# Temporal Problem Relaxation Through Conflict-Directed Diagnosis

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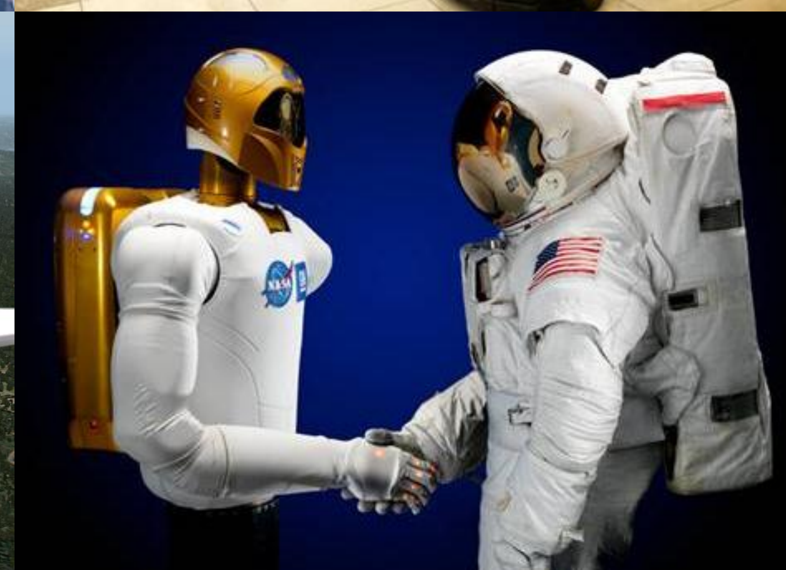
# Outline

- Motivation
- Previous Works
- Problem Definition and Approach
- Experimental Results
- Conclusion

# Motivation

- Robot-Human cooperation is very common nowadays.

