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BPM 2018

Construction Process Modelling: Representing Activities, Items and their Interplay.

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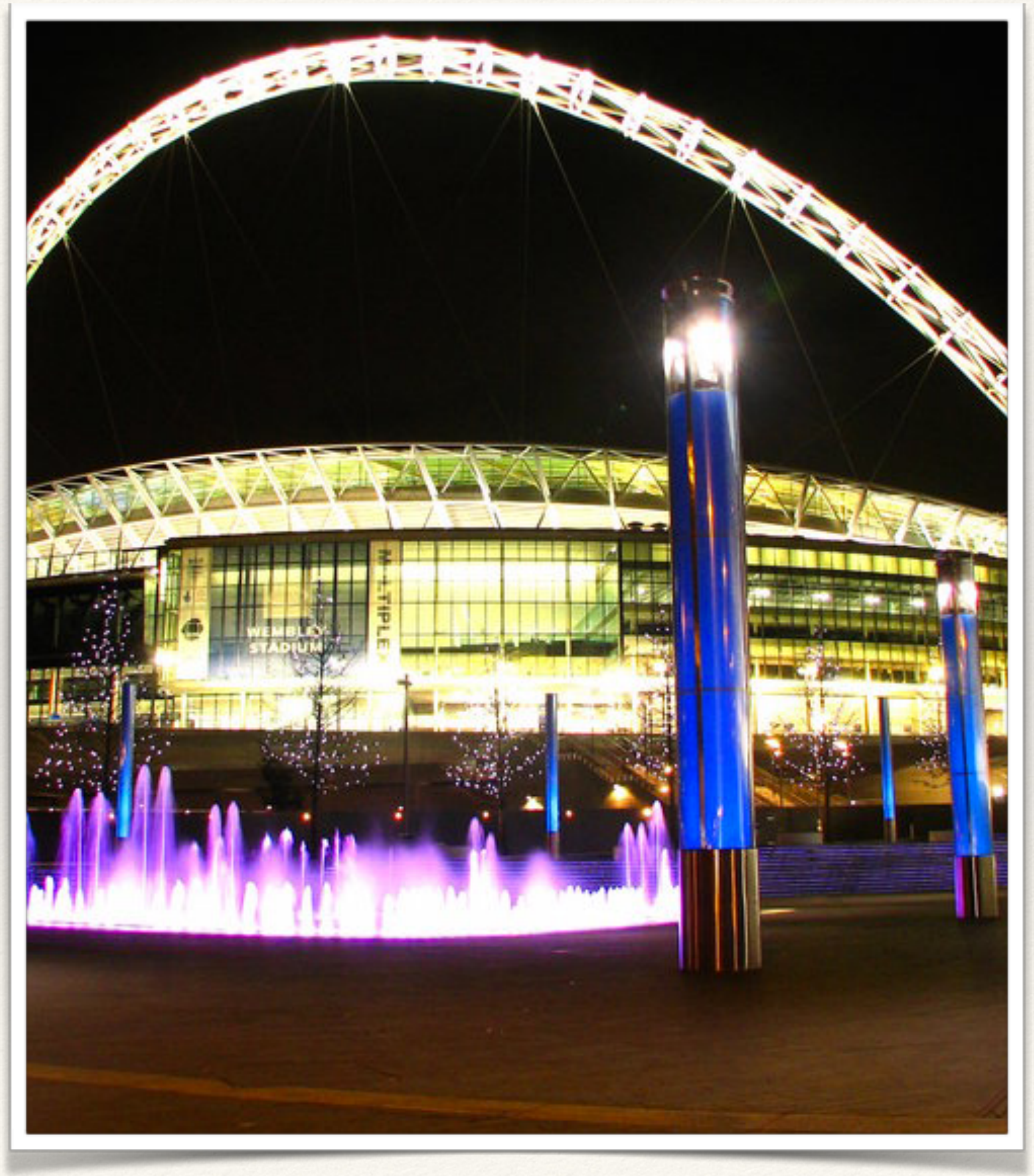
REPUBBLICA ITALIANA

Construction Projects are “Rarely” On-Time/On-Budget

- Wembley National Stadium
  - Commenced: 2002
  - Planned Completion: Early 2006
  - Opened: March 2007
  - *Delay: 1 year*
  - Planned Cost: £757m
  - Final Cost (approx.): £1bn
  - *Increased cost: 32%*



http://www.globalconstructionreview.com/

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Construction Projects are “Rarely” On-Time/On-Budget

- Berlin Airport
  - Commenced: 2006
  - Planned Completion: 2011
  - Opened: ??? (2020)
  - *Delay: 9 Years*
  - Planned cost: €2bn
  - Current Cost: €6bn
  - *Increased cost: 200%*

https://www.economist.com/the-economist-explains/

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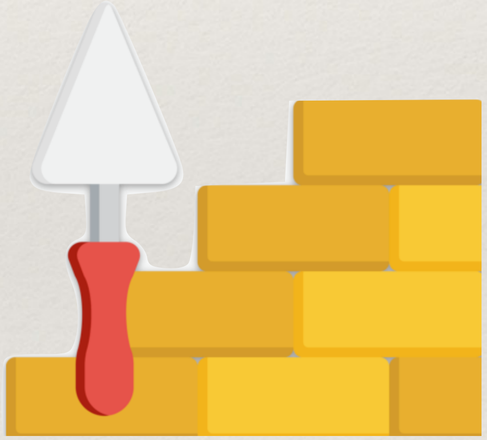
Why Are They Special?

In Construction

- Projects are one of a kind (difficult to make estimates)



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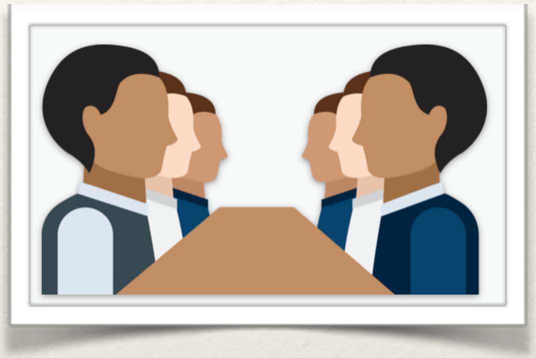

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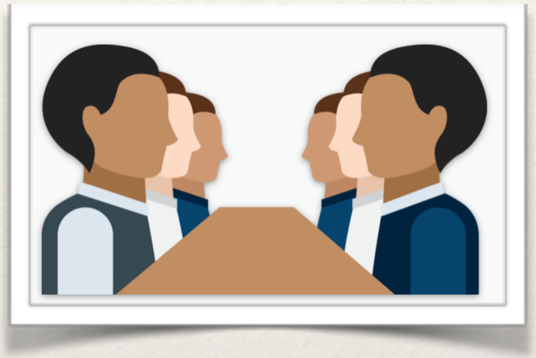

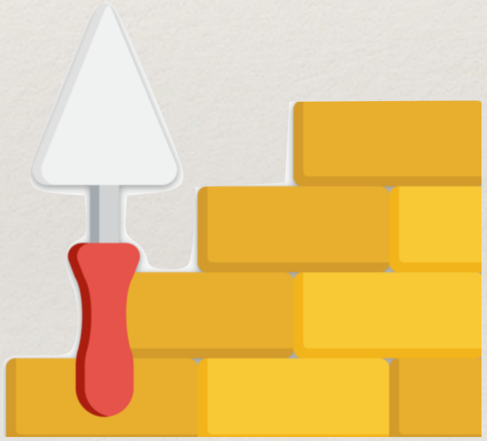

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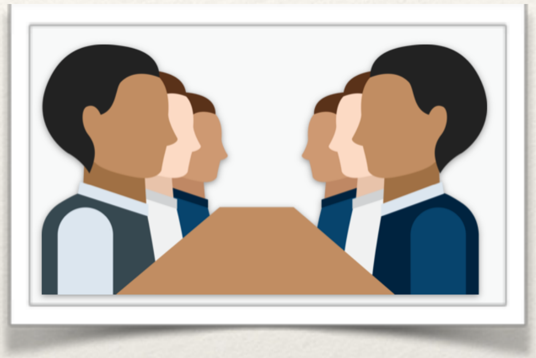
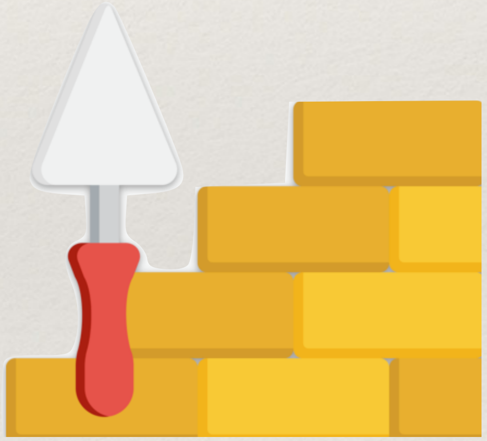
Why Are They Special?

In Construction

- Projects are one of a kind (difficult to make estimates)
- Many companies are involved
- Unpredictable events
- Projects are complex and long





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- Projects are one of a kind (difficult to make estimates)
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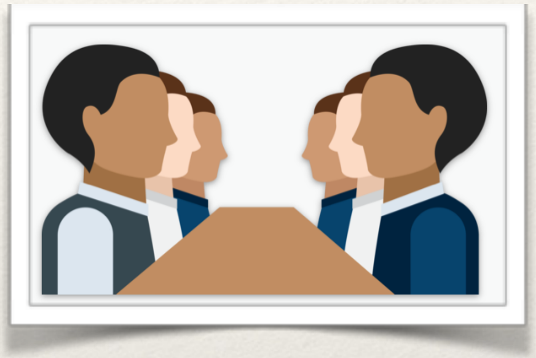
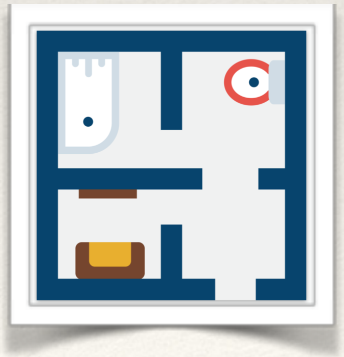
- Shared resources/locations





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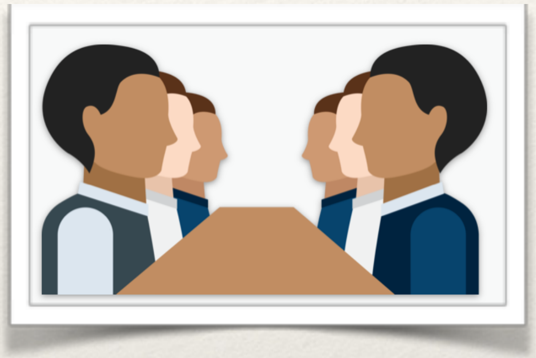
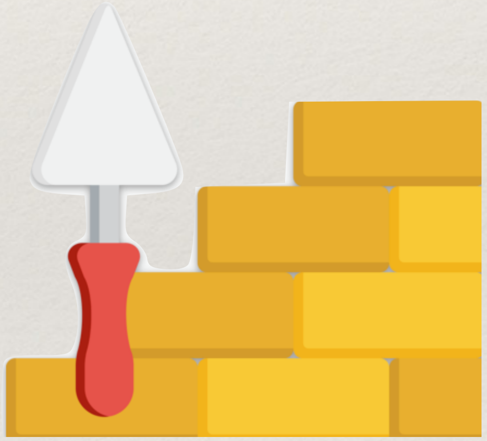
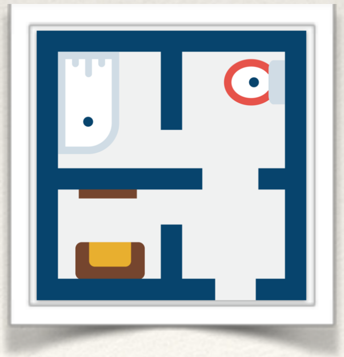
Why Are They Special?

In Construction

- Projects are one of a kind (difficult to make estimates)
- Many companies are involved
- Unpredictable events
- Projects are complex and long
- Shared resources/locations
- Changing requirements







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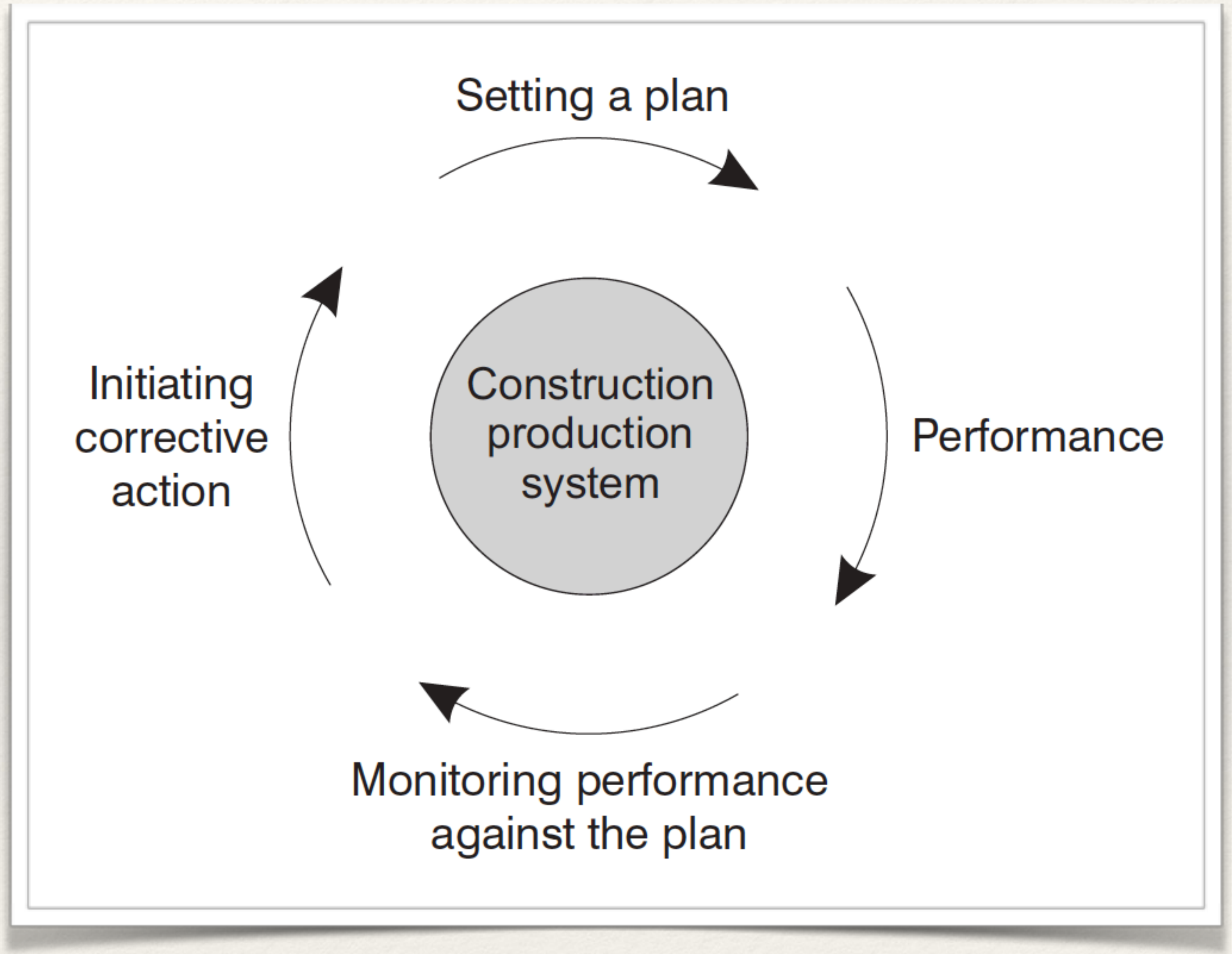
Traditional Approach

