluding some solutions

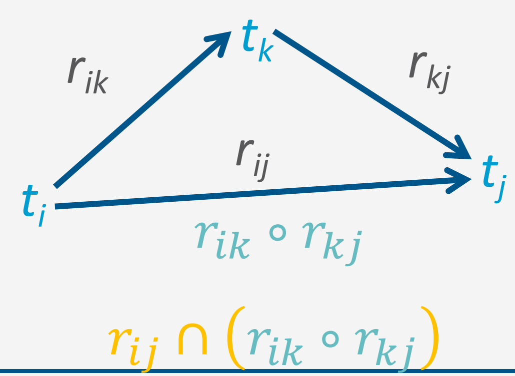


Operations on STNs

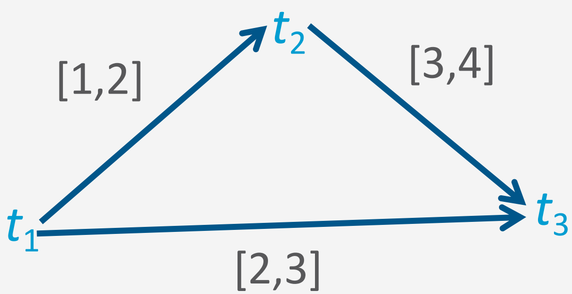
- Intersection, $\cap$
  - $t_j - t_i \in r_{ij} = [a_{ij}, b_{ij}]$
  - $t_j - t_i \in r'_{ij} = [a'_{ij}, b'_{ij}]$
  - Infer
    $t_j - t_i \in r_{ij} \cap r'_{ij} = [\max(a_{ij}, a'_{ij}), \min(b_{ij}, b'_{ij})]$
- Composition, $\circ$
  - $t_k - t_i \in r_{ik} = [a_{ik}, b_{ik}]$
  - $t_j - t_k \in r_{kj} = [a_{kj}, b_{kj}]$
  - Infer
    $t_j - t_i \in r_{ik} \circ r_{kj} = [a_{ik} + a_{kj}, b_{ik} + b_{kj}]$
    - Reasoning: add up shortest and longest times
- Consistency checking
  - Three constraints r_{ik}, r_{kj}, r_{ij} are consistent only if $r_{ij} \cap (r_{ik} \circ r_{kj}) \neq \emptyset$ (*empty interval*)



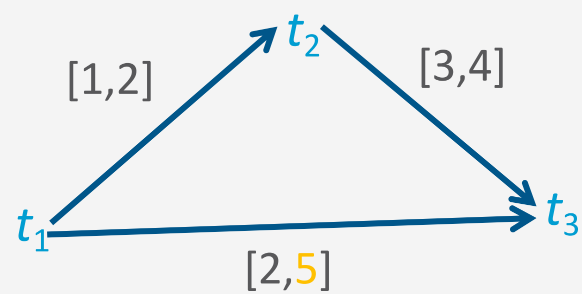




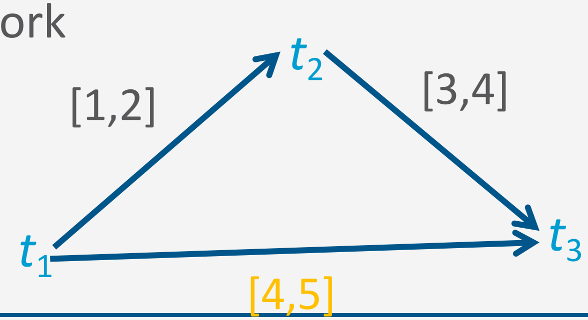
Two Examples



- STN $(\mathcal{V}, \mathcal{E})$, where
  - $\mathcal{V} = \{t_1, t_2, t_3\}$
  - $\mathcal{E} = \{r_{12} = [1{,}2], r_{23} = [3{,}4], r_{13} = [2{,}3]\}$
- Composition
  - $r'_{13} = r_{12} \circ r_{23} = [1{,}2] \circ [3{,}4] = [4{,}6]$
- Cannot satisfy both r_{13} and r'_{13}
  - $r_{13} \cap r'_{13} = [2{,}3] \cap [4{,}6] = \emptyset$
- $(\mathcal{V}, \mathcal{E})$ is inconsistent



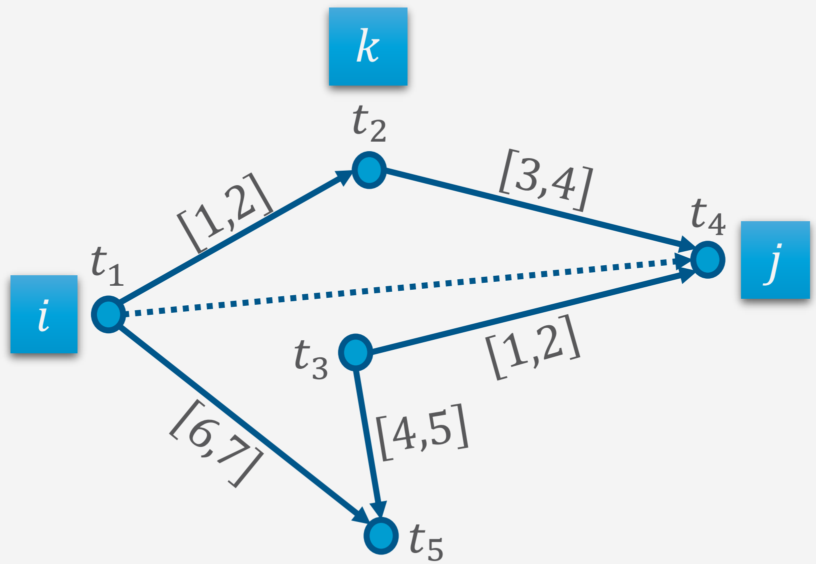
- STN $(\mathcal{V}, \mathcal{E})$, where
  - $\mathcal{V} = \{t_1, t_2, t_3\}$
  - $\mathcal{E} = \{r_{12} = [1{,}2], r_{23} = [3{,}4], r_{13} = [2{,}5]\}$
- Composition (as before)
  - $r'_{13} = r_{12} \circ r_{23} = [4{,}6]$
- $(\mathcal{V}, \mathcal{E})$ is consistent
  - $r_{13} \cap r'_{13} = [2{,}5] \cap [4{,}6] = [4{,}5]$
- Minimal network
  - $r_{13} = [4{,}5]$