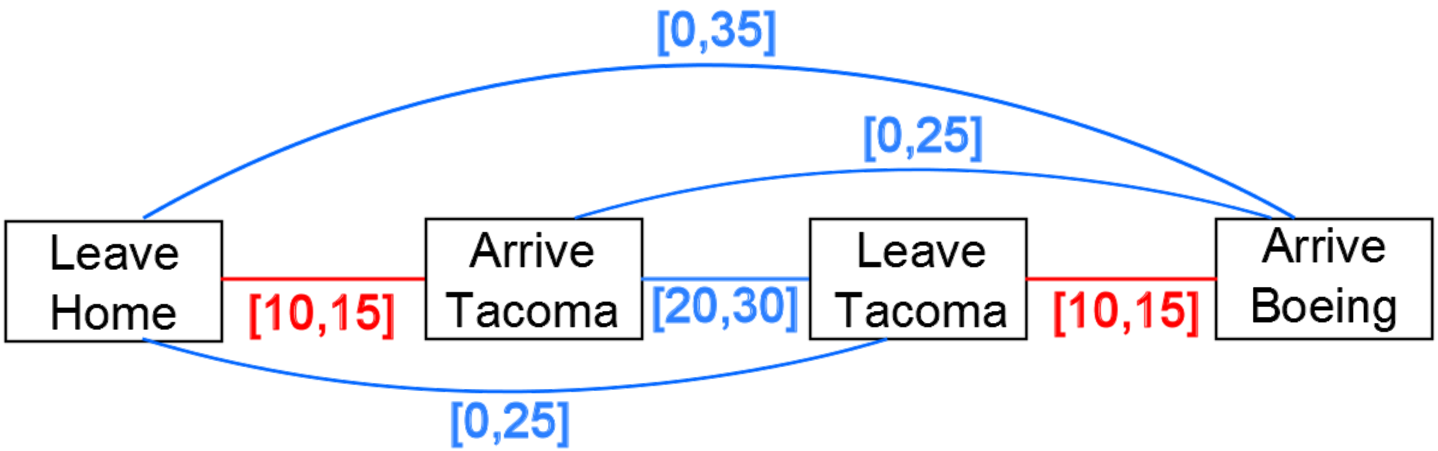


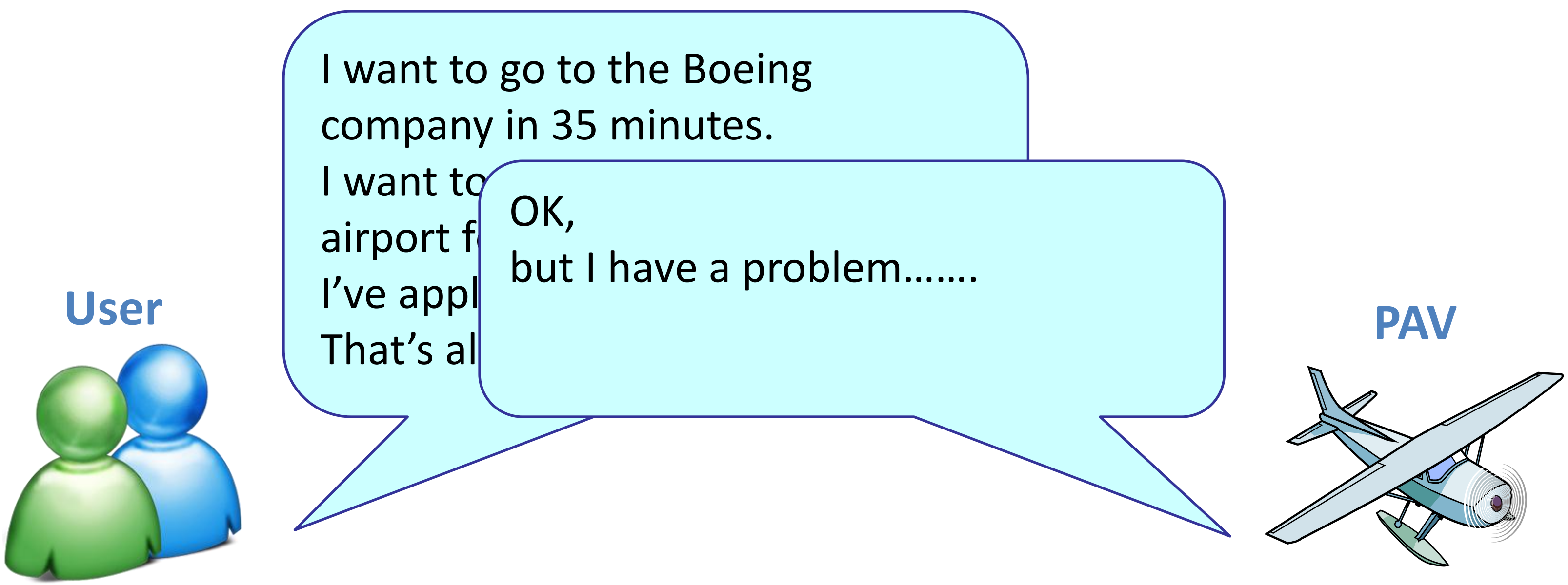



# Personal Transportation System

# Motivation

- Robot-Human cooperation is very common nowadays.



# Motivation

- Robot-Human cooperation is very common nowadays.
- However, inconsistencies are commonly observed during operations.
- Early systems only **signal failures** or **show many resolutions**.

I found 64 solutions:
1. Don’t stop at Tacoma.
2. Don’t go to work.

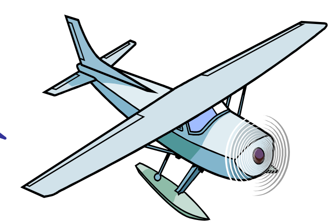
… …

64. ……

Which one do you choose?