- **Planning:**
  - Define the activities, orders in which they occur and milestones
- **Scheduling:**
  - Define timetables
- **Control:**
  - Detect deviations from the plan



Setting a plan

Performance

Monitoring performance against the plan

Initiating corrective action

Construction production system

Traditional Approach: Some Considerations

- **Locations:**
  - Physical locations are not considered explicitly
  - No location-based relationship between the activities
- **Planning as Gantt Chart:**
  - Represent a commitment to a date
  - Lack of flexibility: not clear what are the dependences
  - Become outdated very soon
  - Never updated

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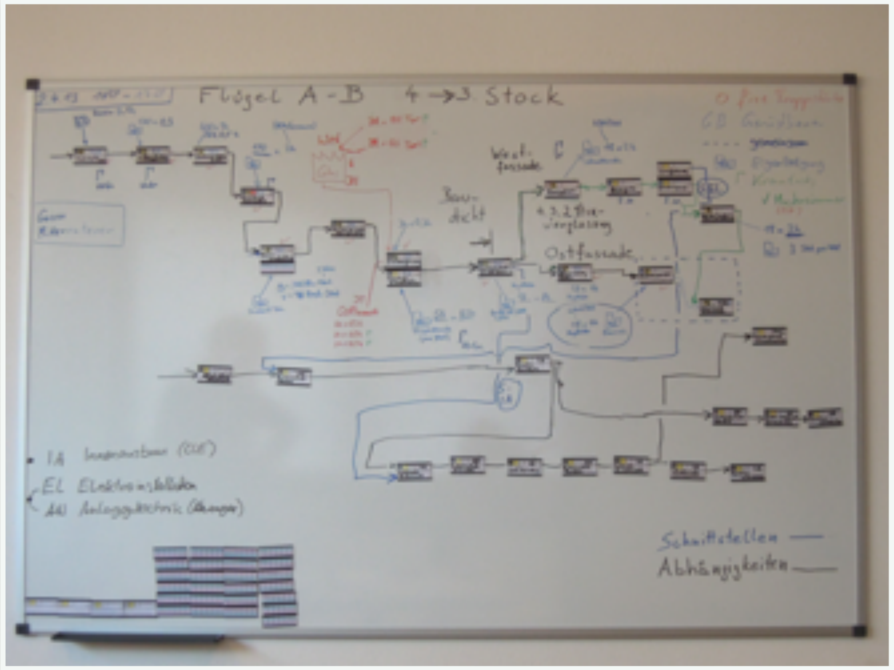
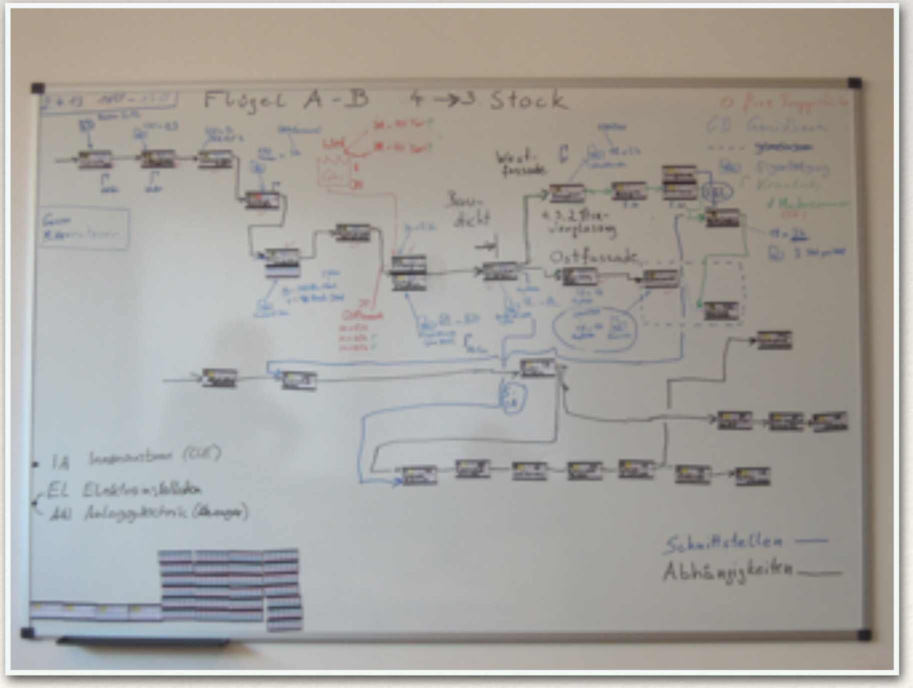
Tentative Solution

- Planning
  - Decoupled from scheduling
  - Define **What** and **Where** (not yet when)
  - Collaborative modelling



Tentative Solution

- Planning
    - Decoupled from scheduling
    - Define **What** and **Where** (not yet when)
    - Collaborative modelling
- Scheduling
    - Define **How** and **When**



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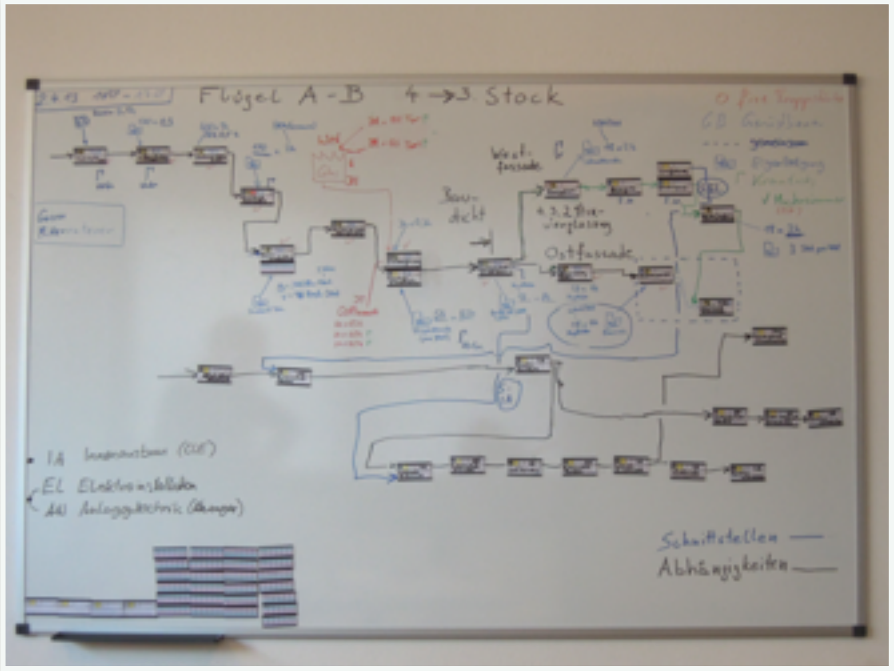
Tentative Solution

- Planning
  - Decoupled from scheduling
  - Define **What** and **Where** (not yet when)
  - Collaborative modelling
- Scheduling
  - Define **How** and **When**
- Control
  - New requirements: **Re-plan**
  - Delays: **Re-schedule**



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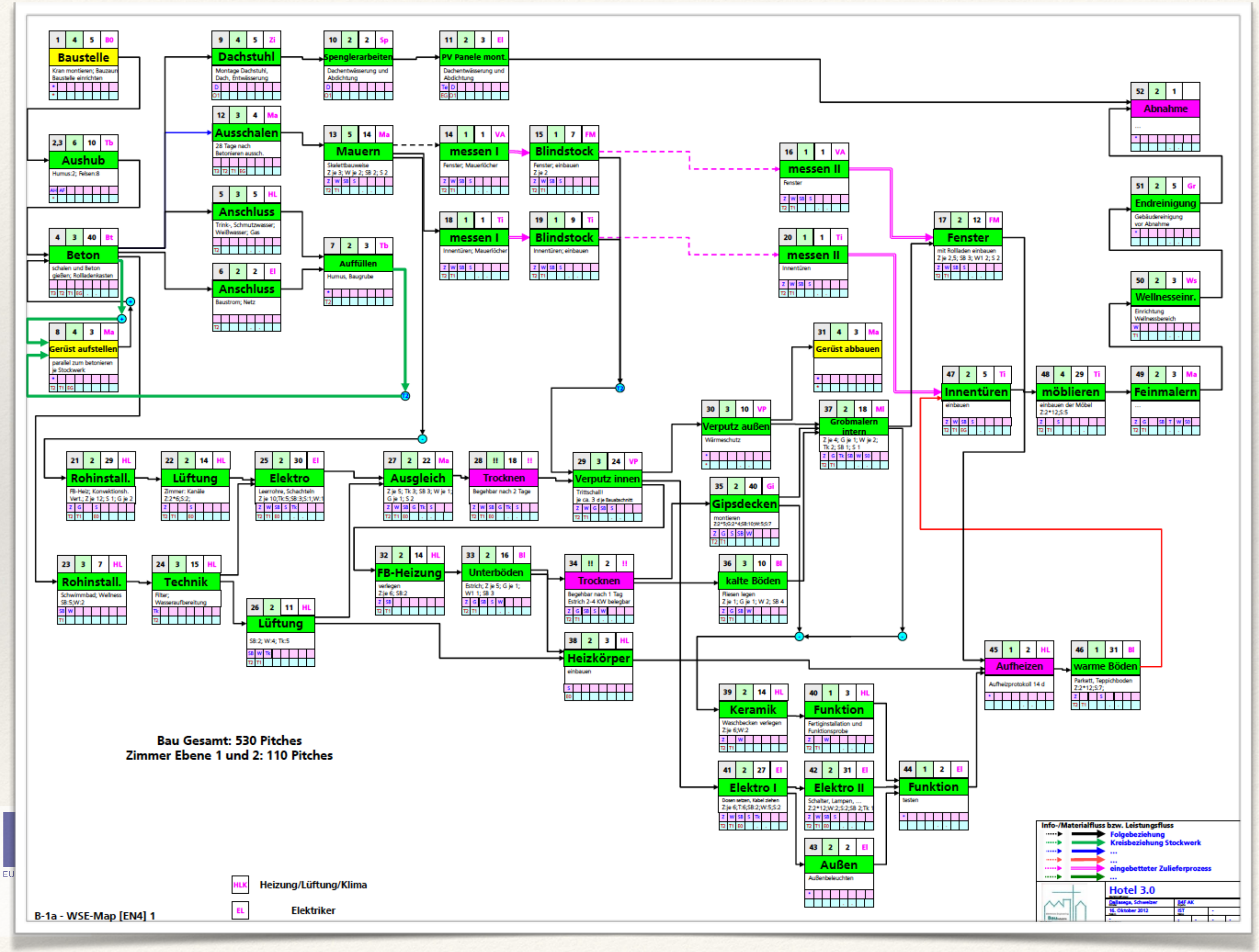
Hospital of Bolzano



1 | 4 | 5 | B0 — Baustelle — Kran montieren; Bauzaun Baustelle einrichten

2,3 | 6 | 10 | Tb — Aushub — Humus:2; Felsen:8

4 | 3 | 40 | Bt — Beton — schalen und Beton gießen; Rolladenkasten

8 | 4 | 3 | Ma — Gerüst aufstellen — parallel zum betonieren je Stockwerk

9 | 4 | 5 | Zi — Dachstuhl — Montage Dachstuhl, Dach, Entwässerung

10 | 2 | 2 | Sp — Spenglerarbeiten — Dachentwässerung und Abdichtung

11 | 2 | 3 | El — PV Panele mont. — Dachentwässerung und Abdichtung

12 | 3 | 4 | Ma — Ausschalen — 28 Tage nach Betonieren aussch.

13 | 5 | 14 | Ma — Mauern — Skelettbauweise Z je 3; W je 2; SB 2; S 2

5 | 3 | 5 | HL — Anschluss — Trink-, Schmutzwasser; Weißwasser; Gas

6 | 2 | 2 | El — Anschluss — Baustrom; Netz

7 | 2 | 3 | Tb — Auffüllen — Humus, Baugrube

14 | 1 | 1 | VA — messen I — Fenster; Mauerlöcher

15 | 1 | 7 | FM — Blindstock — Fenster; einbauen Z je 2

18 | 1 | 1 | Ti — messen I — Innentüren; Mauerlöcher

19 | 1 | 9 | Ti — Blindstock — Innentüren; einbauen

16 | 1 | 1 | VA — messen II — Fenster

20 | 1 | 1 | Ti — messen II — Innentüren

17 | 2 | 12 | FM — Fenster — mit Rolladen einbauen Z je 2,5; SB 3; W1 2; S 2

52 | 2 | 1 — Abnahme — ....

51 | 2 | 5 | Gr — Endreinigung — Gebäudereinigung vor Abnahme

50 | 2 | 3 | Ws — Wellnesseinr. — Einrichtung Wellnessbereich

31 | 4 | 3 | Ma — Gerüst abbauen

47 | 2 | 5 | Ti — Innentüren — einbauen

48 | 4 | 29 | Ti — möblieren — einbauen der Möbel Z:2*12;S:5

49 | 2 | 3 | Ma — Feinmalern — ....

30 | 3 | 10 | VP — Verputz außen — Wärmeschutz

37 | 2 | 18 | MI — Grobmalern intern — Z je 4; G je 1; W je 2; Tk 2; SB 1; S 1

21 | 2 | 29 | HL — Rohinstall. — FB-Heiz; Konvektionsh. Vert.; Z je 12; S 1; G je 2

22 | 2 | 14 | HL — Lüftung — Zimmer: Kanäle Z:2*6;S:2;

25 | 2 | 30 | El — Elektro — Leerrohre, Schachteln Z je 10;Tk:5;SB:3;S:1;W:1

27 | 2 | 22 | Ma — Ausgleich — Z je 5; Tk 3; SB 3; W je 1; G je 1; S 2

28 | !! | 18 | !! — Trocknen — Begehbar nach 2 Tage

29 | 3 | 24 | VP — Verputz innen — Trittschall! je ca. 3 d je Bauabschnitt

35 | 2 | 40 | Gi — Gipsdecken — montieren Z:2*5;G:2*4;SB:10;W:5;S:7

23 | 3 | 7 | HL — Rohinstall. — Schwimmbad; Wellness SB:5;W:2

24 | 3 | 15 | HL — Technik — Filter; Wasseraufbereitung

26 | 2 | 11 | HL — Lüftung — SB:2; W:4; Tk:5

32 | 2 | 14 | HL — FB-Heizung — verlegen Z:je 6; SB:2

33 | 2 | 16 | Bl — Unterböden — Estrich; Z je 5; G je 1; W1 1; SB 3

34 | !! | 2 | !! — Trocknen — Begehbar nach 1 Tag Estrich 2-4 KW belegbar

36 | 3 | 10 | Bl — kalte Böden — Fliesen legen Z je 1; G je 1; W 2; SB 4

38 | 2 | 3 | HL — Heizkörper — einbauen

45 | 1 | 2 | HL — Aufheizen — Aufheizprotokoll 14 d

46 | 1 | 31 | Bl — warme Böden — Parkett, Teppichboden Z:2*12;S:7;

39 | 2 | 14 | HL — Keramik — Waschbecken verlegen Z:je 6;W:2

40 | 1 | 3 | HL — Funktion — Fertiginstallation und Funktionsprobe

41 | 2 | 27 | El — Elektro I — Dosen setzen, Kabel ziehen Z:je 6;T:6;SB:2;W:5;S:2

42 | 2 | 31 | El — Elektro II — Schalter, Lampen, ... Z:2*12;W:2;S:2;SB 2;Tk 1

44 | 1 | 2 | El — Funktion — testen

43 | 2 | 2 | El — Außen — Außenbeleuchten

Bau Gesamt: 530 Pitches
Zimmer Ebene 1 und 2: 110 Pitches

HLK Heizung/Lüftung/Klima

EL Elektriker

B-1a - WSE-Map [EN4] 1

Info-/Materialfluss bzw. Leistungsfluss

- Folgebeziehung
- Kreisbeziehung Stockwerk
- ...
- ...
- eingebetteter Zulieferprozess
- ...