Operations on STNs

- PC (*Path Consistency*) algorithm:
  - Consistency checking on all triples
  - If an edge has no constraint, use $[-\infty, +\infty]$
  - n constraints → n^3 triples → time $O(n^3)$
- Example:
  - $k = 2, i = 1, j = 4$
  - $r_{12} = [1,2]$
  - $r_{24} = [3,4]$
  - $r_{14} = [-\infty, \infty]$
  - $r_{12} \circ r_{24} = [1 + 3, 2 + 4] = [4,6]$
  - $r_{14} \leftarrow [\max(-\infty, 4), \min(\infty, 6)] = [4,6]$

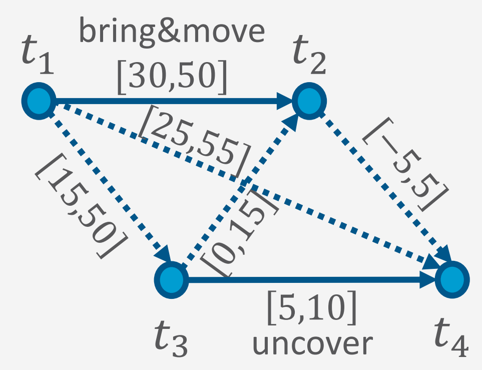
```
PC(𝒱,ℰ)
    for 1 ≤ k ≤ n do
        for 1 ≤ i < j ≤ n, i ≠ j, j ≠ k do
            r_ij ← r_ij ∩ [r_ik ∘ r_kj]
            if r_ij = ∅ then
                return inconsistent
    return consistent
```



Operations on STNs

```
PC(𝒱,ℰ)
    for 1 ≤ k ≤ n do
        for 1 ≤ i < j ≤ n, i ≠ j, j ≠ k do
            r_ij ← r_ij ∩ [r_ik ∘ r_kj]
            if r_ij = ∅ then
                return inconsistent
    return consistent
```

- PC makes network minimal
  - Shrinks each r_{ij} to exclude values that are not in any solution
  - Doing so, it detects inconsistent networks
    - $r_{ij} = [a_{ij}, b_{ij}]$ empty → inconsistent
- Graph: dashed lines
  - Constraints that were shrunk
- Can modify PC to make it incremental
  - Input
    - A consistent, minimal STN
    - A new constraint r'_{ij}
  - Incorporate r'_{ij} in time $O(n^2)$



Pruning TemPlan's search space

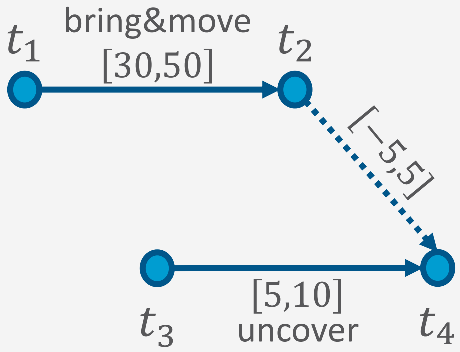
- Take the time constraints in $\mathcal{C}$
  - Write them as an STN
  - Use PC to check whether STN is consistent
  - If it is inconsistent, TemPlan can backtrack

Controllability

Constraint Management with Uncertain Durations

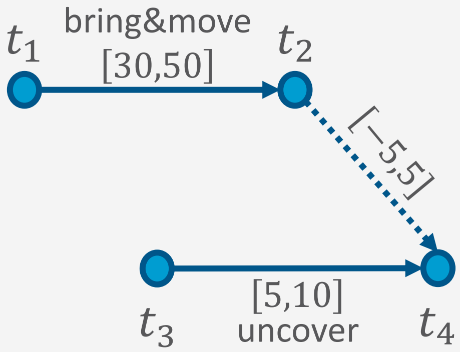
Controllability

- Suppose TemPlan gives you a chronicle and you want to execute it
  - Constraints on time points
  - Need to reason about these to decide when to start each action



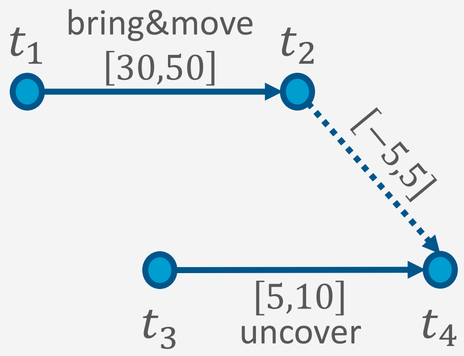
Controllability

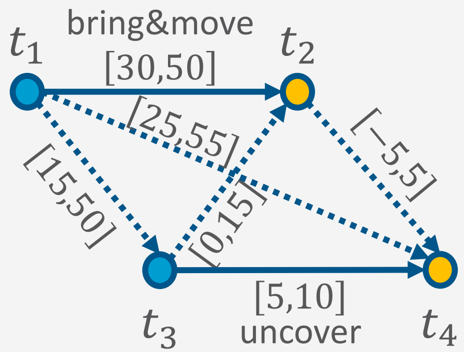
- Solid lines: duration constraints
  - Robot will do bring&move, will take 30 to 50 time units
  - Crane will do uncover, will take 5 to 10 time units
- Dashed line: synchronization constraint
  - Do not want either the crane or robot to wait long
  - At most 5 seconds between the two ending times
- Objective
  - Choose time points that will satisfy all the constraints



