Change the Plan - How hard can that be?

Gregor Behnke, Daniel Höller, Pascal Bercher, Susanne Biundo

Ulm University, Institute of Artificial Intelligence

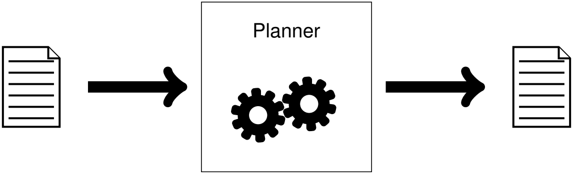
June 17, 2016

ICAPS 2016 – London

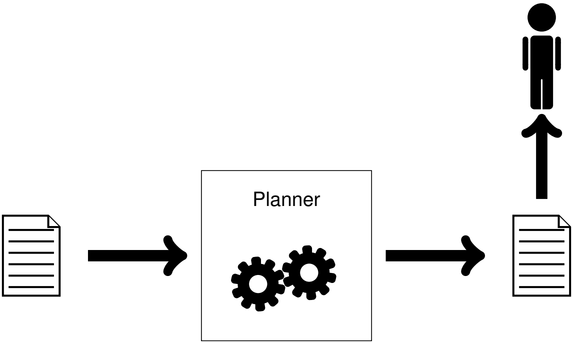
sfb transregio 62
Companion Technology

Deutsche
Forschungsgemeinschaft
DFG

Changing Plans

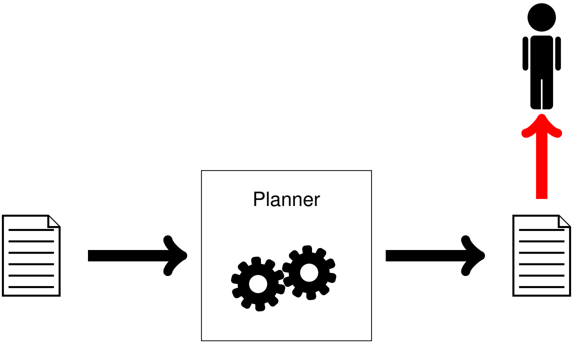


Changing Plans



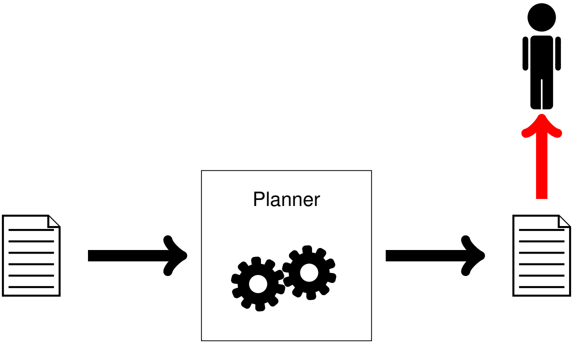
- Planning doesn’t take place in a vacuum

Changing Plans



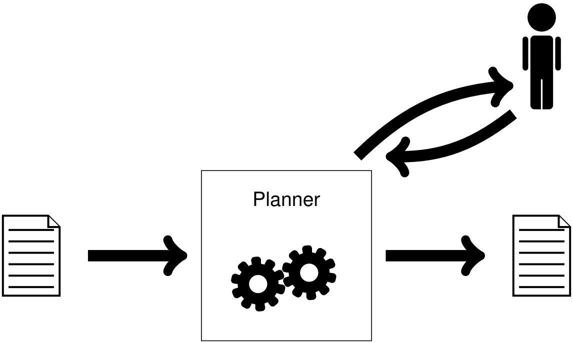
- Planning doesn’t take place in a vacuum
- Planners can generate solutions users might not like

Changing Plans



- Planning doesn't take place in a vacuum
- Planners can generate solutions users might not like
- Preferences can be infeasible
  - Users might not know their preferences
  - ... or cannot be expected to be asked about them