Hotel 3.0
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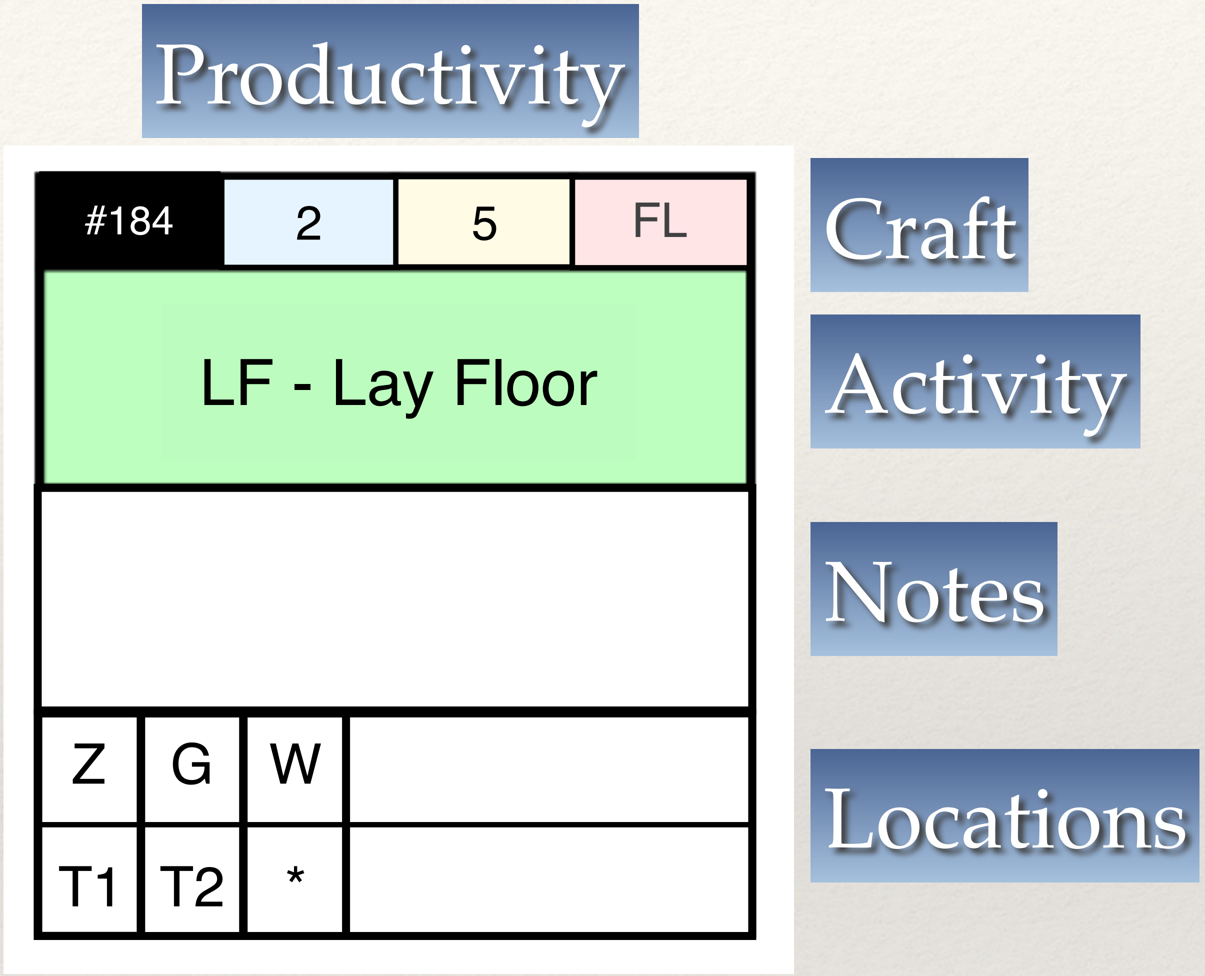
16. Oktober 2012 | IST | -

Elements in the model

- Tasks
  - What: Activity
  - Who: Craft
  - Where: Locations
  - How long: Productivity
  - Notes



Productivity

Craft

Activity

Notes

Locations

#184	2	5	FL

LF - Lay Floor

Z	G	W	
T1	T2	*	

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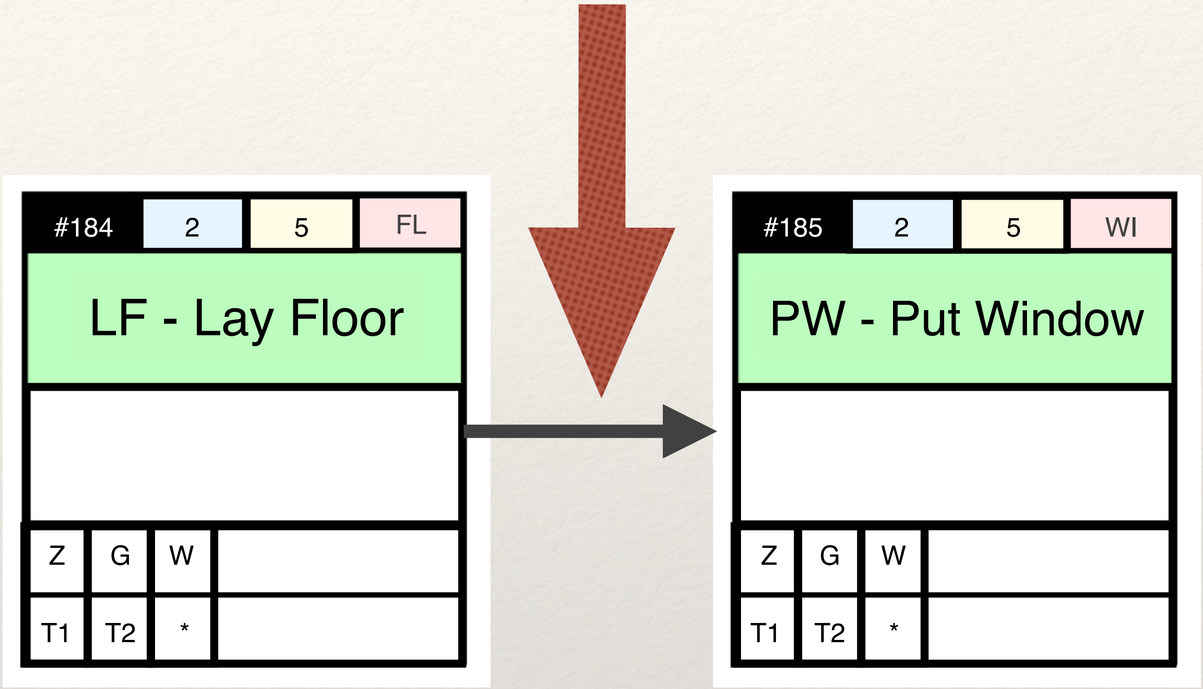
Elements in the model

- Tasks
  - What: Activity
  - Who: Craft
  - Where: Locations
  - How long: Productivity
  - Notes
- Synchronisation
  - Declarative precedences



#184 2 5 FL

LF - Lay Floor

Z G W

T1 T2 *

#185 2 5 WI

PW - Put Window

Z G W

T1 T2 *

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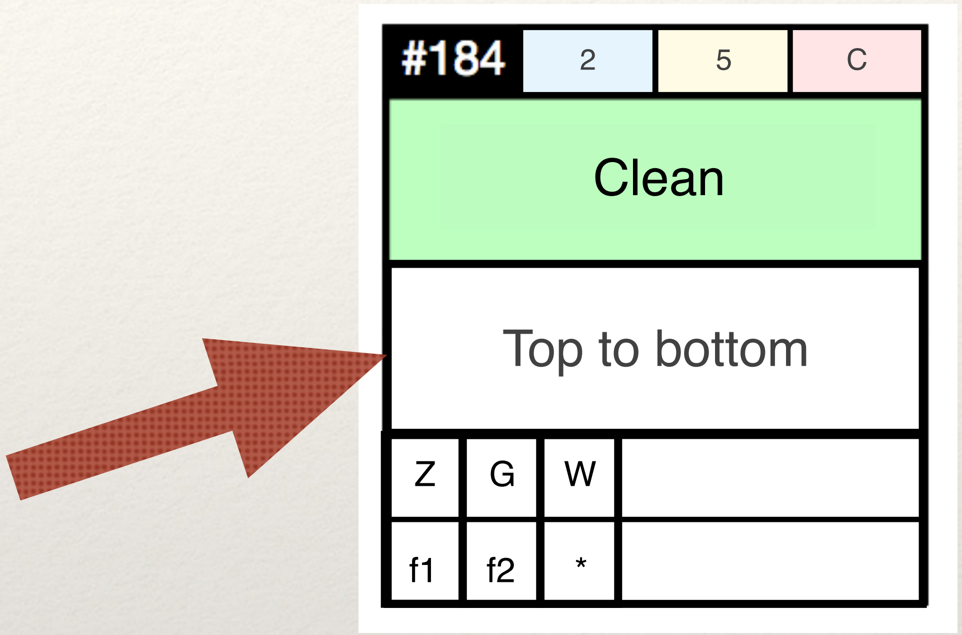
Hidden Knowledge and Ambiguities

- **Orderings**
  among the locations
  (bottom to top, top to bottom)



#184 2 5 C

Clean

Top to bottom

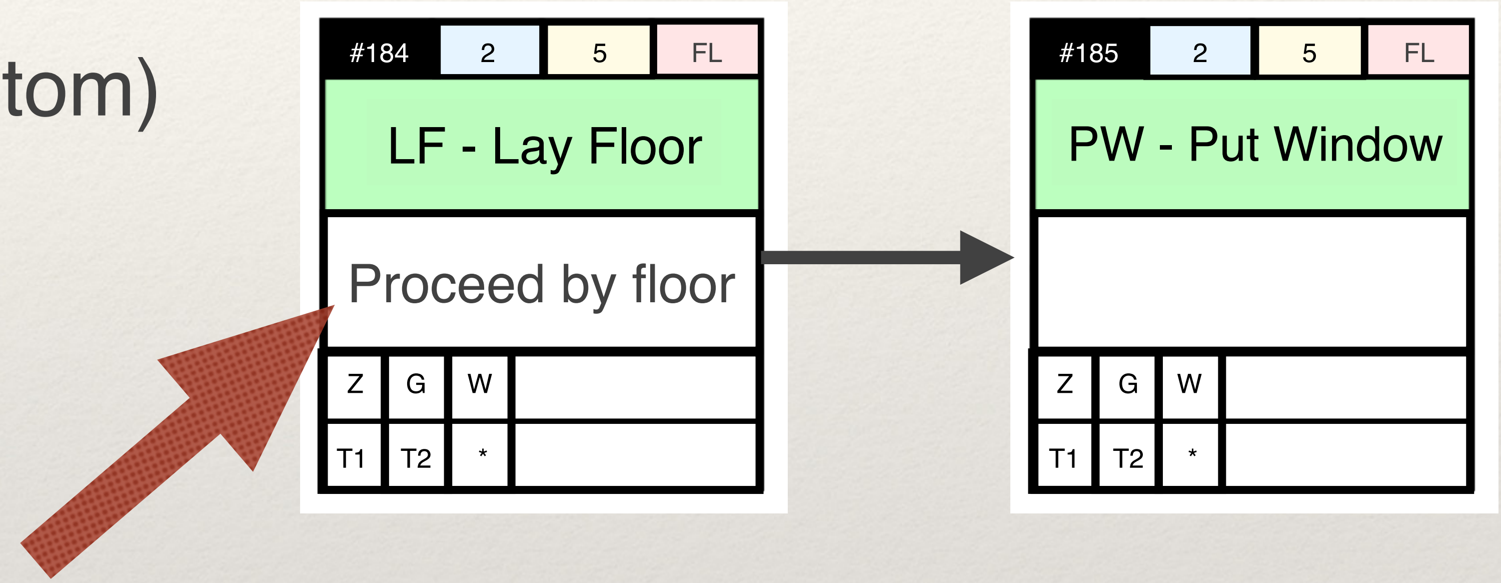
Z G W

f1 f2 *

Hidden Knowledge and Ambiguities

- **Orderings**
  among the locations
  (bottom to top, top to bottom)

- Precedence **Scope**
  (floor, activity, building)



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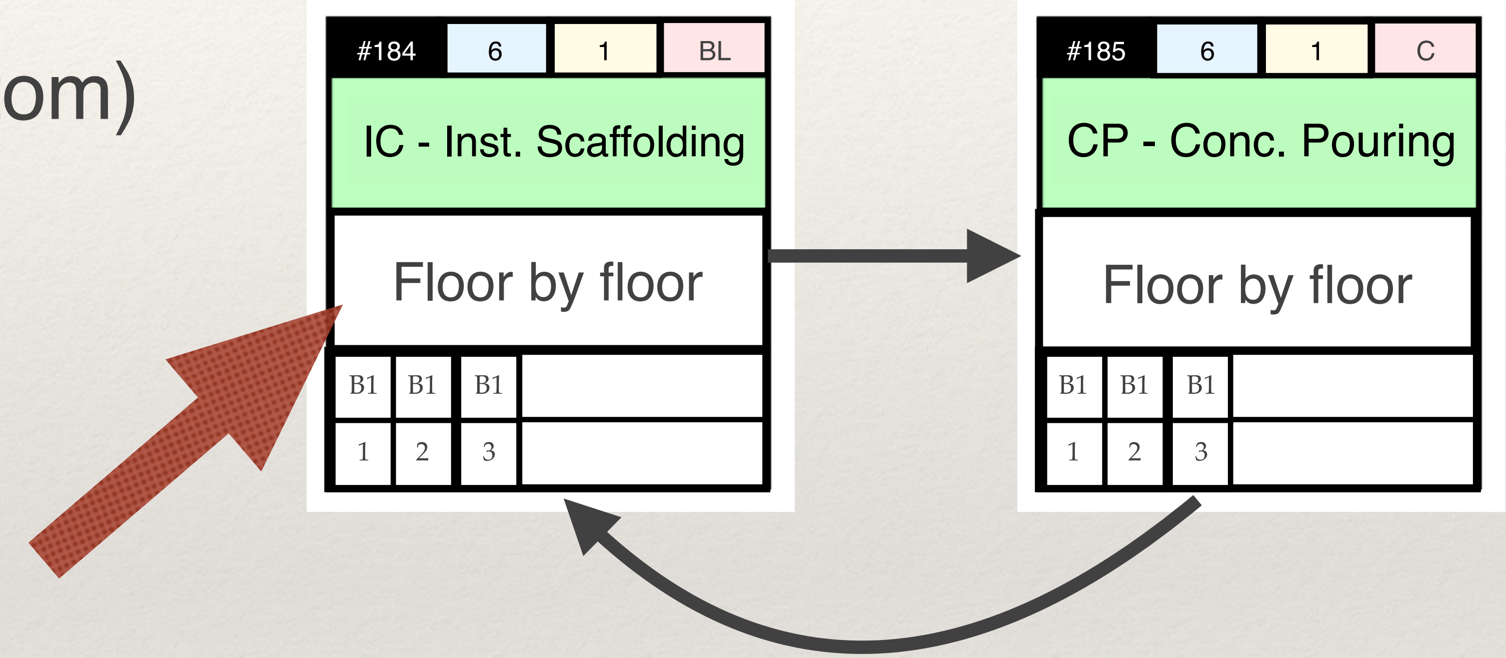
Hidden Knowledge and Ambiguities

- **Orderings**
  among the locations
  (bottom to top, top to bottom)

- Precedence **Scope**
  (floor, activity, building)

- How to perform **Loops**



#184 | 6 | 1 | BL

IC - Inst. Scaffolding

Floor by floor

B1 | B1 | B1

1 | 2 | 3

#185 | 6 | 1 | C

CP - Conc. Pouring

Floor by floor

B1 | B1 | B1

1 | 2 | 3

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How to Schedule?