Controllability

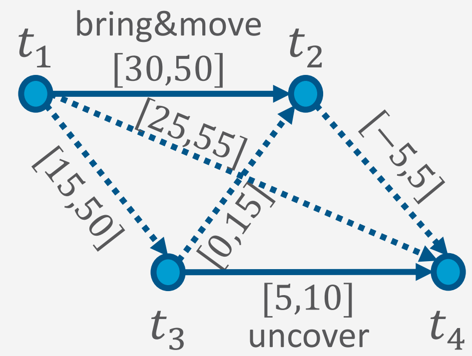
- Suppose we run PC
- PC returns a minimal and consistent network
  - There *exist* time points that satisfy all the constraints
- Would work if we could choose all four time points
  - But we cannot choose t_2 and t_4
- t_1 and t_3 are controllable
  - Actor can control when each action starts
- t_2 and t_4 are contingent
  - Cannot control how long the actions take
  - Random variables that are known to satisfy the duration constraints
    - $t_2 \in [t_1 + 30, t_1 + 50]$
    - $t_4 \in [t_3 + 5, t_3 + 10]$





Controllability

- Cannot guarantee that all constraints will be satisfied
- Start bring&move at time $t_1 = 0$
- Suppose the durations are
  - bring&move 30, uncover 10
  - $t_2 = t_1 + 30 = 30$
  - $t_4 = t_3 + 10$
  - $t_4 - t_2 = t_3 - 20$
- Constraint r_{24}:
  - $-5 \le t_4 - t_2 \le 5$
    $-5 \le t_3 - 20 \le 5$
    $15 \le t_3 \le 25$
- Must start uncover at $t_3 \le 25$



- But if we start uncover at $t_3 \le 25$, neither action has finished yet
  - We do not yet know how long they will take
- Durations might instead be
  - bring&move 50, uncover 5
  - $t_2 = t_1 + 50 = 50$
  - $t_4 = t_3 + 5 \le 25 + 5 = 30$
  - $t_4 - t_2 \le 30 - 50 = -20$
    - Violates r_{24}

STNUs

- STNU (Simple Temporal Network with Uncertainty):
  - A 4-tuple $(\mathcal{V}, \tilde{\mathcal{V}}, \mathcal{E}, \tilde{\mathcal{E}})$
    - $\mathcal{V}$ ={controllable time points}
      - E.g., starting times of actions
    - $\tilde{\mathcal{V}}$ ={contingent time points}
      - E.g., ending times of actions
    - $\mathcal{E}$ ={controllable constraints}
    - $\tilde{\mathcal{E}}$ ={contingent constraints}
- Controllable and contingent constraints:
  - Synchronization between two starting times: *controllable*
  - Duration of an action: *contingent*
  - Synchronization between ending points of two actions: *contingent*
  - Synchronization between end of one action, start of another:
    - *Controllable* if the new action starts after the old one ends
    - *Contingent* if the new action starts before the old one ends
- Want a way for the actor to choose time points in $\mathcal{V}$ (starting times) that guarantee that constraints are satisfied

Three kinds of controllability

- $(\mathcal{V}, \tilde{\mathcal{V}}, \mathcal{E}, \tilde{\mathcal{E}})$ is strongly controllable if the actor can choose values for $\mathcal{V}$ such that success will occur for all values of $\tilde{\mathcal{V}}$ that satisfy $\tilde{\mathcal{E}}$
  - Actor can choose the values for $\mathcal{V}$ offline
  - The right choice will work regardless of $\tilde{\mathcal{V}}$
- $(\mathcal{V}, \tilde{\mathcal{V}}, \mathcal{E}, \tilde{\mathcal{E}})$ is weakly controllable if the actor can choose values for $\mathcal{V}$ such that success will occur for *at least one* combination of values for $\tilde{\mathcal{V}}$
  - Actor can choose the values for $\mathcal{V}$ only if the actor knows in advance what the values of $\tilde{\mathcal{V}}$ will be
- Dynamic controllability:
  - Game-theoretic model: actor vs. environment
  - A player's strategy: a function σ telling what to do in every situation
    - Choices may differ depending on what has happened so far
  - $(\mathcal{V}, \tilde{\mathcal{V}}, \mathcal{E}, \tilde{\mathcal{E}})$ is dynamically controllable if ∃ strategy for an actor that will guarantee success regardless of the environment's strategy

Dynamic Execution

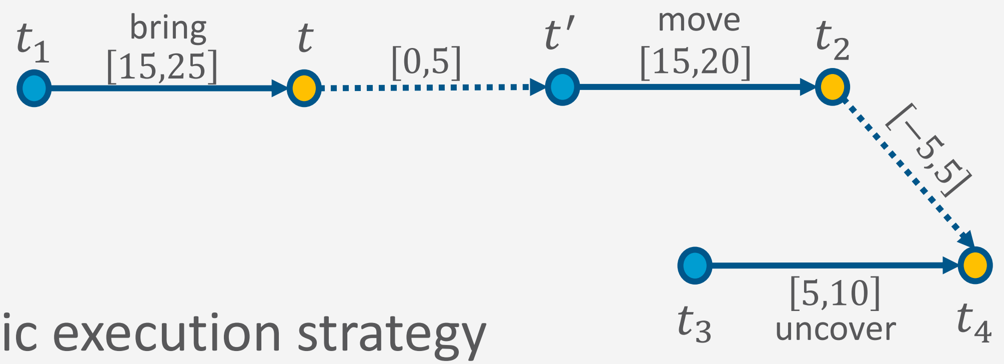
- For $t = 0, 1, 2, \ldots$
  1. Actor chooses an unassigned set of variables $\mathcal{V}_t \subseteq \mathcal{V}$ that all can be assigned the value t without violating any constraints in $\mathcal{E}$
     - ≈ actions the actor chooses to start at time t
  2. Simultaneously, environment chooses an unassigned set of variables $\tilde{\mathcal{V}}_t \subseteq \tilde{\mathcal{V}}$ that all can be assigned the value t without violating any constraints in $\tilde{\mathcal{E}}$
     - ≈ actions that finish at time t
  3. Each chosen time point v is assigned $v \leftarrow t$
  4. Failure if any of the constraints in $\mathcal{E} \cup \tilde{\mathcal{E}}$ are violated
     - There might be violations that neither $\mathcal{V}_t$ nor $\tilde{\mathcal{V}}_t$ caused individually
  5. Success if all variables in $\mathcal{V} \cup \tilde{\mathcal{V}}$ have values and no constraints are violated