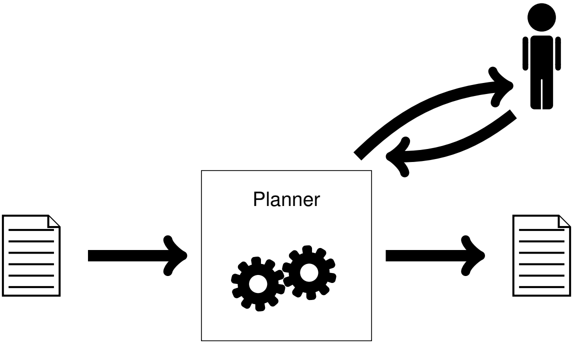
Changing Plans



- Planning doesn't take place in a vacuum
- Planners can generate solutions users might not like
- Preferences can be infeasible
  - Users might not know their preferences
  - ... or cannot be expected to be asked about them

⇒ Integrate the user into the planning process

Changing Plans



- Planning doesn't take place in a vacuum
- Planners can generate solutions users might not like
- Preferences can be infeasible
  - Users might not know their preferences
  - ... or cannot be expected to be asked about them

$\Rightarrow$ Integrate the user into the planning process

$\Rightarrow$ We have to allow for changes to plans

Changing Plans

Changing plans is important for user-centred planning applications, e.g., mixed-initiative planning

Changing Plans

Changing plans is important for user-centred planning applications,
e.g., mixed-initiative planning

We want to understand its theoretical foundations

Changing Plans

Changing plans is important for user-centred planning applications, e.g., mixed-initiative planning

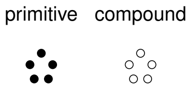
We want to understand its theoretical foundations

- Discuss what changing plans means in an HTN context
- Provide formal descriptions of several change operations
- Investigate their computational complexity

Hierarchical Task Network (HTN) Planning

$$\mathcal{P} = (P, C, c_I, M, L, s_I)$$

Hierarchical Task Network (HTN) Planning



$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks

Hierarchical Task Network (HTN) Planning

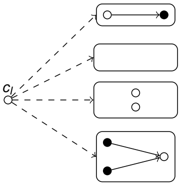
$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks
- $c_I \in C$ the initial task

A solution $tn \in Sol(\mathcal{P})$ must

- be a refinement of the initial task

Hierarchical Task Network (HTN) Planning



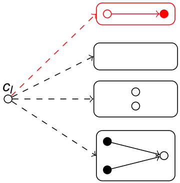
$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks
- $c_I \in C$ the initial task
- $M \subseteq C \times 2^{TN}$ the methods

A solution $tn \in Sol(\mathcal{P})$ must

- be a refinement of the initial task

Hierarchical Task Network (HTN) Planning



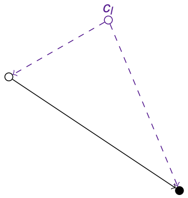
$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks
- $c_I \in C$ the initial task
- $M \subseteq C \times 2^{TN}$ the methods

A solution $tn \in Sol(\mathcal{P})$ must

- be a refinement of the initial task

Hierarchical Task Network (HTN) Planning



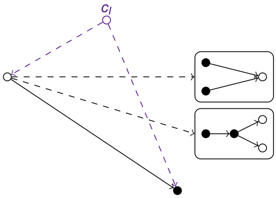
$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks
- $c_I \in C$ the initial task
- $M \subseteq C \times 2^{TN}$ the methods

A solution $tn \in Sol(\mathcal{P})$ must

- be a refinement of the initial task

Hierarchical Task Network (HTN) Planning



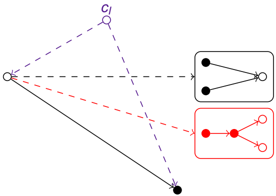
$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks
- $c_I \in C$ the initial task
- $M \subseteq C \times 2^{TN}$ the methods

A solution $tn \in Sol(\mathcal{P})$ must

- be a refinement of the initial task

Hierarchical Task Network (HTN) Planning



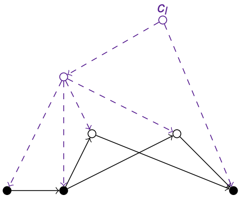
$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks
- $c_I \in C$ the initial task
- $M \subseteq C \times 2^{TN}$ the methods