- Preconditions for **manual** and **automatic** scheduling
  - Represent explicitly the hidden knowledge
  - Make the language non-ambiguous (Formal)

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How to Schedule?

- Preconditions for **manual** and **automatic** scheduling
  - Represent explicitly the hidden knowledge
  - Make the language non-ambiguous (Formal)

- We extended the language (inspired by Declare)
- Provide a logic-based (LTLf) semantics

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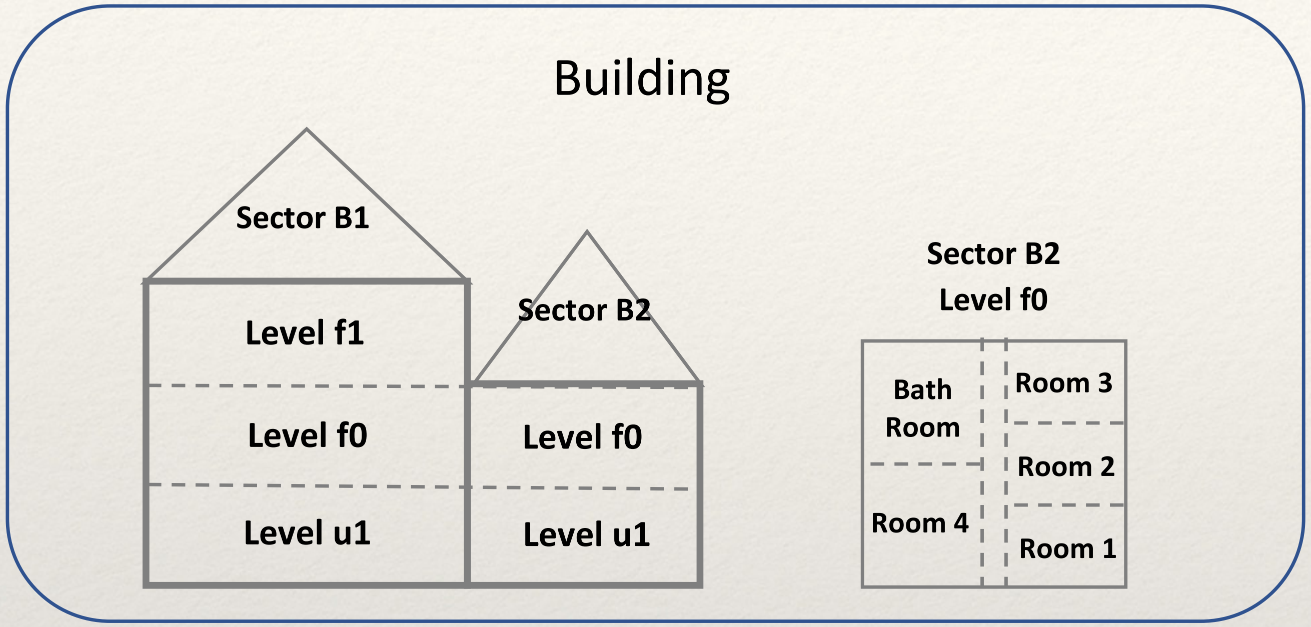
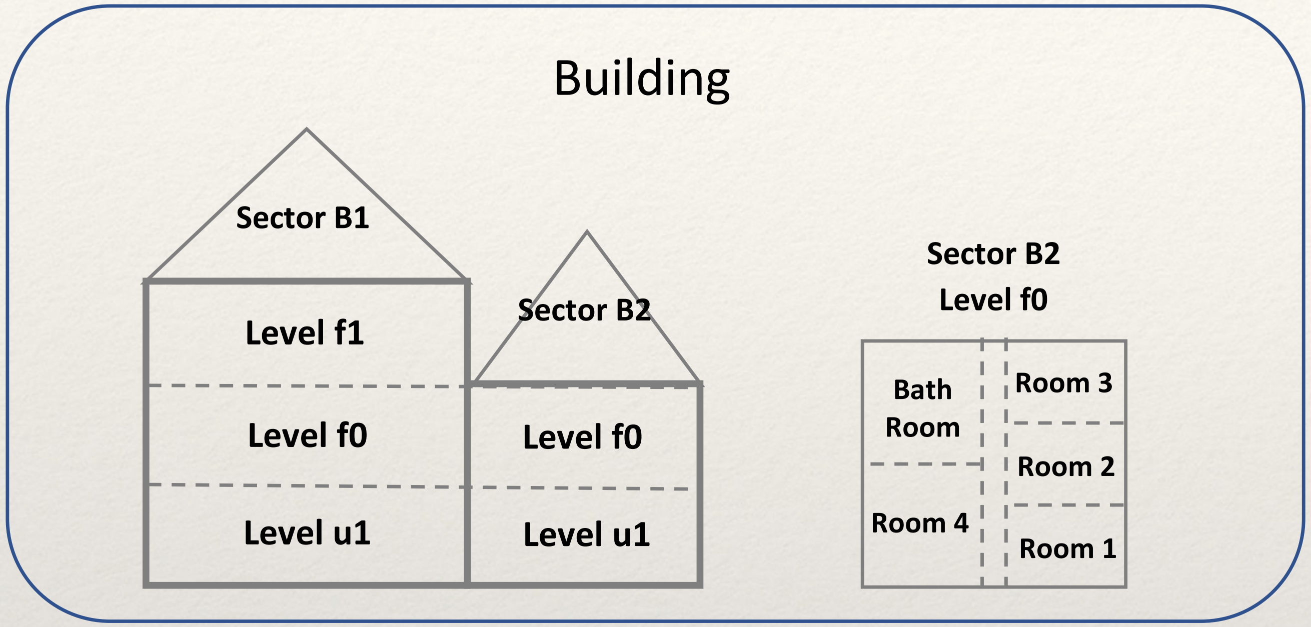
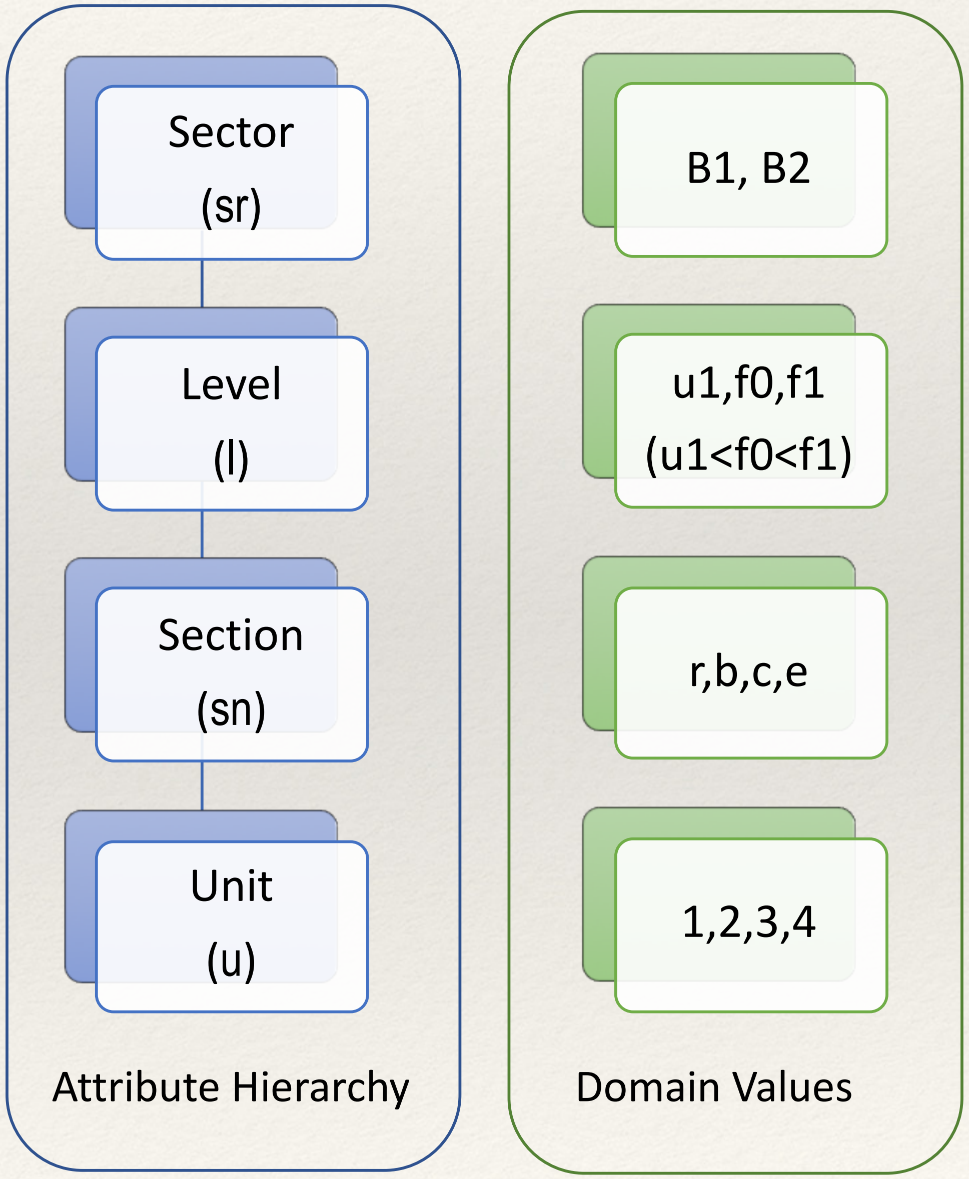
Customisable Building Representation



Customisable Building Representation





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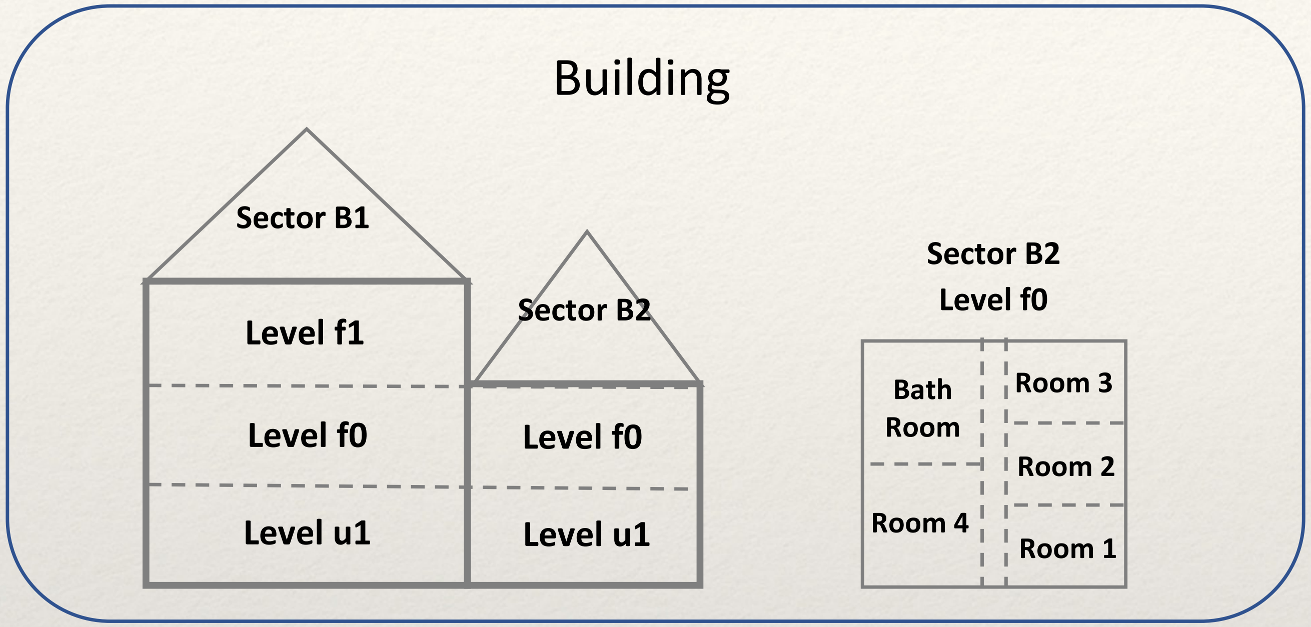