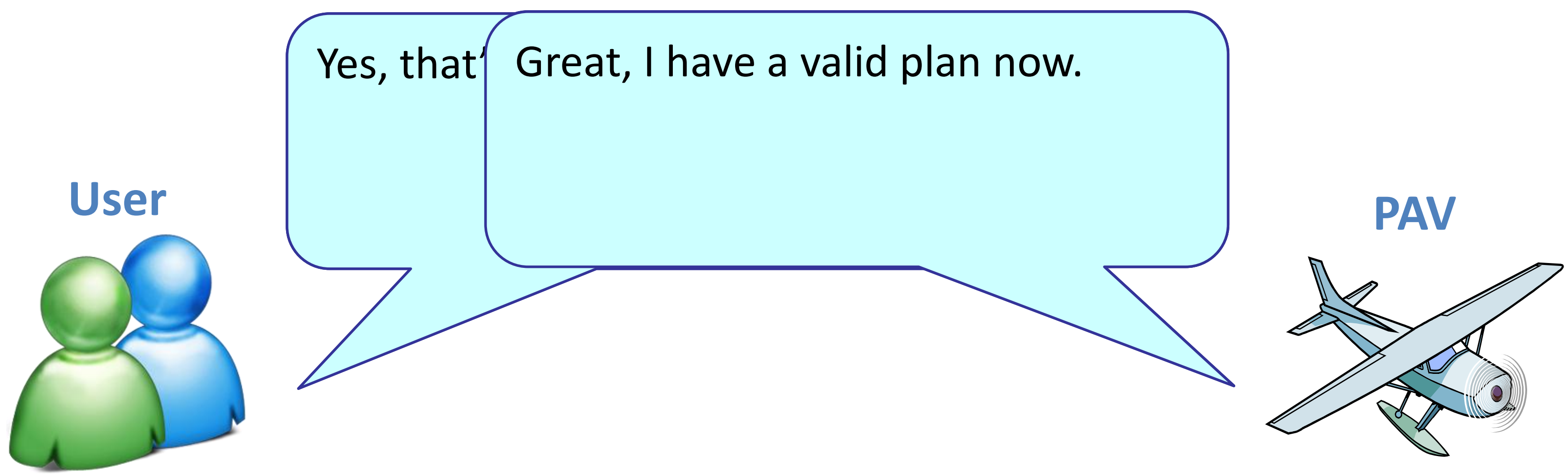
User

PAV



# Conflict-Directed Temporal Relaxation Algorithm

- Objective: Restore consistency of over-constrained plans.
- New features:
  - Provide a few **compact** and **preferred** solutions.
  - **Continuously** relax temporal constraints.
  - Accept both quantitative and **qualitative** preferences.

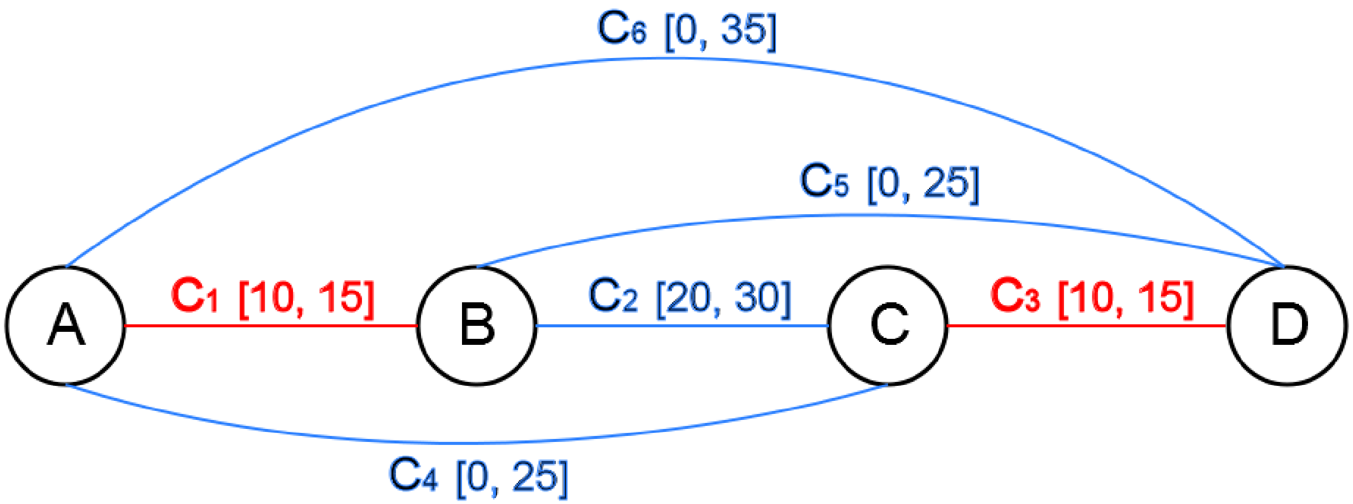


# Previous Work On Over-constrained Problems

| | Discrete Variables | Continuous Variables | User Preferences | Compact Results | Discrete Relaxations | Continuous Relaxations |
|---|---|---|---|---|---|---|
| de Kleer & Williams,1987 | ● | | | ● | ◌ | |
| Freuder & Wallace, 1992 | ● | | | | ● | |
| Williams & Ragno, 2003 | ● | | ● | | ● | |
| Bailey & Stucky, 2005 | ● | | | ● | ● | |
| Beaumont, et.al, 2001 | | ● | | | ● | |
| Moffitt & Pollack, 2005 | | ● | | ● | ● | |
| Peintner, et.al, 2005 | | ● | ● | | ● | |
| CTR | | ● | ● | ● | ● | ● |

# Problem Statement: Input

- Temporal Constraint Relaxation Problems:
  - Events.
    - With different time of occurrence.
  - Constraints.
    - Base: C1, C3.
    - Relaxable: C2, C4, C5, C6.