A solution $tn \in Sol(\mathcal{P})$ must

- be a refinement of the initial task

Hierarchical Task Network (HTN) Planning



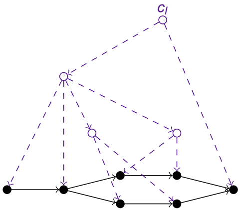
$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks
- $c_I \in C$ the initial task
- $M \subseteq C \times 2^{TN}$ the methods

A solution $tn \in Sol(\mathcal{P})$ must

- be a refinement of the initial task

Hierarchical Task Network (HTN) Planning



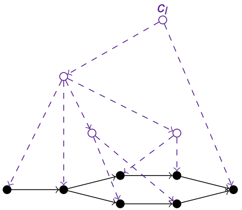
$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks
- $c_I \in C$ the initial task
- $M \subseteq C \times 2^{TN}$ the methods

A solution $tn \in Sol(\mathcal{P})$ must

- be a refinement of the initial task
- only contain primitive tasks

Hierarchical Task Network (HTN) Planning



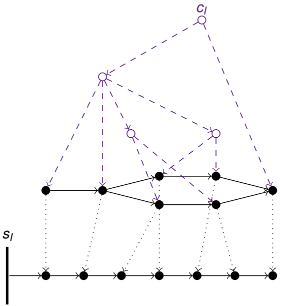
$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks
- $c_I \in C$ the initial task
- $M \subseteq C \times 2^{TN}$ the methods
- L a set of variables
- $s_I \subseteq L$ the initial state

A solution $tn \in Sol(\mathcal{P})$ must

- be a refinement of the initial task
- only contain primitive tasks

Hierarchical Task Network (HTN) Planning



$\mathcal{P} = (P, C, c_I, M, L, s_I)$

- P a set of primitive tasks
- C a set of compound tasks
- $c_I \in C$ the initial task
- $M \subseteq C \times 2^{TN}$ the methods
- L a set of variables
- $s_I \subseteq L$ the initial state

A solution $tn \in Sol(\mathcal{P})$ must

- be a refinement of the initial task
- only contain primitive tasks
- have a linearization,
  executable from the initial state

Motivation of Hierarchies

HTN planning problems can pose restrictions that classical planning cannot

Motivation of Hierarchies

HTN planning problems can pose restrictions that classical planning cannot

- Every plan must contain the same amount of *a*'s and *b*'s
- *a* can be executed twice in a row, but not thrice
- HTNs can express all context free and some context sensitive language, while classical planning is limited to regular structures
- Precondition-free HTNs can express classical planning

Motivation of Hierarchies

HTN planning problems can pose restrictions that classical planning cannot

- Every plan must contain the same amount of *a*'s and *b*'s
- *a* can be executed twice in a row, but not thrice
- HTNs can express all context free and some context sensitive language, while classical planning is limited to regular structures
- Precondition-free HTNs can express classical planning

When changing plans, we can either:

- Ignore the domain's hierarchy and just try to find an executable solution
- Find a solution adhering to the hierarchy, s.t. we keep all restrictions

Motivation of Hierarchies

HTN planning problems can pose restrictions that classical planning cannot

- Every plan must contain the same amount of *a*'s and *b*'s
- *a* can be executed twice in a row, but not thrice
- HTNs can express all context free and some context sensitive language, while classical planning is limited to regular structures
- Precondition-free HTNs can express classical planning

When changing plans, we can either:

- Ignore the domain's hierarchy and just try to find an executable solution
- **Find a solution adhering to the hierarchy, s.t. we keep all restrictions**

Results

We've investigated a wide range of change requests

- 5 request objectives
- 3 request restrictions

	add	delete	exchange	order	avoid effect
no changes	**NP**	**NP**	**NP**	**NP**	**NP**
k changes	**NEXPTIME**	**NEXPTIME**	**NEXPTIME**	**NEXPTIME**	**NEXPTIME**
any changes	*un-dec*	*un-dec*	*un-dec*	*un-dec*	*un-dec*

Results

We've investigated a wide range of change requests

- 5 request objectives
- 3 request restrictions

	add	delete	exchange	order	avoid effect
no changes	**NP**	**NP**	**NP**	**NP**	**NP**
k changes	**NEXPTIME**	**NEXPTIME**	**NEXPTIME**	**NEXPTIME**	**NEXPTIME**
any changes	*un-dec*	*un-dec*	*un-dec*	*un-dec*	*un-dec*

- Most proofs are structurally similar
- We will only show one from each group

Add Task – no changes

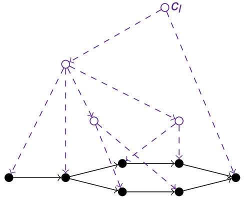
Definition (ADD-NO-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and task t.
ADD-NO-CHANGE is to decide whether the task network tn', which is tn with an additional task t and some ordering constraints added, is still a solution.