$r_{ij} = [l, u]$ is violated if t_i and t_j have values and $t_j - t_i \notin [l, u]$

- Dynamic execution strategies σ_A for actor, σ_E for environment
  - $\sigma_A(h_{t-1})$ = {what events in $\mathcal{V}$ to trigger at time t, given h_{t-1}}
  - $\sigma_E(h_{t-1})$ = {what events in $\tilde{\mathcal{V}}$ to trigger at time t, given h_{t-1}}
    - $h_t = h_{t-1} \cdot \big(\sigma_A(h_{t-1}) \cup \sigma_E(h_{t-1})\big)$
- $\big(\mathcal{V}, \tilde{\mathcal{V}}, \mathcal{E}, \tilde{\mathcal{E}}\big)$ is dynamically controllable if $\exists\, \sigma_A$ that will guarantee success $\forall\, \sigma_E$

Example

- Instead of a single bring&move task, two separate bring and move tasks



- Actor's dynamic execution strategy
  - Trigger t_1 at whatever time you want
  - Wait and observe t
  - Trigger t' at any time from t to $t + 5$
  - Trigger $t_3 = t' + 10$
  - For every $t_2 \in [t' + 15, t' + 20]$ and $t_4 \in [t_3 + 5, t_3 + 10]$
    - $t_4 \in [t' + 15, t' + 20]$
    - So, $t_4 - t_2 \in [-5, 5]$
  - Thus, all constraints are satisfied

Dynamic Controllability Checking

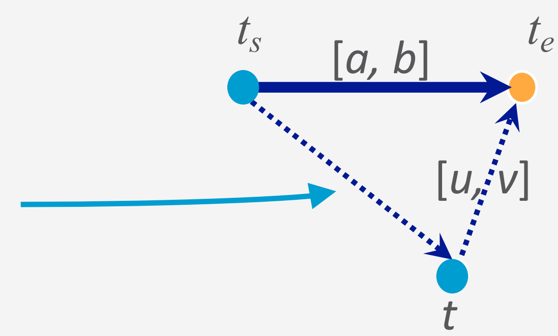
- For a chronicle $\phi = (\mathcal{A}, \mathcal{S}, \mathcal{T}, \mathcal{C})$
  - Temporal constraints in $\mathcal{C}$ correspond to an STNU
  - Adapt TemPlan to test not only consistency but also dynamic controllability (*) of the STNU
  - If we detect cases where it is not dynamically controllable, then backtrack

* Use PC as well
  - If PC($\mathcal{V} \cup \tilde{\mathcal{V}}, \mathcal{E} \cup \tilde{\mathcal{E}}$) reduces a contingent constraint, then $\left(\mathcal{V}, \tilde{\mathcal{V}}, \mathcal{E}, \tilde{\mathcal{E}}\right)$ is not dynamically controllable

    $\Rightarrow$ Can prune this branch
  - If it *does not* reduce any contingent constraints, we do not know whether $\left(\mathcal{V}, \tilde{\mathcal{V}}, \mathcal{E}, \tilde{\mathcal{E}}\right)$ is dynamically controllable
    - Only necessary, not sufficient condition
  - Two options
    - Either continue down this branch and backtrack later if necessary, or
    - Extend PC to detect more cases where $\left(\mathcal{V}, \tilde{\mathcal{V}}, \mathcal{E}, \tilde{\mathcal{E}}\right)$ is not dynamically controllable
      - Additional constraint propagation rules

Additional Constraint Propagation Rules

- Case 1: $u \geq 0$
  - t must come before t_e
- Add a composition constraint $[a', b']$
  - Find $[a', b']$ such that $[a', b'] \circ [u, v] = [a, b]$
    - $[a' + u, b' + v] = [a, b]$
    - $a' = a - u, b' = b - v$

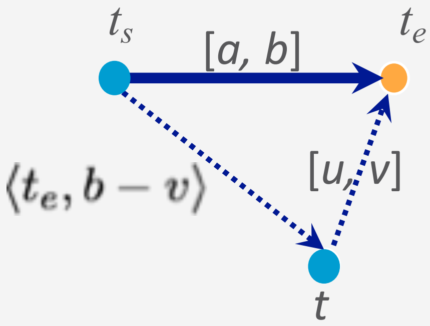


Conditions	Propagated constraint
$t_s \overset{[a,b]}{\Longrightarrow} t_e$, $t \xrightarrow{[u,v]} t_e$, $u \geq 0$	$t_s \xrightarrow{[b',a']} t$
$t_s \overset{[a,b]}{\Longrightarrow} t_e$, $t \xrightarrow{[u,v]} t_e$, $u < 0$, $v \geq 0$	$t_s \xrightarrow{\langle t_e,b'\rangle} t$
$t_s \overset{[a,b]}{\Longrightarrow} t_e$, $t_s \xrightarrow{\langle t_e,u\rangle} t$	$t_s \xrightarrow{[min\{a,u\},\infty]} t$
$t_s \xrightarrow{\langle t_e,b\rangle} t$, $t' \xrightarrow{[u,v]} t$	$t_s \xrightarrow{\langle t_e,b'\rangle} t'$
$t_s \xrightarrow{\langle t_e,b\rangle} t$, $t' \overset{[u,v]}{\Longrightarrow} t$, $t_e \neq t$	$t_s \xrightarrow{\langle t_e,b-u\rangle} t'$

$\Longrightarrow$ contingent $\longrightarrow$ controllable $a' = a - u, b' = b - v$

Additional Constraint Propagation Rules

- Case 2: $u < 0$ and $v \geq 0$
  - t may be before or after t_e
- Add a wait constraint $\langle t_e, \alpha \rangle$
  - α defined w.r.t.
    some controllable time point t_s
  - Wait until either t_e occurs or current time is $t_s + \alpha$, whichever comes first