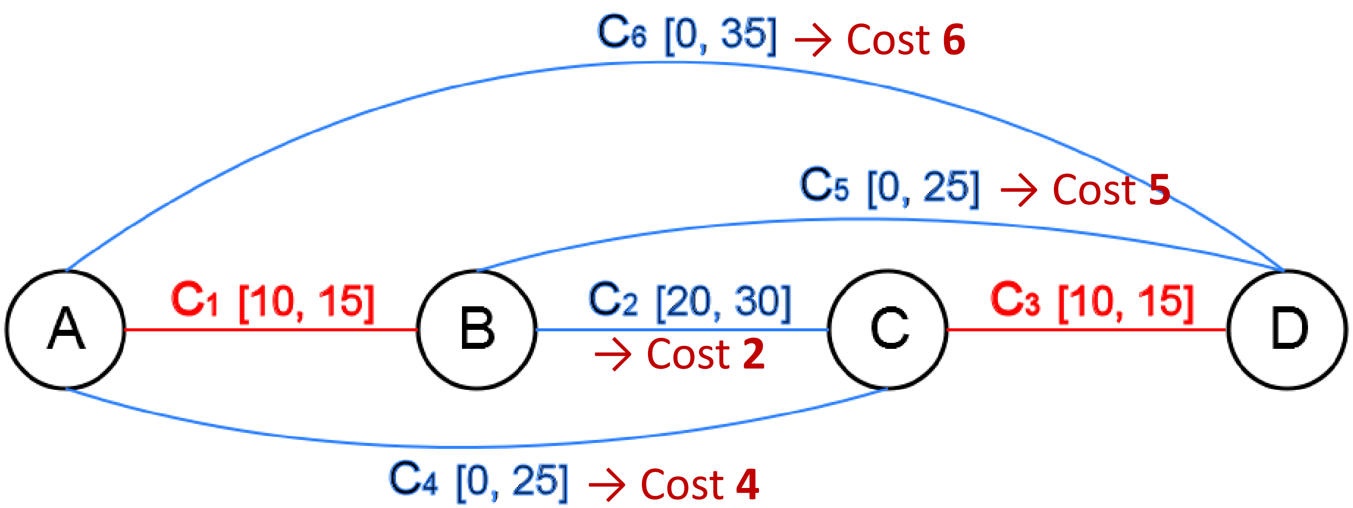


# Problem Statement: Preferences

- Quantitative Constraint Relaxation Cost:

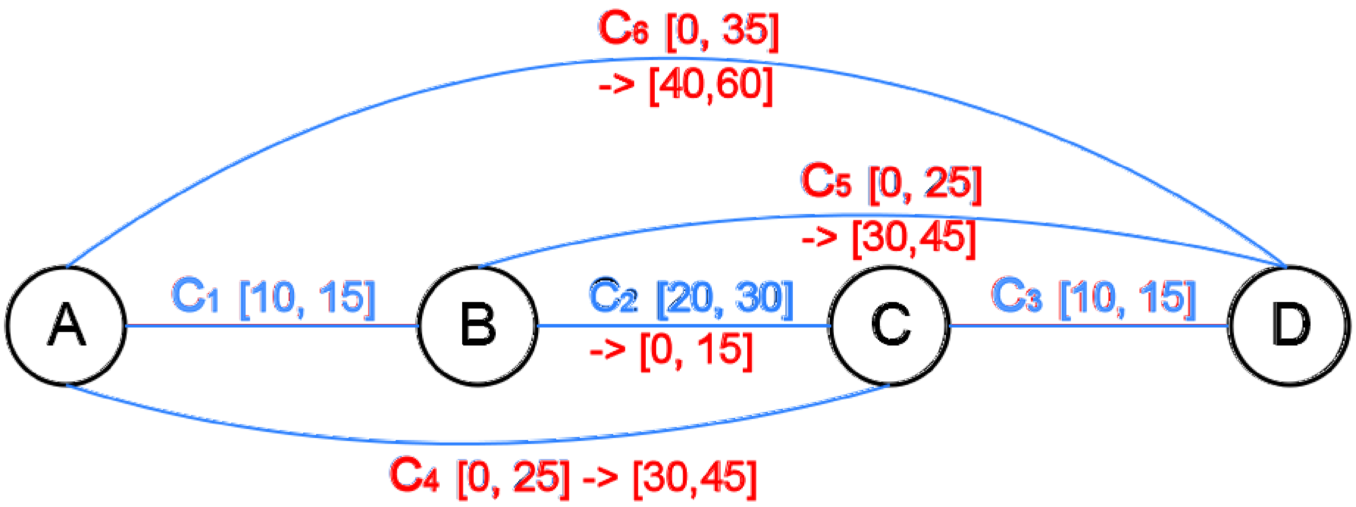
$$f: C_i \rightarrow \mathbb{R}$$

  - Activated when constraints are relaxed.
    - Relax C2: Cost 2.
    - Relax C4, C6: Cost 10.
  - Assume Mutual Preferential Independence.