Add Task – no changes

Definition (ADD-NO-CHANGE)

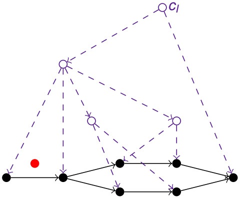
Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and task t.
ADD-NO-CHANGE is to decide whether the task network tn', which is tn with an additional task t and some ordering constraints added, is still a solution.



Add Task – no changes

Definition (ADD-NO-CHANGE)

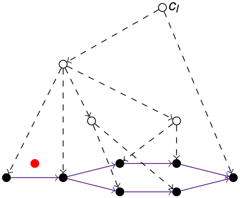
Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and task t.
ADD-NO-CHANGE is to decide whether the task network tn', which is tn with an additional task t and some ordering constraints added, is still a solution.



Add Task – no changes

Definition (ADD-NO-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and task t.
ADD-NO-CHANGE is to decide whether the task network tn', which is tn with an additional task t and some ordering constraints added, is still a solution.

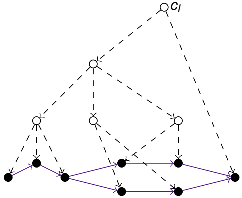


- Decomposition becomes invalid

Add Task – no changes

Definition (ADD-NO-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and task t.
ADD-NO-CHANGE is to decide whether the task network tn', which is tn with an additional task t and some ordering constraints added, is still a solution.

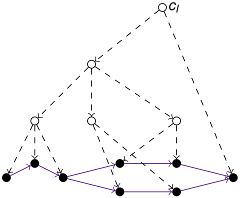


- Decomposition becomes invalid

Add Task – no changes

Definition (ADD-NO-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and task t.
ADD-NO-CHANGE is to decide whether the task network tn', which is tn with an additional task t and some ordering constraints added, is still a solution.



- Decomposition becomes invalid
- We (potentially) have to find a new linearisation

Plan Verification

Definition (VERIFYTN)

Given a planning problem $\mathcal{P}$ and a task network *tn*. Is $tn \in Sol(\mathcal{P})$?

Plan Verification

Definition (VERIFYTN)

Given a planning problem $\mathcal{P}$ and a task network *tn*. Is $tn \in Sol(\mathcal{P})$?

What do we have to check?

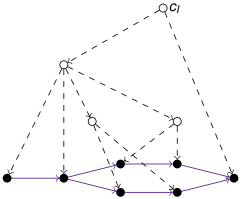
Plan Verification

Definition (VerifyTN)

Given a planning problem $\mathcal{P}$ and a task network *tn*. Is $tn \in Sol(\mathcal{P})$?

What do we have to check?

- Refinement



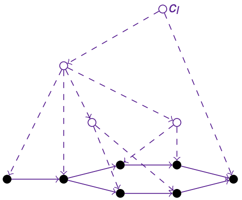
Plan Verification

Definition (VERIFYTN)

Given a planning problem $\mathcal{P}$ and a task network *tn*. Is $tn \in Sol(\mathcal{P})$?

What do we have to check?

- Refinement
- Primitive



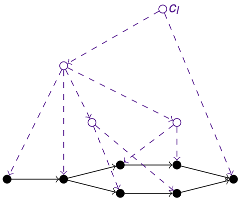
Plan Verification

Definition (VERIFYTN)

Given a planning problem $\mathcal{P}$ and a task network *tn*. Is $tn \in Sol(\mathcal{P})$?

What do we have to check?

- Refinement
- Primitive
- Executability



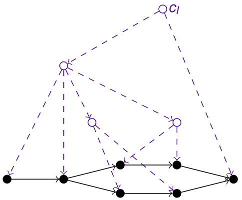
Plan Verification

Definition (VERIFYTN)

Given a planning problem $\mathcal{P}$ and a task network *tn*. Is $tn \in Sol(\mathcal{P})$?