Conditions	Propagated constraint
$t_s \xRightarrow{[a,b]} t_e\ ,\ t \xrightarrow{[u,v]} t_e\ ,\ u \geq 0$	$t_s \xrightarrow{[b',a']} t$
$t_s \xRightarrow{[a,b]} t_e\ ,\ t \xrightarrow{[u,v]} t_e\ ,\ u < 0\ ,\ v \geq 0$	$t_s \xrightarrow{\langle t_e,b' \rangle} t$
$t_s \xRightarrow{[a,b]} t_e\ ,\ t_s \xrightarrow{\langle t_e,u \rangle} t$	$t_s \xrightarrow{[min\{a,u\},\infty]} t$
$t_s \xrightarrow{\langle t_e,b \rangle} t\ ,\ t' \xrightarrow{[u,v]} t$	$t_s \xrightarrow{\langle t_e,b' \rangle} t'$
$t_s \xrightarrow{\langle t_e,b \rangle} t\ ,\ t' \xRightarrow{[u,v]} t\ ,\ t_e \neq t$	$t_s \xrightarrow{\langle t_e,b-u \rangle} t'$

$\Longrightarrow$ contingent $\longrightarrow$ controllable $a' = a - u, b' = b - v$

Extended Version of PC

- We want a fast algorithm that TemPlan can run at each node, to decide whether to backtrack
- There is an extended version of PC that runs in polynomial time, but it has high overhead
- Possible compromise: use ordinary PC most of the time
  - Run extended version occasionally, or at end of search before returning plan

Conditions	Propagated constraint
$t_s \xRightarrow{[a,b]} t_e \; , \; t \xrightarrow{[u,v]} t_e \; , \; u \geq 0$	$t_s \xrightarrow{[b',a']} t$
$t_s \xRightarrow{[a,b]} t_e \; , \; t \xrightarrow{[u,v]} t_e \; , \; u < 0 \; , \; v \geq 0$	$t_s \xrightarrow{\langle t_e,b' \rangle} t$
$t_s \xRightarrow{[a,b]} t_e \; , \; t_s \xrightarrow{\langle t_e,u \rangle} t$	$t_s \xrightarrow{[\min\{a,u\},\infty]} t$
$t_s \xrightarrow{\langle t_e,b \rangle} t \; , \; t' \xrightarrow{[u,v]} t$	$t_s \xrightarrow{\langle t_e,b' \rangle} t'$
$t_s \xrightarrow{\langle t_e,b \rangle} t \; , \; t' \xRightarrow{[u,v]} t \; , \; t_e \neq t$	$t_s \xrightarrow{\langle t_e,b-u \rangle} t'$

$\Longrightarrow$ contingent $\longrightarrow$ controllable $a' = a - u, b' = b - v$

Intermediate Summary

- Constraint management
  - Consistency of object constraints
    - Constraint-satisfaction problem
  - Consistency of time constraints
    - STN, solution, minimality, consistency
    - PC
- Controllability
  - STNU, controllable, contingent
  - Dynamic controllability

Outline per the Book

4.2 Representation

- Timelines
- Actions and tasks
- Chronicles

4.3 Temporal Planning

- Resolvers and flaws
- Search space

4.4 Constraint Management

- Consistency of object constraints and time constraints
- Controlling the actions when we do not know how long they will take

4.5 Acting with Temporal Models

- Acting with atemporal refinement
- Dispatching
- Observation actions

Atemporal Refinement of Primitive Actions

- TemPlan's action templates may correspond to compound tasks
  - In RAE, refine into commands with refinement methods
  - TemPlan's action template (descriptive model)

leave(r,d,w)
    assertions: $[t_s,t_e]$ loc(r): (d,w)
                $[t_s,t_e]$ occupant(d): (r,empty)
    constraints: $t_e \leq t_s + \delta_1$
                adj(d,w)

  - RAE's refinement method (operational model)

m-leave(r,d,w,e)
    task: leave(r,d,w)
    pre: loc(r)=d, adj(d,w), exit(e,d,w)
    body: until empty(e)
              wait(1)
          goto(r,e)