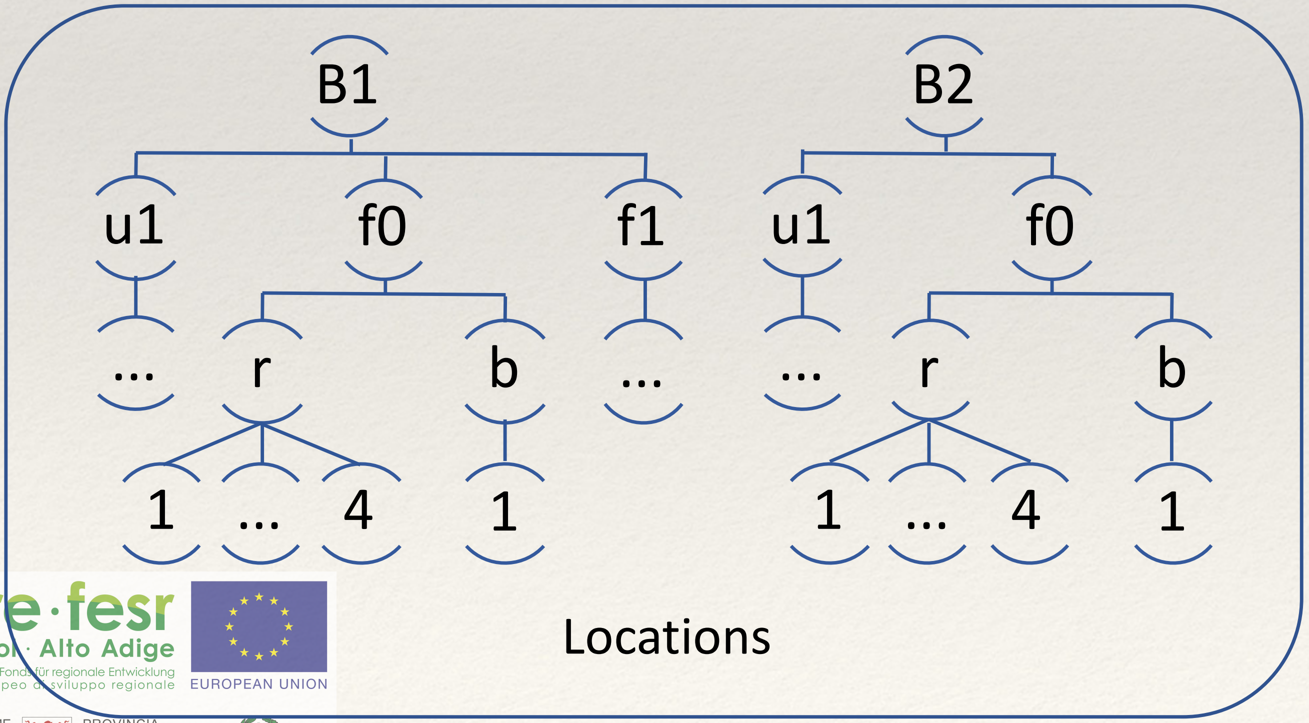

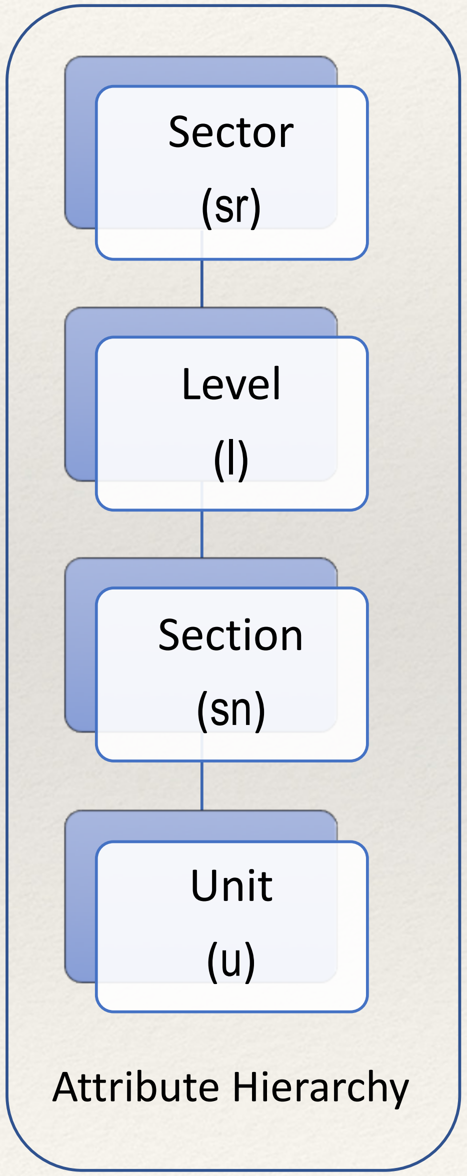

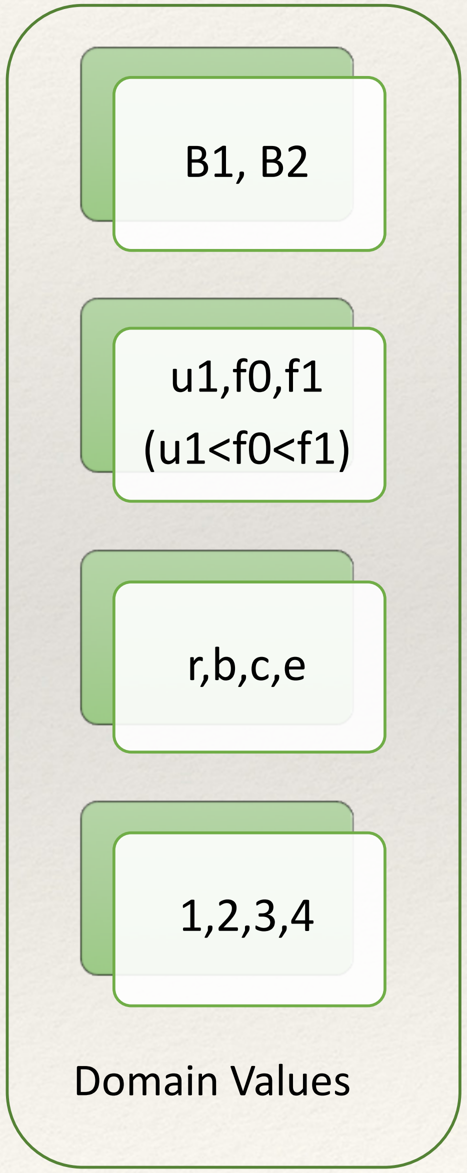

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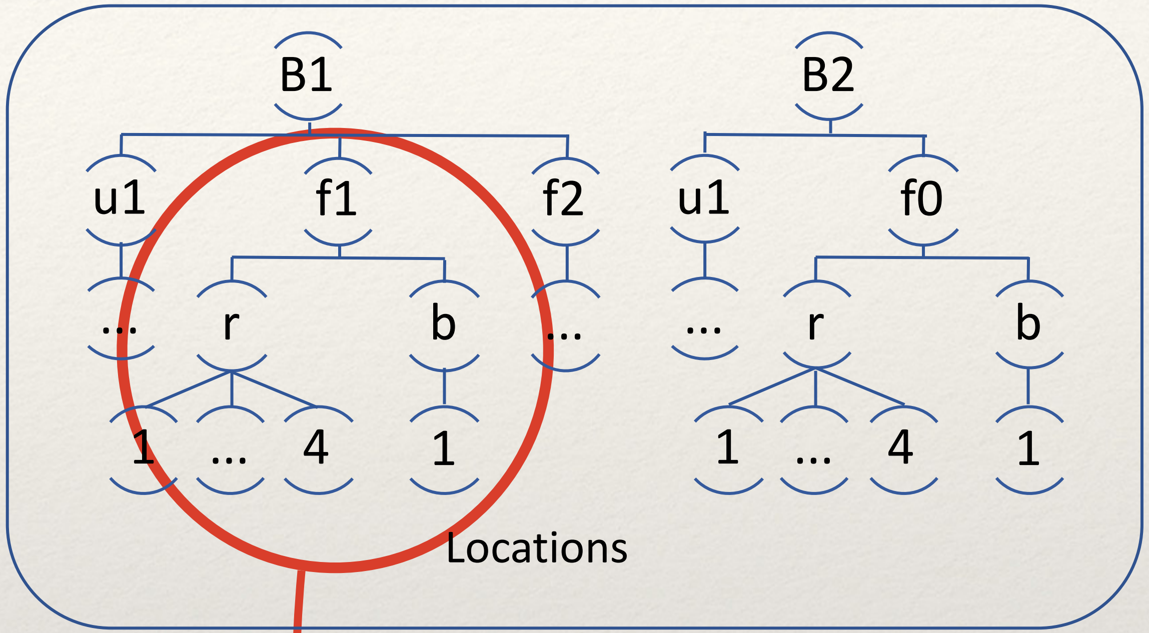
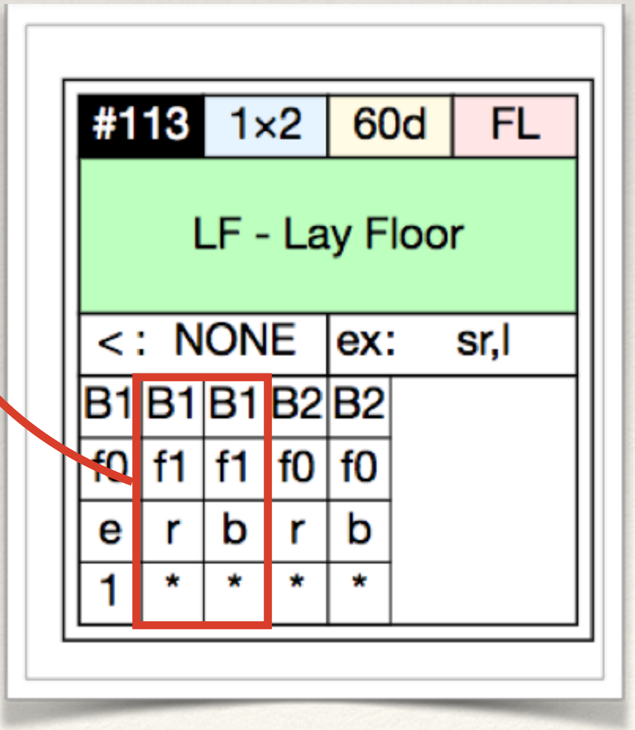
Representation of Locations

- A building is abstractly represented as a tree
- Locations in the tasks are **subtrees**



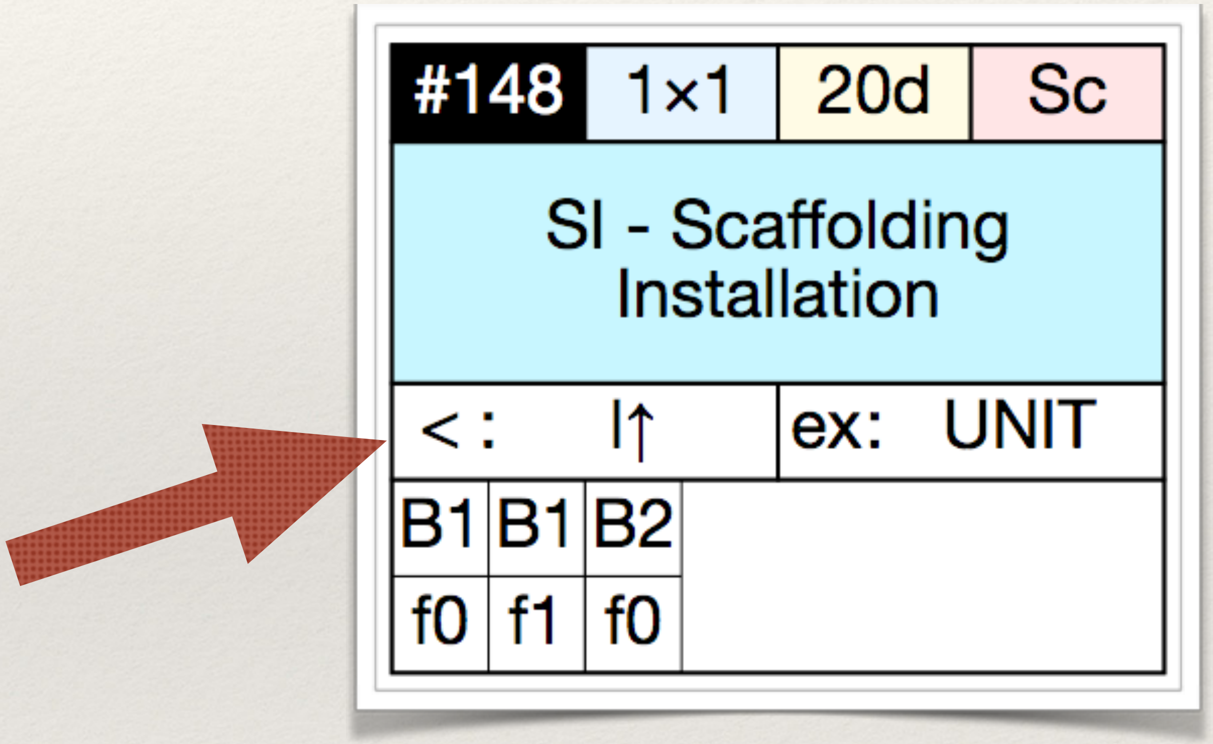
<B1,f1,r,*>
<B1,f1,b,*>



#113	1×2	60d	FL	
LF - Lay Floor				
< : NONE		ex: sr,l		
B1	B1	B1	B2	B2
f0	f1	f1	f0	f0
e	r	b	r	b
1	*	*	*	*

Ordering Constraints

- Attribute domain values can be ordered
- **Ascending** and **descending** ordering constraints



#148	1×1	20d	Sc
SI - Scaffolding Installation			
< : I↑		ex: UNIT	

B1	B1	B2
f0	f1	f0

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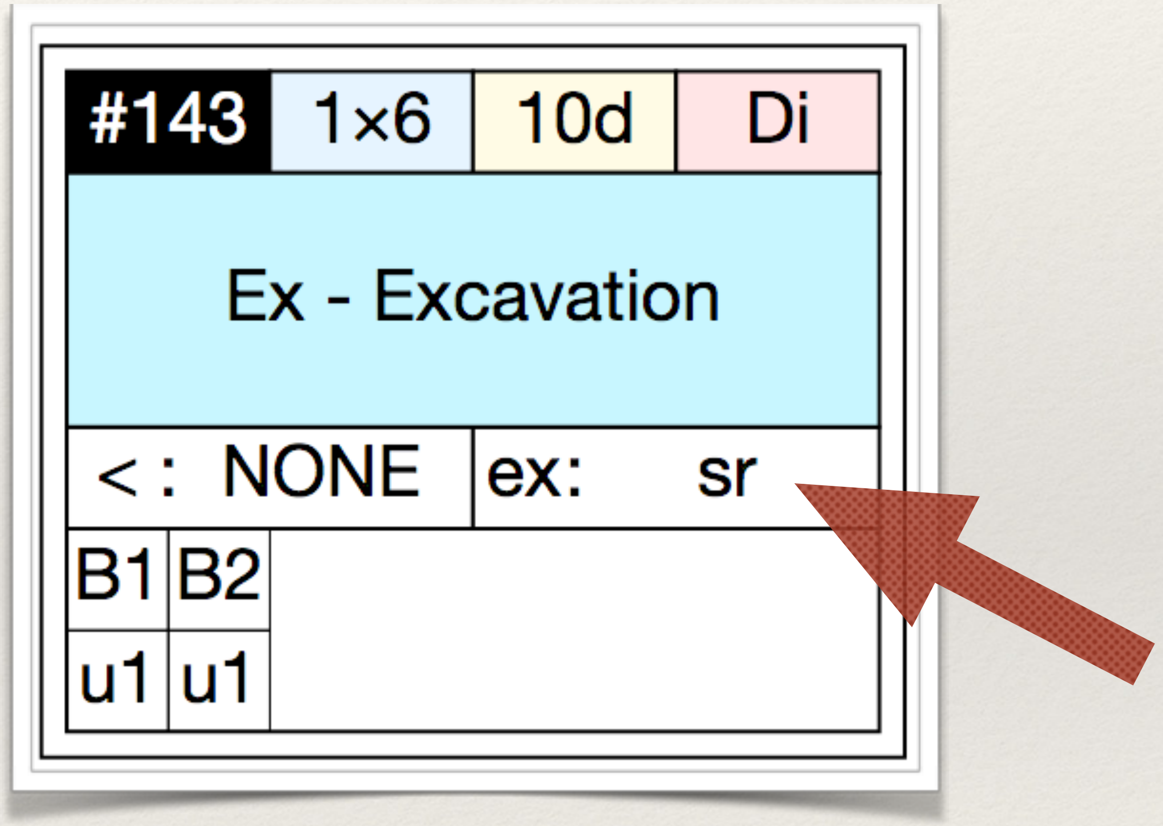
Exclusivity Constraints

- Once the task is started, **no other task** can be performed there
- By default: exclusivity at the **unit level**