What do we have to check?

- Refinement
- Primitive
- Executability



Theorem

VERIFYTN *is* **NP**-*complete*

Add Task – no changes

Theorem

ADD-NO-CHANGE *is* **NP***-complete.*

Proof:

Add Task – no changes

Theorem

ADD-NO-CHANGE *is* **NP***-complete.*

Proof: Membership:

- Add the new task *t* and guess some additional ordering constraints
- Check the resulting task network using the **NP** algorithm for VERIFYTN

Add Task – no changes

Theorem

ADD-NO-CHANGE *is* **NP**-*complete.*

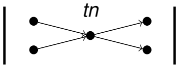
Proof: Hardness: Reduction from VERIFYTN.

Add Task – no changes

Theorem

ADD-NO-CHANGE *is* **NP***-complete.*

Proof: Hardness: Reduction from VERIFYTN.

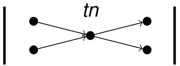


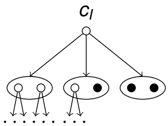
Add Task – no changes

Theorem

ADD-NO-CHANGE *is* **NP***-complete.*

Proof: Hardness: Reduction from VERIFYTN.



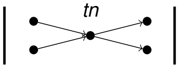


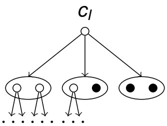
Add Task – no changes

Theorem

ADD-NO-CHANGE *is* **NP***-complete.*

Proof: Hardness: Reduction from VERIFYTN.





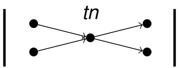
Add Task – no changes

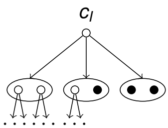
Theorem

ADD-NO-CHANGE *is* **NP**-*complete.*

Proof: <u>Hardness:</u> Reduction from VERIFYTN.

Also holds if the domain does not contain preconditions and effects.





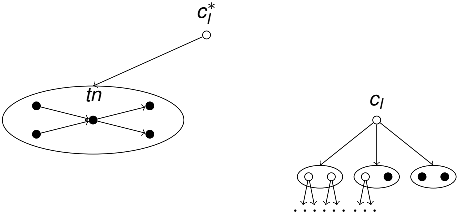
Add Task – no changes

Theorem

ADD-NO-CHANGE *is* **NP**-*complete.*

Proof: Hardness: Reduction from VERIFYTN.

Also holds if the domain does not contain preconditions and effects.



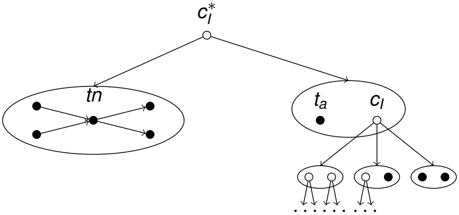
Add Task – no changes

Theorem

ADD-NO-CHANGE *is* **NP**-*complete.*

Proof: Hardness: Reduction from VERIFYTN.

Also holds if the domain does not contain preconditions and effects.



- Can we add t_a to tn?

□

Add Ordering – k changes

Definition (ORDERING-K-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and two tasks t_1, t_2 from tn. ORDERING-K-CHANGE is to decide whether another solution tn' can be obtained from tn by at most k of the following operations

- Adding/removing a primitive task
- Adding/removing an ordering constraint

such that $t_1 < t_2$ holds in tn' and neither t_1 nor t_2 are deleted.

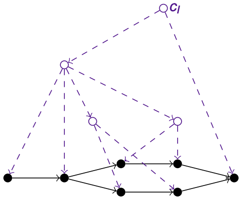
Add Ordering – k changes

Definition (ORDERING-K-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and two tasks t_1, t_2 from tn. ORDERING-K-CHANGE is to decide whether another solution tn' can be obtained from tn by at most k of the following operations

- Adding/removing a primitive task
- Adding/removing an ordering constraint

such that $t_1 < t_2$ holds in tn' and neither t_1 nor t_2 are deleted.