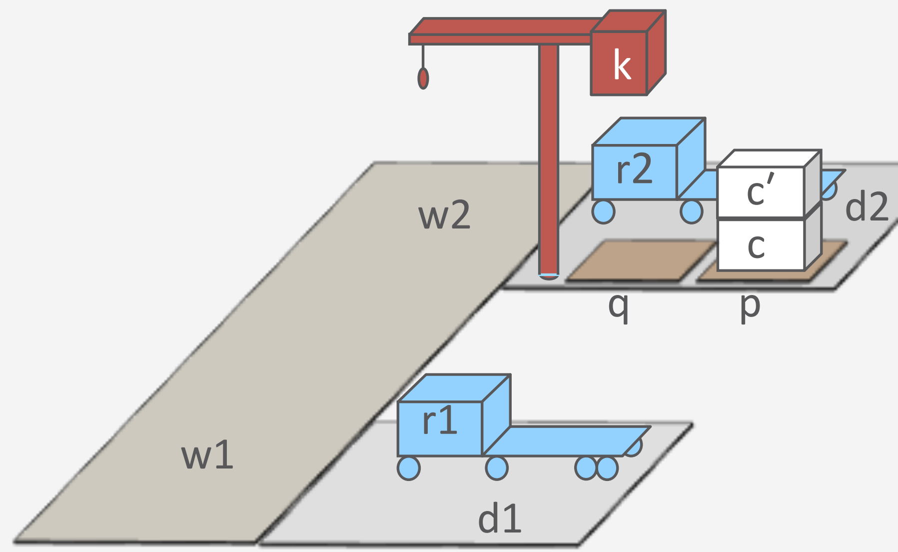
Discussion

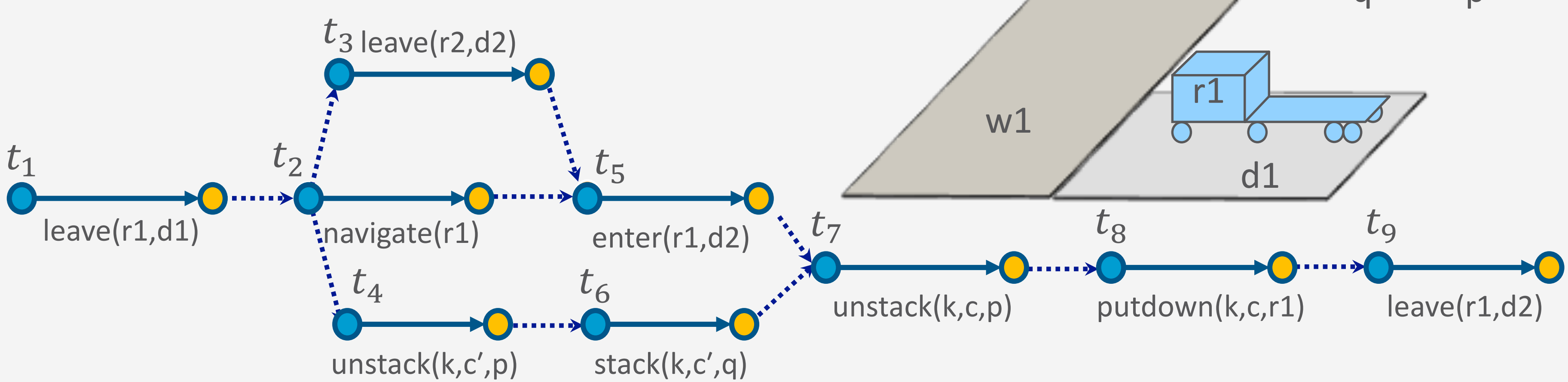
- Pros
  - Simple online refinement with RAE
  - Avoids breaking down uncertainty of contingent duration
  - Can be augmented with temporal monitoring functions in RAE
    - E.g., watchdogs, methods with duration preferences
- Cons
  - Does not handle temporal requirements at the command level,
    - E.g., synchronise two robots that must act concurrently

- Can augment RAE to include temporal reasoning
  - Call it eRAE
  - One essential component: a dispatching function

Acting With Temporal Models

- Dispatching procedure: a dynamic execution strategy
  - Controls when to start each action
  - Given a dynamically controllable plan with executable primitives, it triggers corresponding commands from online observations
- Example
  - robot $r2$ needs to leave dock $d2$ before robot $r1$ can enter $d2$
  - crane k needs to uncover c then put c onto $r1$





Dispatching

- Let $(\mathcal{V}, \tilde{\mathcal{V}}, \mathcal{E}, \tilde{\mathcal{E}})$ be a controllable STNU that is grounded
  - Different from a grounded expression in logic
  - At least one time point t^* is instantiated
    - Bounds each time point t within an interval $[l_t, u_t]$

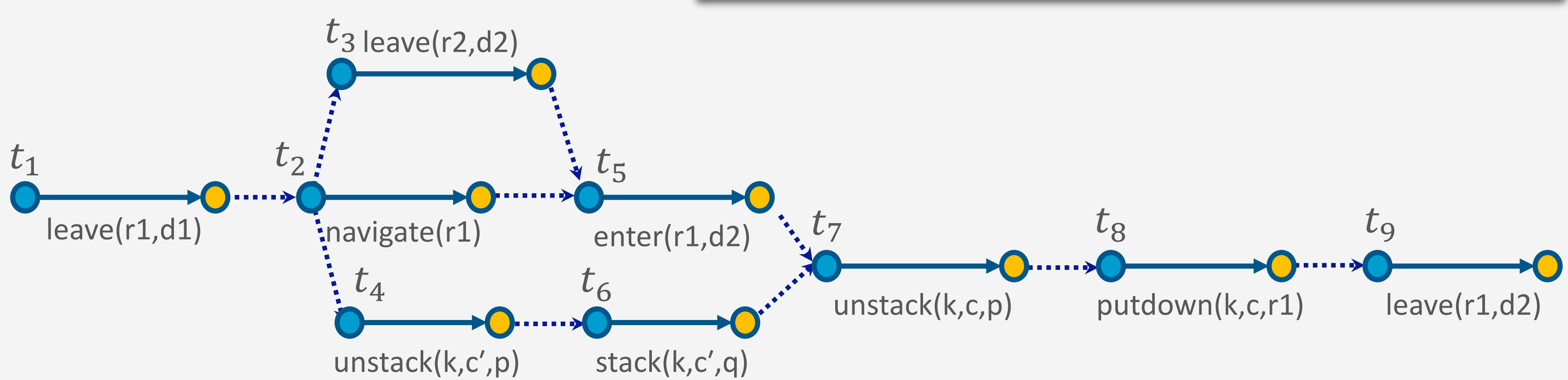
```
Dispatch(𝒱,Ṽ,ℰ,Ẽ)
    initialise the network
    while there are time points in 𝒱 that
              have not been triggered do
        update now
        update the time points in Ṽ that have
              been newly observed
        update enabled
        trigger every t ∈ enabled s.t. now=u_t
        arbitrarily choose other time points
              in enabled and trigger them
        propagate values of triggered
              timepoints (change [l_t,u_t] for
              each future timepoint t)
```

- Controllable time point t in the future:
  - t is alive if current time $now \in [l_t, u_t]$
  - t is enabled if
    - It is alive
    - For every precedence constraint $t' < t$, t' has occurred
    - For every wait constraint $\langle t_e, \alpha \rangle$, t_e has occurred or α has expired
      - α has expired if t_s has occurred and $t_s + \alpha \leq now$

Example

- Trigger t_1, observe leave finish
- Enable and trigger t_2, enables t_3, t_4
- Trigger t_3 soon enough to allow $enter(r1, d2)$ at time t_5
- Trigger t_4 soon enough to allow $stack(k, c')$ at time t_6
- Rest of plan is linear:
  - Choose each t_i after the previous action ends