#143	1×6	10d	Di
Ex - Excavation			
<: NONE		ex: sr	
B1	B2		
u1	u1		

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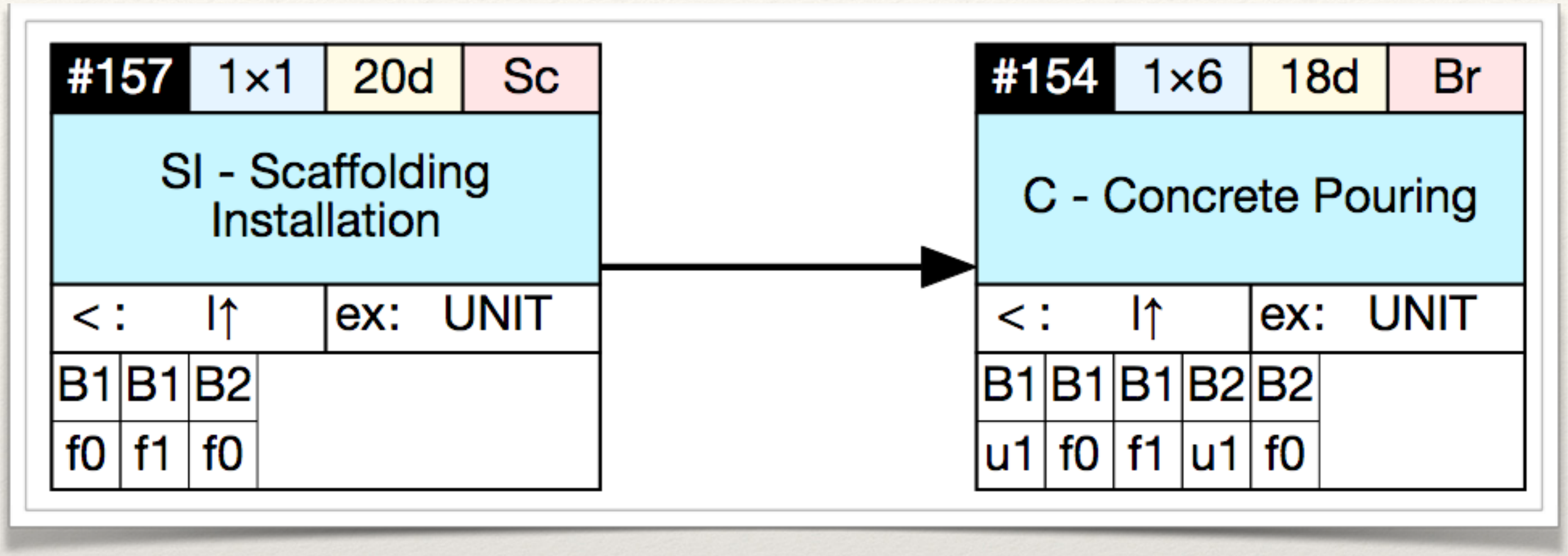
Precedences



#157	1×1	20d	Sc
SI - Scaffolding Installation			
<:	I↑	ex:	UNIT

B1	B1	B2
f0	f1	f0

#154	1×6	18d	Br
C - Concrete Pouring			
<:	I↑	ex:	UNIT

B1	B1	B1	B2	B2
u1	f0	f1	u1	f0

- Precedences between activities

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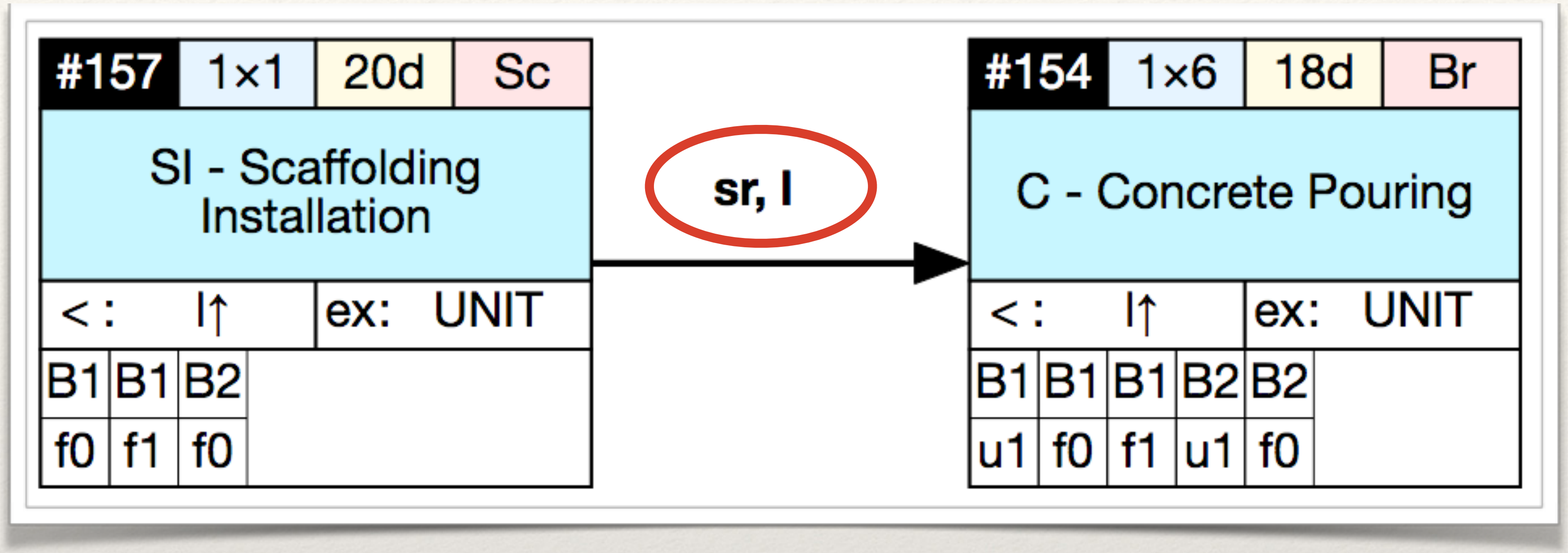
Precedences: Scope



#157	1×1	20d	Sc
SI - Scaffolding Installation			
<: l↑		ex: UNIT	
B1	B1	B2	
f0	f1	f0	

sr, l

#154	1×6	18d	Br	
C - Concrete Pouring				
<: l↑		ex: UNIT		
B1	B1	B1	B2	B2
u1	f0	f1	u1	f0

- The **Scope** specialises the precedence (e.g., precedence by <sector, level>)
- By default: **Activity level**

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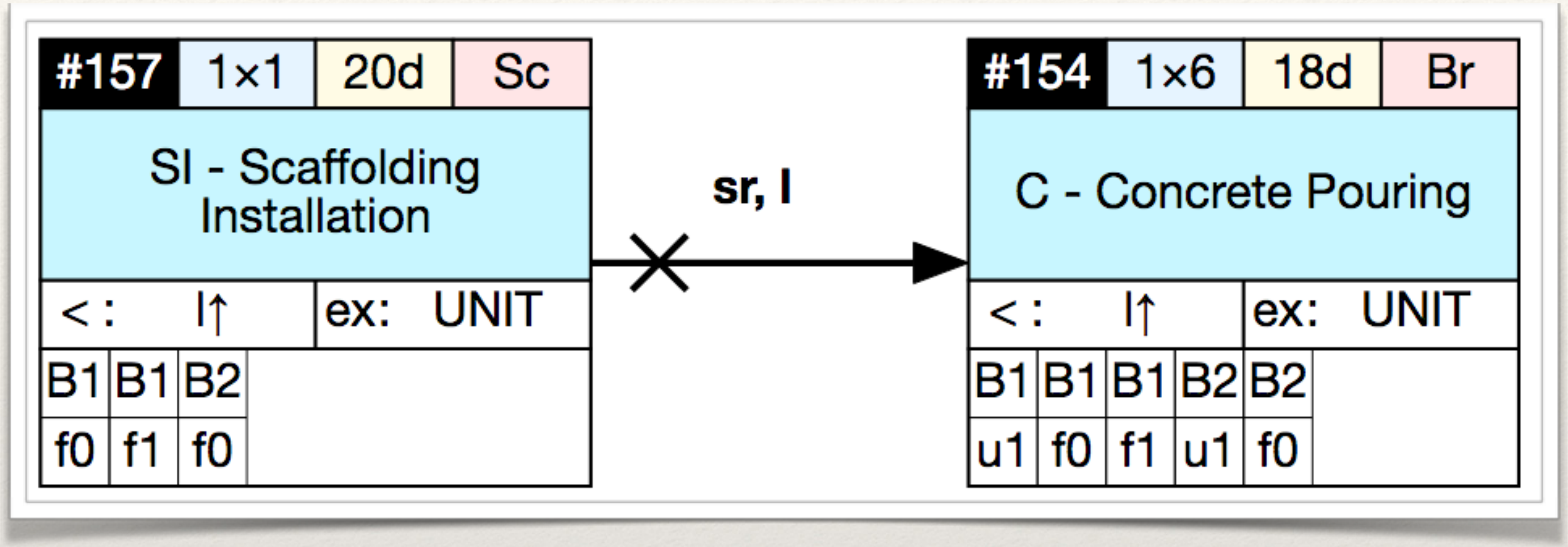
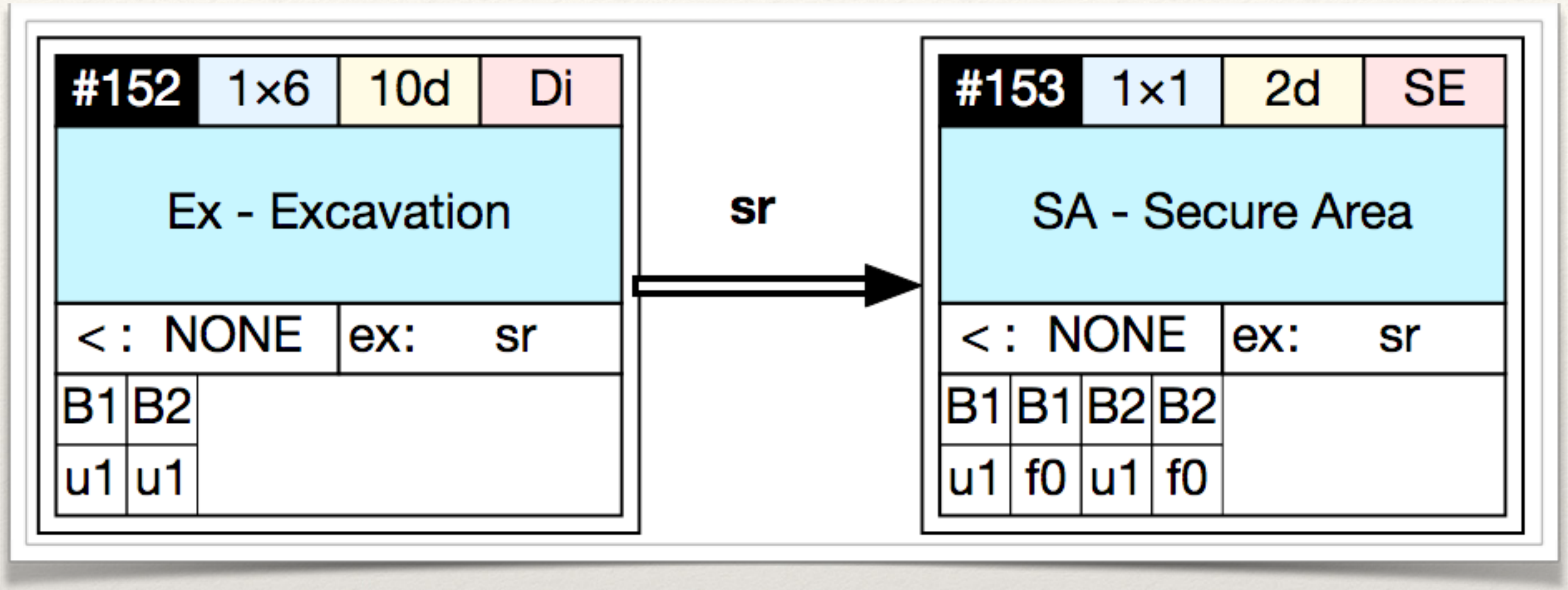
Precedences: Alternate Precedence



- **Alternation** between antecedent and consequent:
  - antecedent **before** consequent
  - **and** the antecedent has to **wait** for the consequent

Precedences: Chain Precedence



#152 1×6 10d Di

Ex - Excavation

<: NONE ex: sr

B1 B2

u1 u1

sr

#153 1×1 2d SE

SA - Secure Area

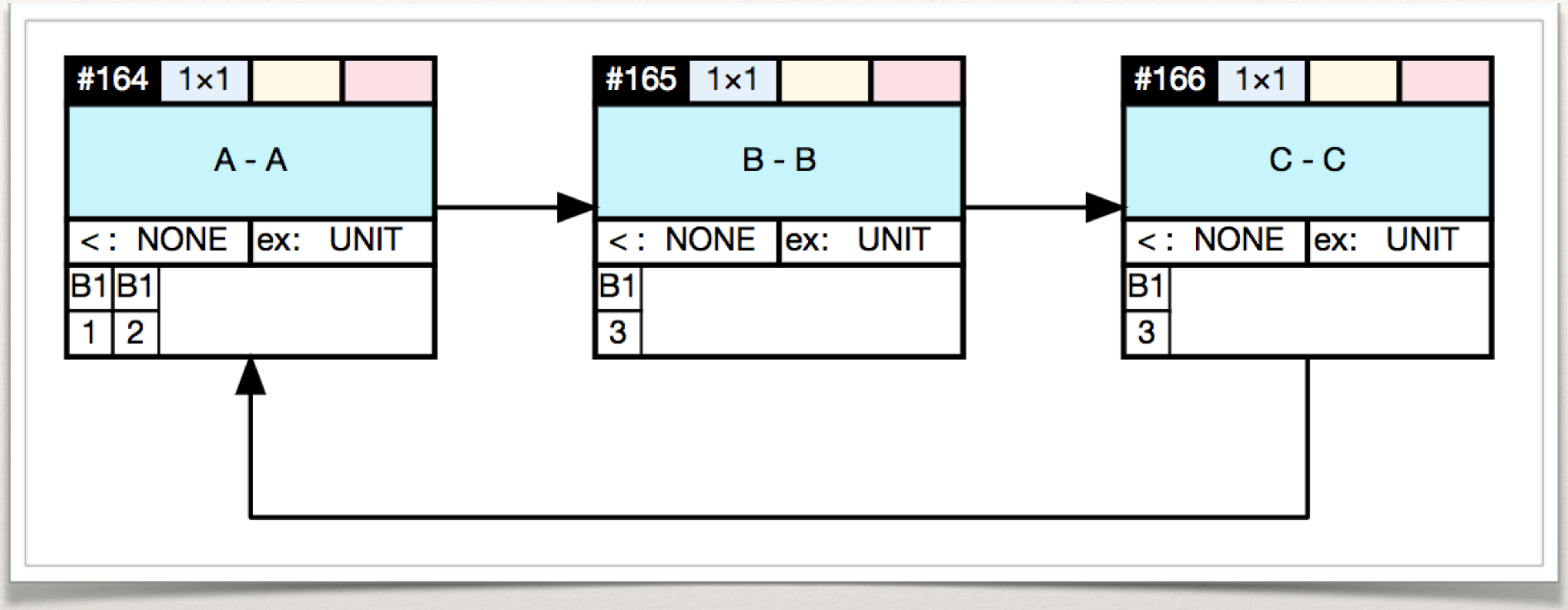
<: NONE ex: sr

B1 B1 B2 B2

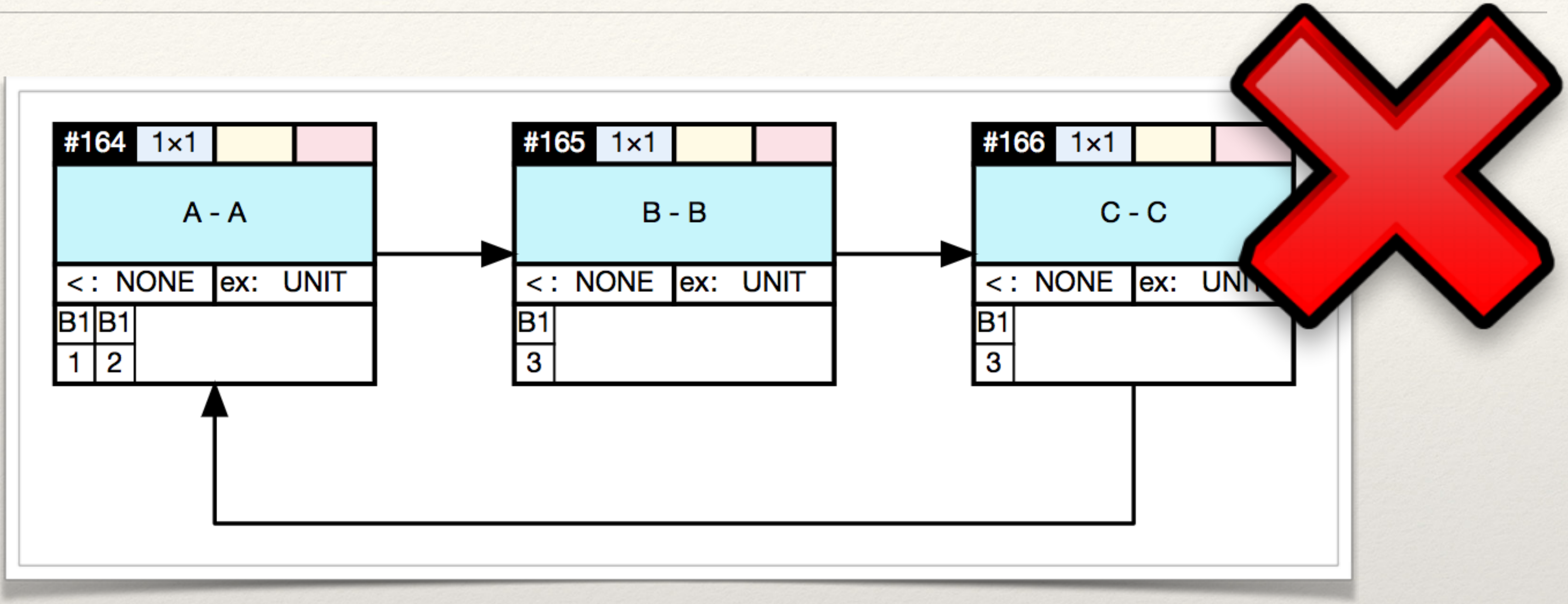
u1 f0 u1 f0

- **Chain** between two activities:
  - **no** other activities can be performed **in-between**

Does my model make sense?