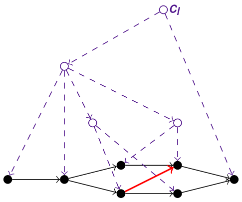
Add Ordering – k changes

Definition (ORDERING-K-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and two tasks t_1, t_2 from tn. ORDERING-K-CHANGE is to decide whether another solution tn' can be obtained from tn by at most k of the following operations

- Adding/removing a primitive task
- Adding/removing an ordering constraint

such that $t_1 < t_2$ holds in tn' and neither t_1 nor t_2 are deleted.



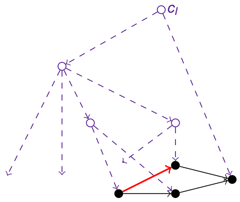
Add Ordering – k changes

Definition (ORDERING-K-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and two tasks t_1, t_2 from tn. ORDERING-K-CHANGE is to decide whether another solution tn' can be obtained from tn by at most k of the following operations

- Adding/removing a primitive task
- Adding/removing an ordering constraint

such that $t_1 < t_2$ holds in tn' and neither t_1 nor t_2 are deleted.



- Remove tasks

Add Ordering – k changes

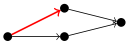
Definition (ORDERING-K-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and two tasks t_1, t_2 from tn. ORDERING-K-CHANGE is to decide whether another solution tn' can be obtained from tn by at most k of the following operations

- Adding/removing a primitive task
- Adding/removing an ordering constraint

such that $t_1 < t_2$ holds in tn' and neither t_1 nor t_2 are deleted.

- Remove tasks
- Old decomposition becomes invalid



Add Ordering – k changes

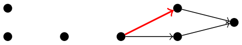
Definition (ORDERING-K-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and two tasks t_1, t_2 from tn. ORDERING-K-CHANGE is to decide whether another solution tn' can be obtained from tn by at most k of the following operations

- Adding/removing a primitive task
- Adding/removing an ordering constraint

such that $t_1 < t_2$ holds in tn' and neither t_1 nor t_2 are deleted.

- Remove tasks
- Old decomposition becomes invalid
- Add new tasks



Add Ordering – k changes

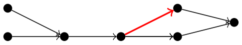
Definition (ORDERING-K-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and two tasks t_1, t_2 from tn. ORDERING-K-CHANGE is to decide whether another solution tn' can be obtained from tn by at most k of the following operations

- Adding/removing a primitive task
- Adding/removing an ordering constraint

such that $t_1 < t_2$ holds in tn' and neither t_1 nor t_2 are deleted.

- Remove tasks
- Old decomposition becomes invalid
- Add new tasks
- Add new ordering constraints



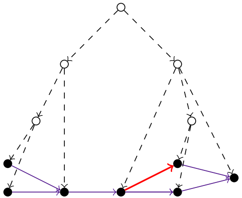
Add Ordering – k changes

Definition (ORDERING-K-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and two tasks t_1, t_2 from tn. ORDERING-K-CHANGE is to decide whether another solution tn' can be obtained from tn by at most k of the following operations

- Adding/removing a primitive task
- Adding/removing an ordering constraint

such that $t_1 < t_2$ holds in tn' and neither t_1 nor t_2 are deleted.



- Remove tasks
- Old decomposition becomes invalid
- Add new tasks
- Add new ordering constraints
- Find new decomposition

Add Ordering – *k* changes

Theorem

ORDERING-K-CHANGE *is* **NEXPTIME***-complete.*

Proof:

Add Ordering – k changes

Theorem

ORDERING-K-CHANGE *is* **NEXPTIME**-*complete.*

Proof: Membership:

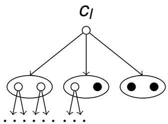
- Guess a number $l \leq k$
- Apply l allowed operations to the task network *tn*
- Check the resulting task network using the **NP** algorithm for VERIFYTN

Add Ordering – *k* changes

Theorem

ORDERING-K-CHANGE *is* **NEXPTIME**-*complete.*

Proof: Hardness: Reduction from SOLUTION in acyclic HTNs.