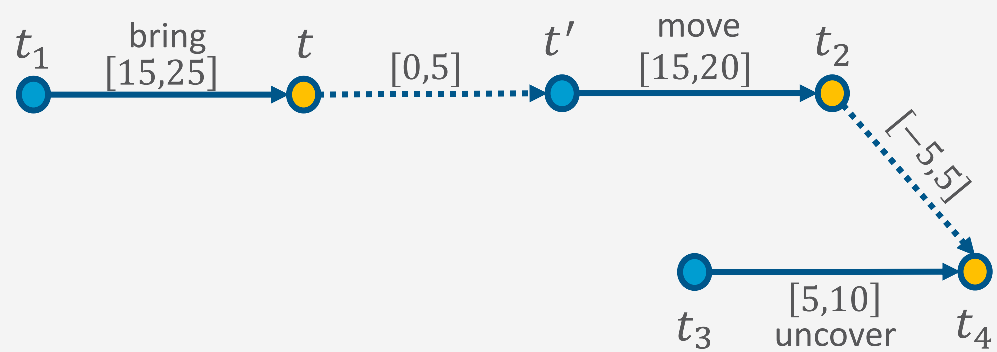
Dispatch($\mathcal{V}$, $\tilde{V}$, $\mathcal{E}$, $\tilde{E}$)
    initialise the network
    while there are time points in $\mathcal{V}$ that have not been triggered **do**
        update *now*
        update the time points in $\tilde{V}$ that have been newly observed
        update *enabled*
        trigger every $t \in$ *enabled* s.t. $now = u_t$
        arbitrarily choose other time points in *enabled* and trigger them
        propagate values of triggered timepoints (change $[l_t, u_t]$ for each future timepoint t)



Example from Slide 61

- Trigger t_1 at time 0
- Wait and observe t; this enables t'
- Trigger t' at any time from t to $t + 5$
- Trigger t_3 at time $t' + 10$
  - $t_2 \in [t' + 15, t' + 20]$
  - $t_4 \in [t_3 + 5, t_3 + 10] = [t' + 15, t' + 20]$
  - so $t_4 - t_2 \in [-5, 5]$

```
Dispatch(𝒱,Ṽ,ℰ,Ẽ)
    initialise the network
    while there are time points in 𝒱 that
              have not been triggered do
        update now
        update the time points in Ṽ that have
              been newly observed
        update enabled
        trigger every t ∈ enabled s.t. now=u_t
        arbitrarily choose other time points
              in enabled and trigger them
        propagate values of triggered
              timepoints (change [l_t,u_t] for
              each future timepoint t)
```



Dispatching

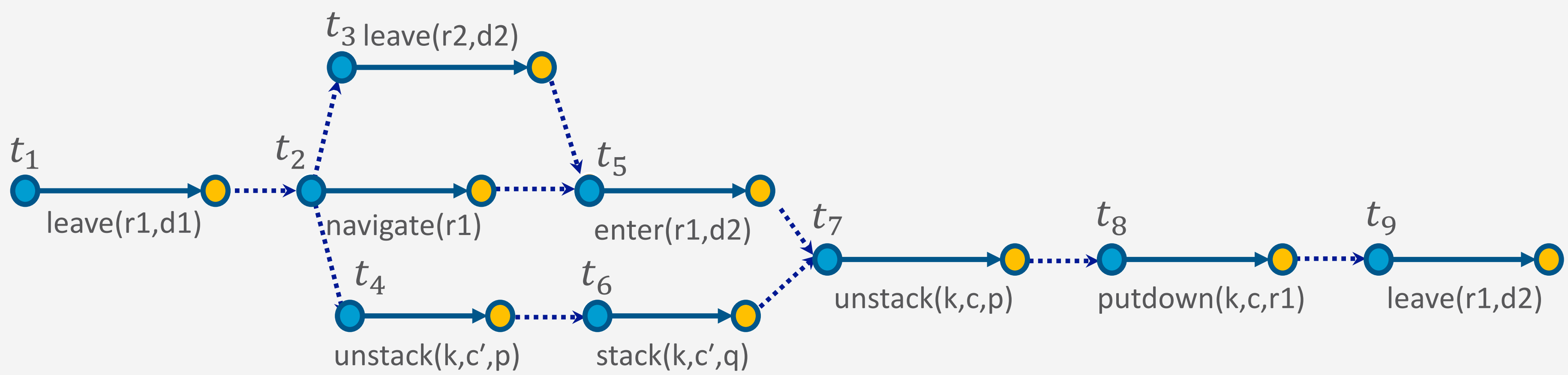
- Propagation step most costly one
  - $O(n^3)$
  - n the number of remaining future time points in network

```
Dispatch(𝒱,Ṽ,ℰ,Ẽ)
    initialise the network
    while there are time points in 𝒱 that
              have not been triggered do
        update now
        update the time points in Ṽ that have
              been newly observed
        update enabled
        trigger every t ∈ enabled s.t. now=u_t
        arbitrarily choose other time points
              in enabled and trigger them
        propagate values of triggered
              timepoints (change [l_t,u_t] for
              each future timepoint t)
```

- Ideally propagation fast enough to allow iterations and updates of now consistent with temporal granularity of plan

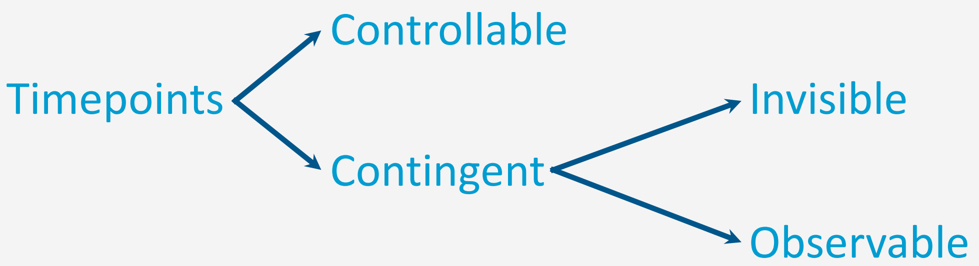
Deadline Failures

- Suppose something makes it impossible to start an action on time
- Do one of the following:
  - Stop the delayed action, and look for new plan
  - Let the delayed action finish, try to repair the plan by resolving violated constraints at the STNU propagation level
    - E.g., accommodate a delay in navigate by delaying the whole plan
  - Let the delayed action finish, try to repair the plan some other way