Does my model make sense?



- Is there an execution satisfying all the constraints?
  Satisfiability Check

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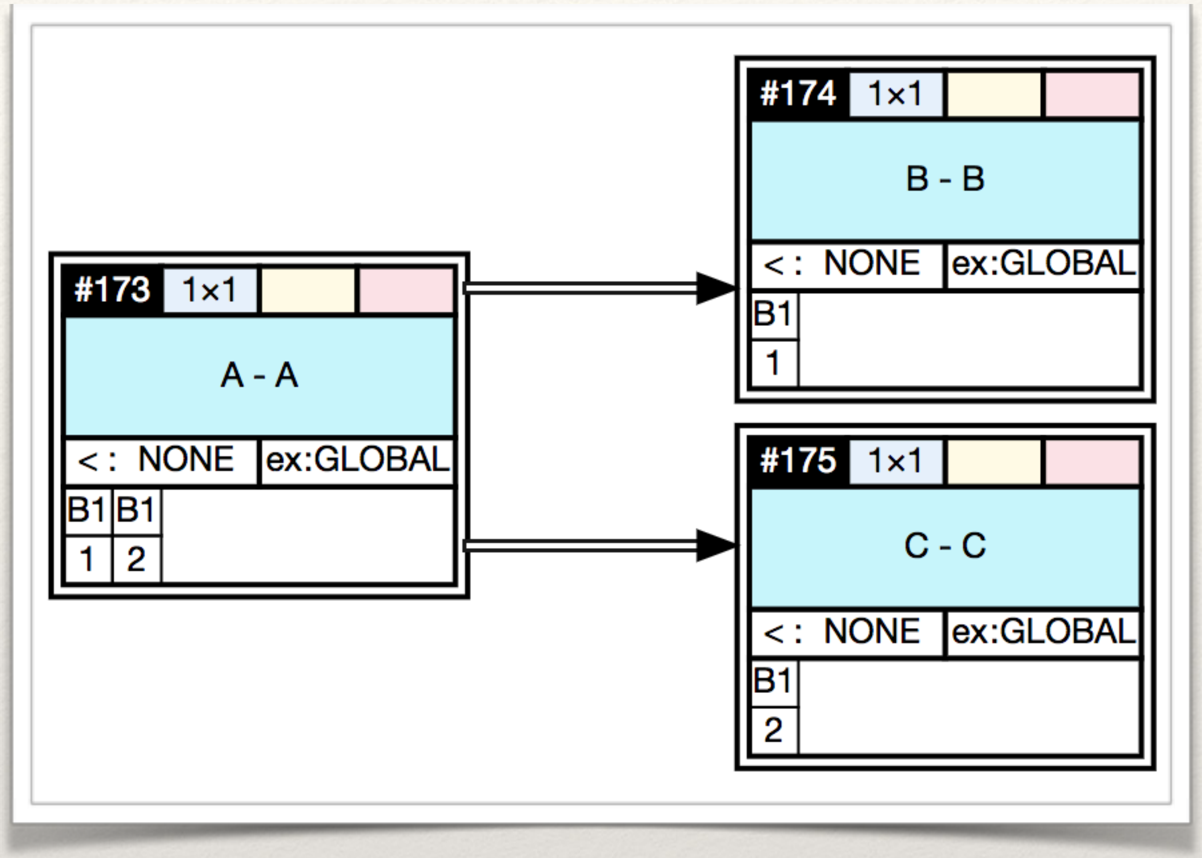
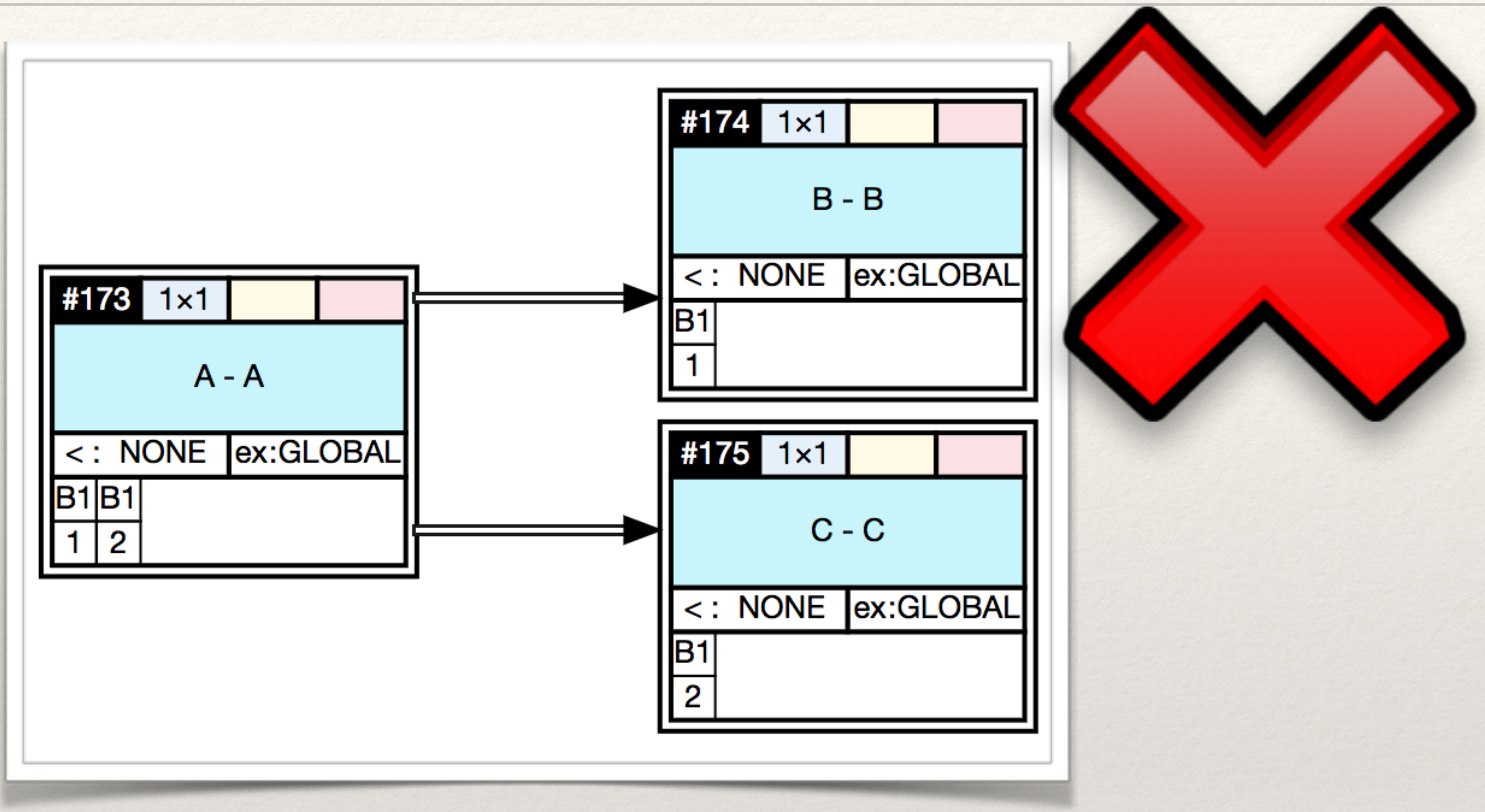
Satisfiability Check



- Is checking for loops enough to determine **Satisfiability**?

Satisfiability Check



#173 1×1

A - A

<: NONE ex:GLOBAL

B1	B1
1	2

#174 1×1

B - B

<: NONE ex:GLOBAL

B1
1

#175 1×1

C - C

<: NONE ex:GLOBAL

B1
2

- Is checking for loops enough to determine **Satisfiability**?
  - **No,**
  - Consider also the **dependencies**, **scopes** and **locations**

How to Check Satisfiability?

- Our model has a logic based semantics (LTLf)
- We can apply model checking techniques
- We performed some experiments using NuSMV

(state-of-the-art model checker)

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How to Check Satisfiability?

	Model	Tasks	Dep.	Loc.	NuSMV
✓	Sat.	8	9	312	**2min 35s**
✗	Non-sat.	8	9	312	**>1h**

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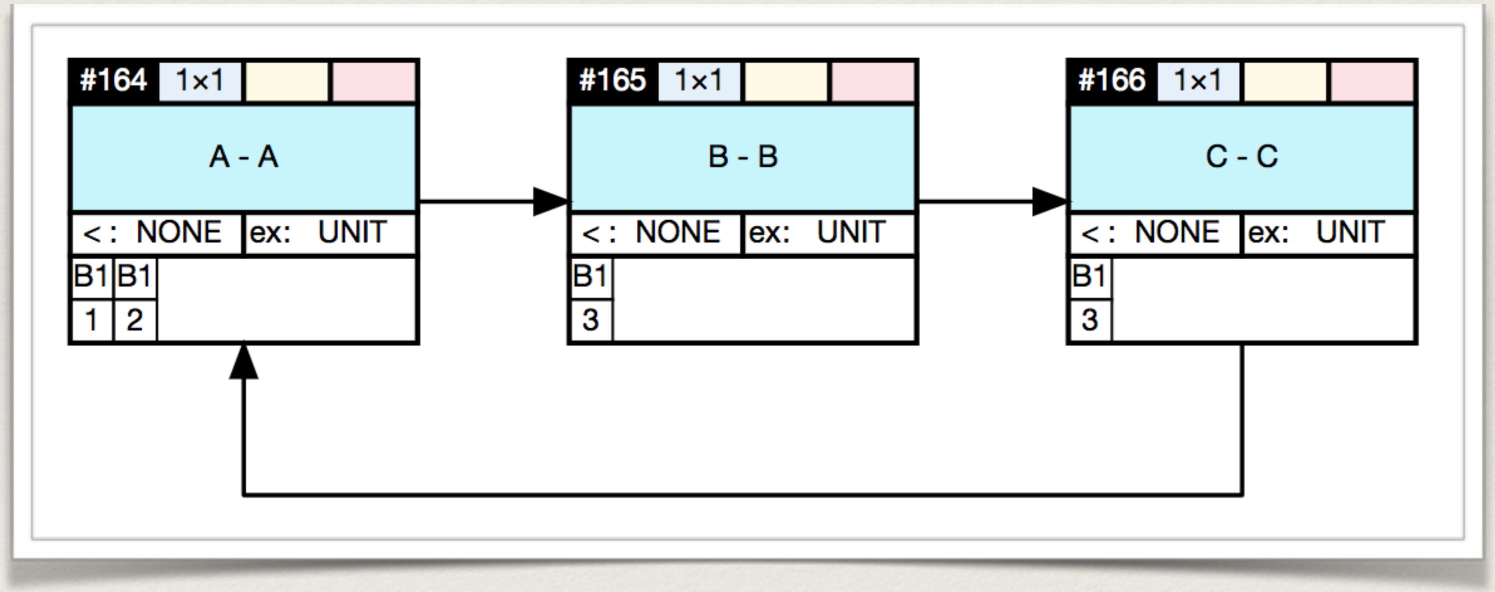
Other Way to Check Satisfiability?