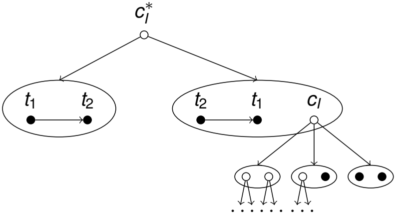


Add Ordering – k changes

Theorem

ORDERING-K-CHANGE *is* **NEXPTIME***-complete.*

Proof: <u>Hardness:</u> Reduction from SOLUTION in acyclic HTNs.

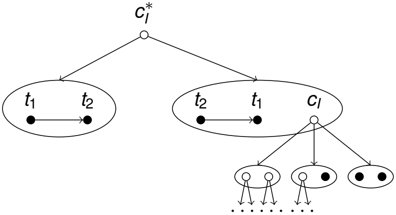


Add Ordering – k changes

Theorem

ORDERING-K-CHANGE *is* **NEXPTIME**-*complete.*

Proof: Hardness: Reduction from SOLUTION in acyclic HTNs.



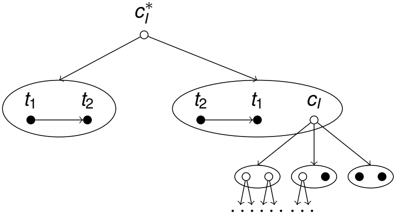
- Any plan has length $\leq m^{|C|}$

Add Ordering – k changes

Theorem

ORDERING-K-CHANGE *is* **NEXPTIME***-complete.*

Proof: Hardness: Reduction from SOLUTION in acyclic HTNs.



- Any plan has length $\leq m^{|C|}$
- Choose $k = m^{|C|} + (m^{|C|})^2$

$\square$

Add Ordering – any changes

Definition (ORDERING-ANY-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and two tasks t_1, t_2. Is there any solution to $\mathcal{P}$ containing t_1 and t_2 and the ordering constraint $t_1 < t_2$?

Add Ordering – any changes

Definition (ORDERING-ANY-CHANGE)

Given a planning problem $\mathcal{P}$, a solution $tn \in Sol(\mathcal{P})$, and two tasks t_1, t_2. Is there any solution to $\mathcal{P}$ containing t_1 and t_2 and the ordering constraint $t_1 < t_2$?

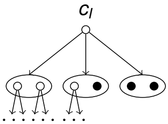
- The solution *tn* does not really help

Add Ordering – any changes

Theorem

ORDERING-ANY-SOLUTION *is undecidable.*

Proof:

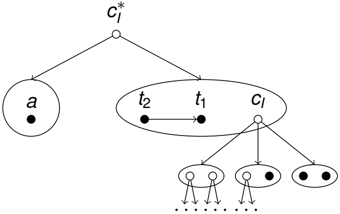


Add Ordering – any changes

Theorem

ORDERING-ANY-SOLUTION *is undecidable.*

Proof:

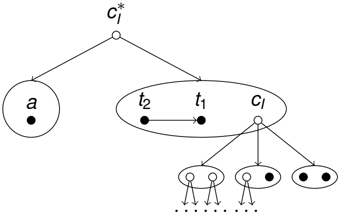


Add Ordering – any changes

Theorem

ORDERING-ANY-SOLUTION *is undecidable.*

Proof:



- The task network containing only a is a solution
- Ask whether a solution containing $t_1 < t_2$ exists

□

Conclusion

- Adding ordering constraints or actions to HTN Plan Verification is
  - **NP**-*complete* if we can't alter the plan otherwise
  - **NEXPTIME**-*complete* if we can perform up to k changing operations
  - *Undecidable* if we can alter the plan arbitrarily

Conclusion

- Adding ordering constraints or actions to HTN Plan Verification is
  - **NP**-*complete* if we can't alter the plan otherwise
  - **NEXPTIME**-*complete* if we can perform up to k changing operations
  - *Undecidable* if we can alter the plan arbitrarily

Further results can be combined to obtain the following classification

	add	delete	exchange	order	avoid effect
no changes	**NP**	**NP**	**NP**	**NP**	**NP**
k changes	**NEXPTIME**	**NEXPTIME**	**NEXPTIME**	**NEXPTIME**	**NEXPTIME**
any changes	*un-dec*	*un-dec*	*un-dec*	*un-dec*	*un-dec*

Provided the first theoretical investigation of MIP requests to change plan