Partial Observability

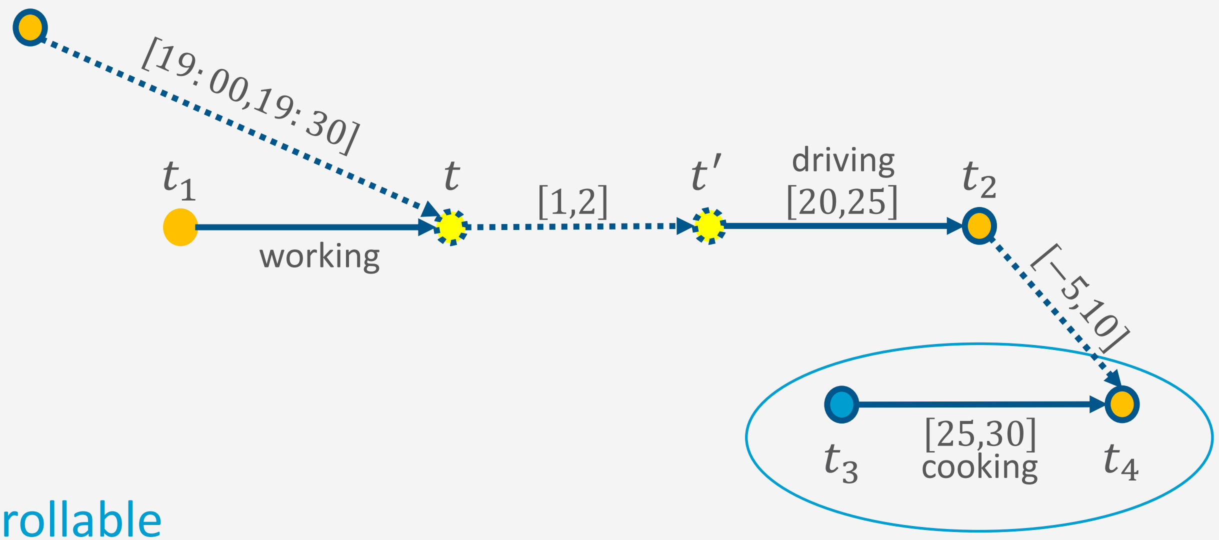
- Tacit assumption: All occurrences of contingent events are observable
  - Observation needed for dynamic controllability
- In general, not all events are observable
- POSTNU (Partially Observable STNU)
  - STNU where the contingent time points are given by a set of invisible and a set of observable timepoints
    - POSTNU = STNU if Invisible = Ø
  - Dynamically controllable?



Arthur Bit-Monnot, Malik Ghallab, Félix Ingrand: “Which Contingent Events to Observe for the Dynamic Controllability of a Plan”, IJCAI-16

Observation Actions

- Example



Controllable

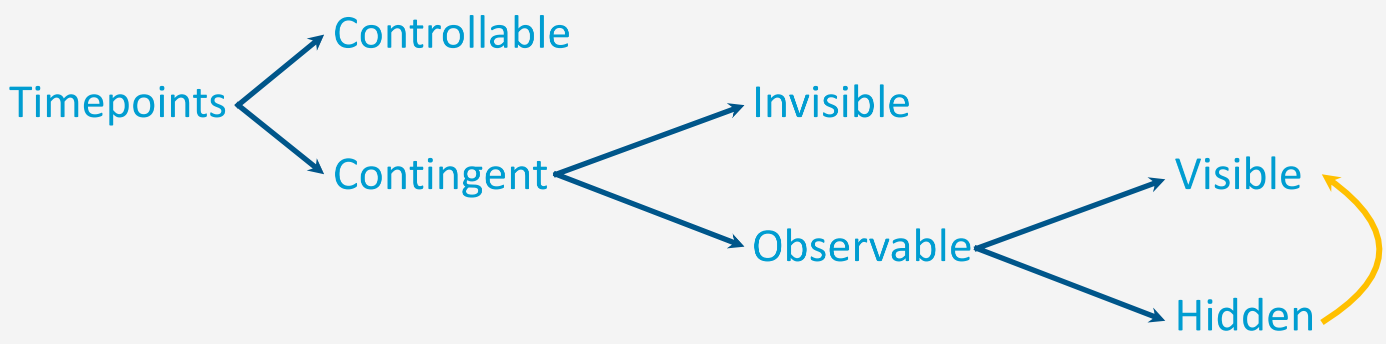
Contingent
- Invisible
- observable

Dynamic Controllability

- A POSTNU is dynamically controllable if
  - there exists an execution strategy that chooses future controllable points to meet all the constraints, given the observation of past *visible* points
- Check dynamic controllability
  - Map an POSTNU to an STNU by deleting invisible time points and adding corresponding constraints on controllable and observable time points
  - Check dynamic controllability of the mapped STNU
    - E.g., using the extended PC algorithm
  - More details in the paper

Dynamic Controllability

- A POSTNU is dynamically controllable if
  - there exists an execution strategy that chooses future controllable points to meet all the constraints, given the observation of past *visible* points
- Observable ≠ visible
  - Observable means it will be known when observed
    - It can be temporarily hidden



- Aim: Find out which time points need to be observed for the plan to be dynamically controllable (details in paper)

Intermediate Summary

- Acting
  - Atemporal refinement
    - eRAE
    - Dispatching
      - Alive, enabled
  - Deadline failures
  - Partial observability
    - Invisible, observable (hidden/visible)

Outline per the Book

4.2 Representation

- Timelines
- Actions and tasks
- Chronicles

4.3 Temporal Planning

- Resolvers and flaws
- Search space

4.4 Constraint Management

- Consistency of object constraints and time constraints
- Controlling the actions when we do not know how long they will take

4.5 Acting with Temporal Models

- Acting with atemporal refinement
- Dispatching
- Observation actions

$\Longrightarrow$ Next: Planning and Acting with Nondeterministic Models