- Translate a Diagram into a Task-Unit (TU) Graph



<A, B1-1>

<A, B1-2>

<B, B1-3>

<C, B1-3>

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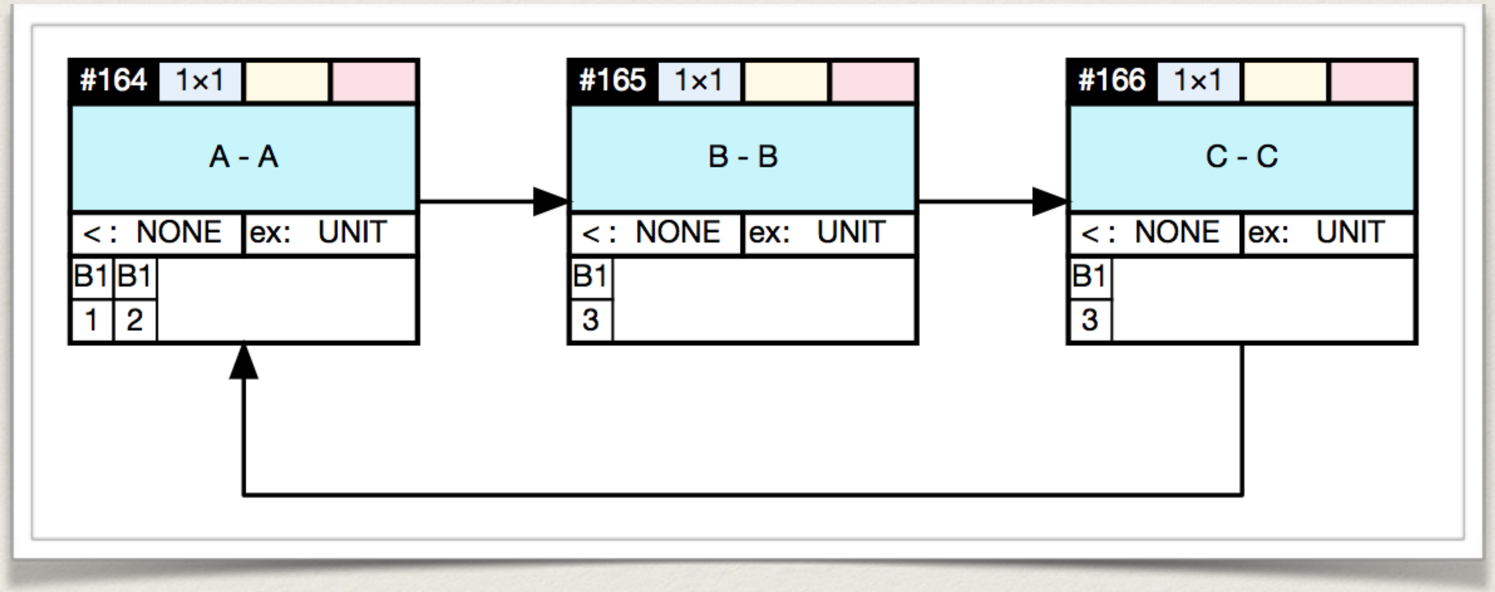
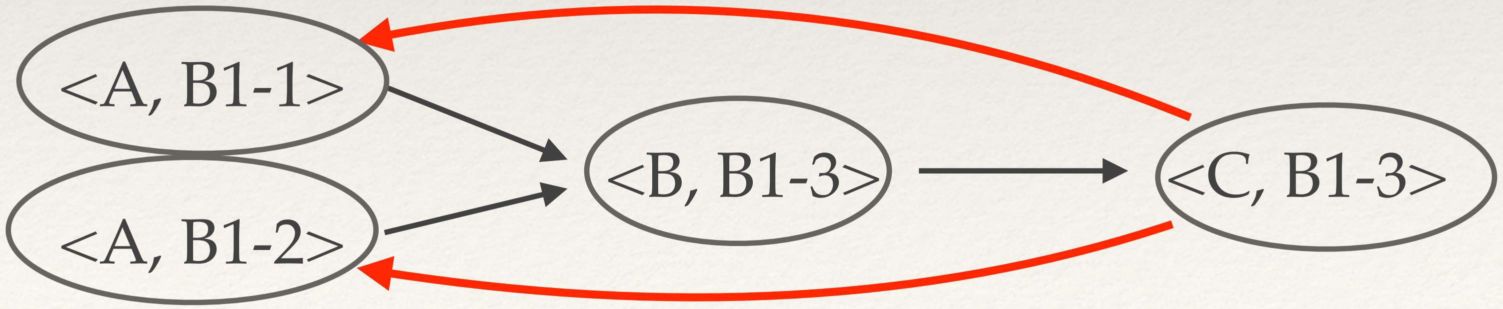
Other Way to Check Satisfiability?

- Translate a Diagram into a Task-Unit (TU) Graph
- Translate the precedences into arrows between TU nodes





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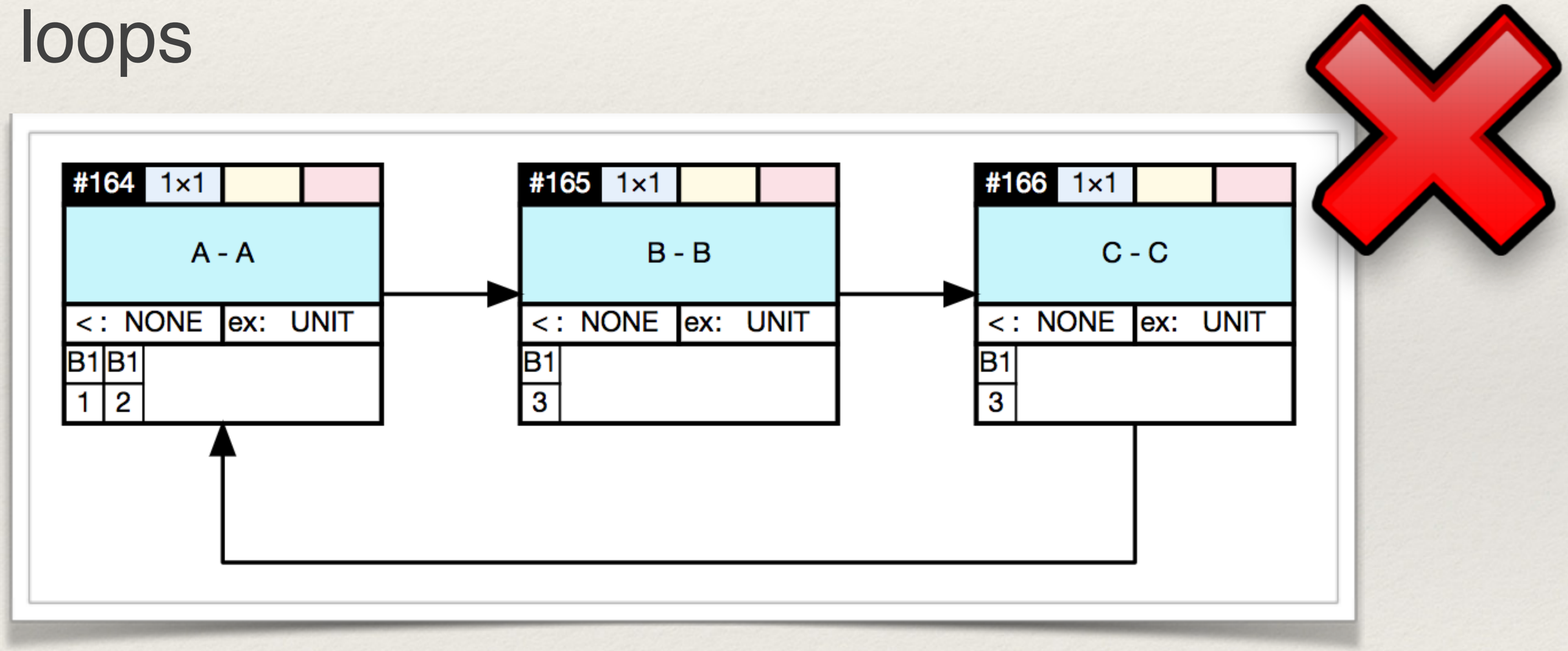
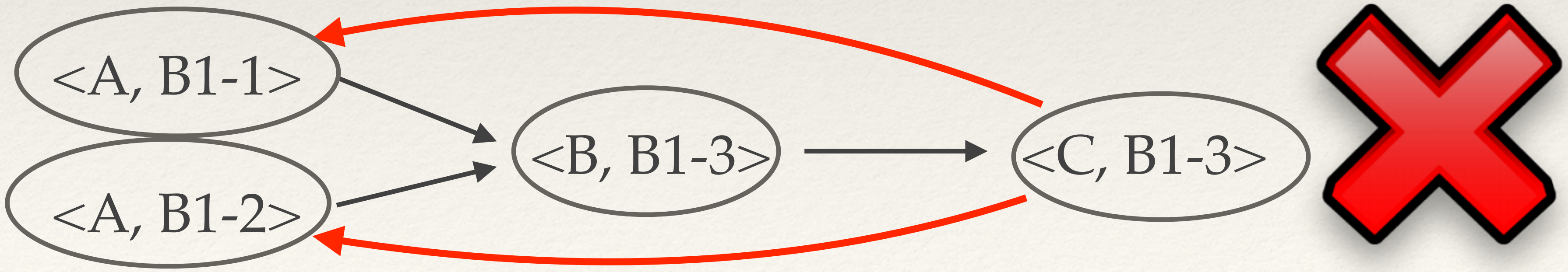
Other Way to Check Satisfiability?

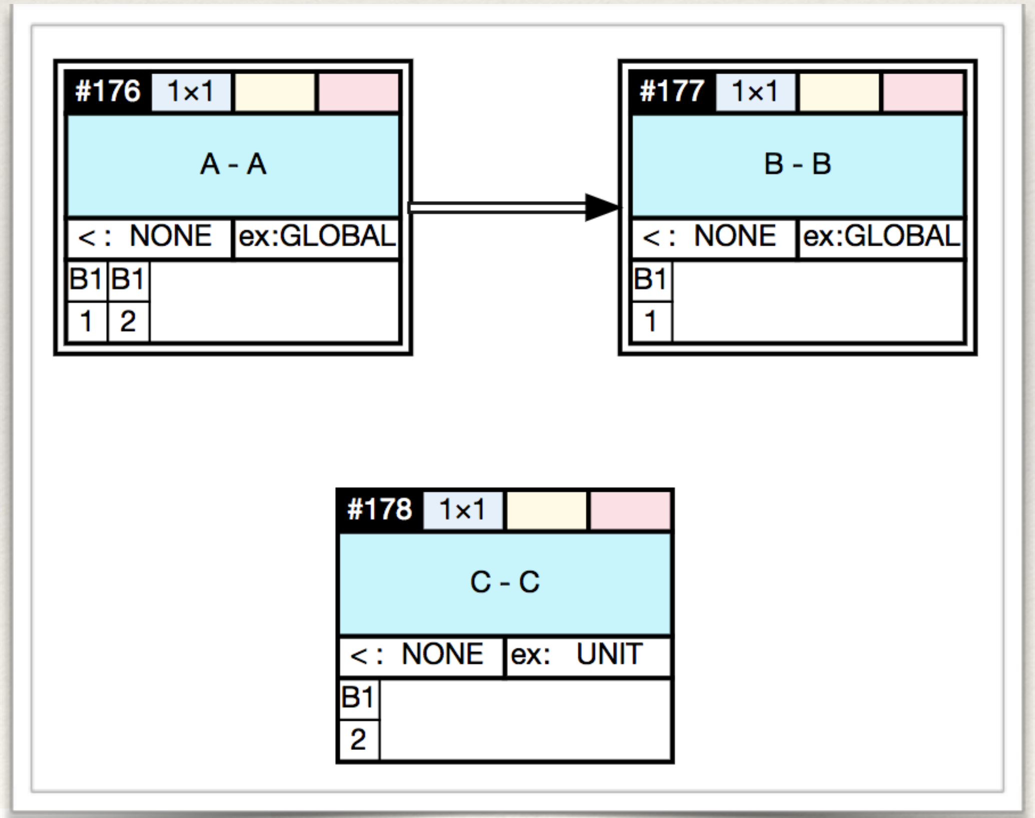
- Translate a Diagram into a Task-Unit (TU) Graph
- Translate the precedences into arrows between TU nodes
- Check for loops

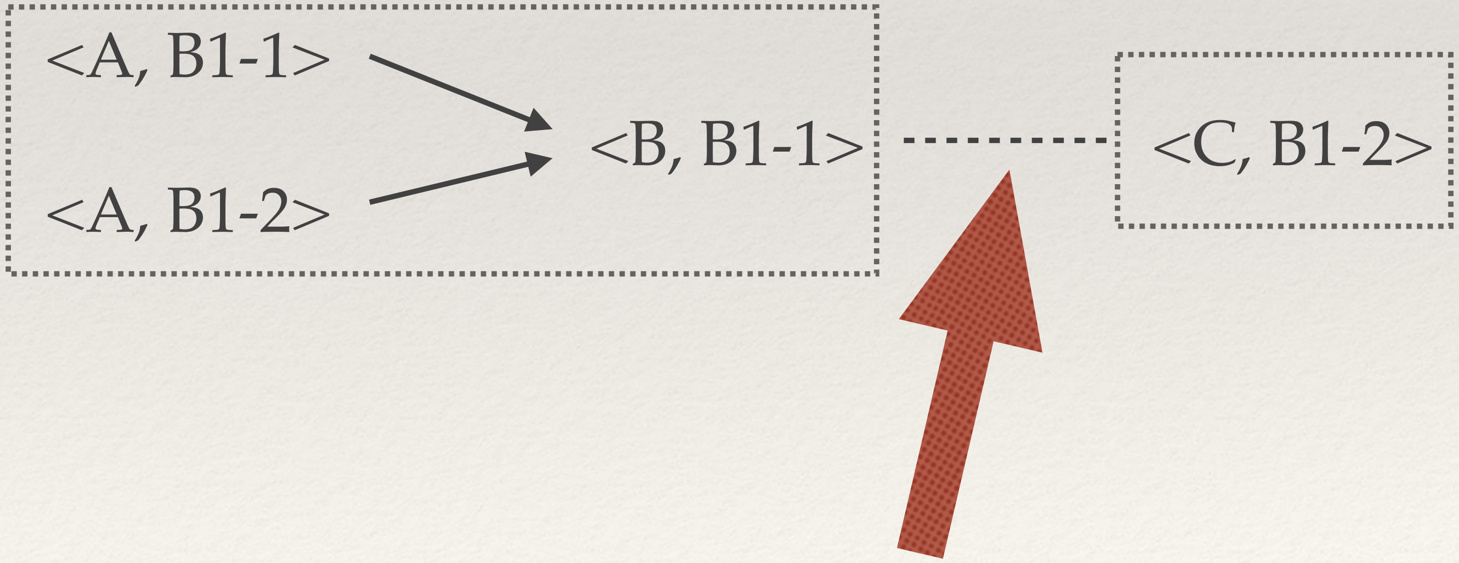




Disjunction in the TU Graph

- Some constraints introduce disjunction
- One has to check possible orientations




<A, B1-1>

<A, B1-2>

<B, B1-1>

<C, B1-2>

Algorithm at a Glance

- **Check for Cycles**
  - Cycles: If the graph contains a cycle then is not orientable

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Algorithm at a Glance

- **Check for Cycles**
  - Cycles: If the graph contains a cycle then is not orientable
- **Deterministic Orientation**
  - Direct the undirected edges for which only one orientation is possible

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Algorithm at a Glance

- **Check for Cycles**
  - Cycles: If the graph contains a cycle then is not orientable
- **Deterministic Orientation**
  - Direct the undirected edges for which only one orientation is possible
- **Divide&Conquer**
  - Partition the graph so that:
    - orientability can be checked for each subgraph
    - by trying all orientations

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Satisfiability Check

	Model	Tasks	Dep.	Loc.	Nodes	Arcs	Edges	NuSMV	US
✓	Sat.	8	9	312	236	9415	524	2min 35s	**27 ms**
✗	Non-sat.	8	9	312	236	10003	521	>1h	**5 ms**

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Satisfiability Check

	Model	Tasks	Dep.	Loc.	Nodes	Arcs	Edges	NuSMV	US
✓	Sat.	8	9	312	236	9415	524	2min 35s	27 ms
✗	Non-sat.	8	9	312	236	10003	521	>1h	5 ms
✗	Bigger	12	14	312 (2)	244	9435	574	>1h	10 ms
✗	More Edges	12	14	312 (47)	424	15131	1740	>1h	23 ms

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Satisfiability Check

	Model	Tasks	Dep.	Nodes	Arcs	Edges	US
✓	Sat.	8	9	236	9415	524	27 ms
✗	Non-sat.	8	9	236	10003	521	5 ms
✗	Bigger	12	14	244	9435	574	10 ms
✗	Adding Locations	12	14	424	15131	1740	23 ms
✗	Bigger	480	1291	16,960	1,436,759	678,680	55,866 ms (~1 min)
✗	Bigger	720	2,526	25,440	3,082,925	1,526,820	379,409 ms (~6.32 min)
✗	Bigger	960	4,187	33,920	5,217,426	2,714,160	OOM

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Summary

- Language **Construction Process Modelling**
    - Graphical
    - Declarative: Captures the constraints (**what** and not **how**)
    - Formal
- Effective algorithm to check satisfiability
- **Demo:** both are implemented in a proof-of-concept tool

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Future Work

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- COCkPiT:
  Collaborative Construction Project managemenT
- Automatic Schedule:
  - Optimised
  - Incremental
  - Align changes: Model 🔄 Schedule

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BPM 2018

Thank you

Elisa Marengo
Werner Nutt
Matthias Perktold

Free University of Bolzano