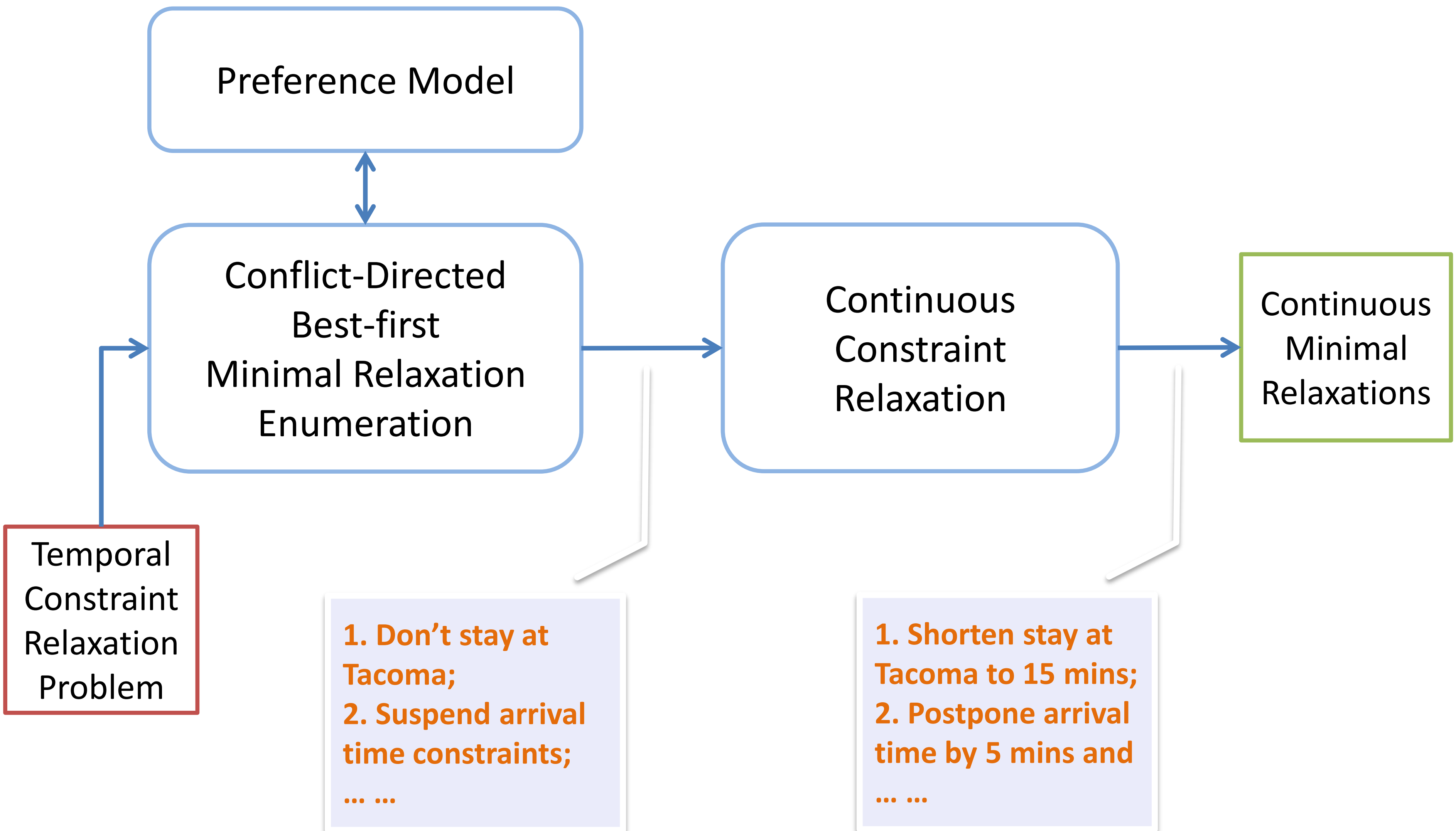


# Problem Statement: Output

- Preferred Continuous Minimal Relaxations.
  - Restore consistency by updating temporal bounds.
    - Relax C2 to [0,15].
    - Relax C4,C5,C6 to [30,45],[30,45],[40,60].
  - No proper subsets of which are valid relaxations.
  - In best-first order according to user preference.



# Conflict-Directed Temporal Relaxation



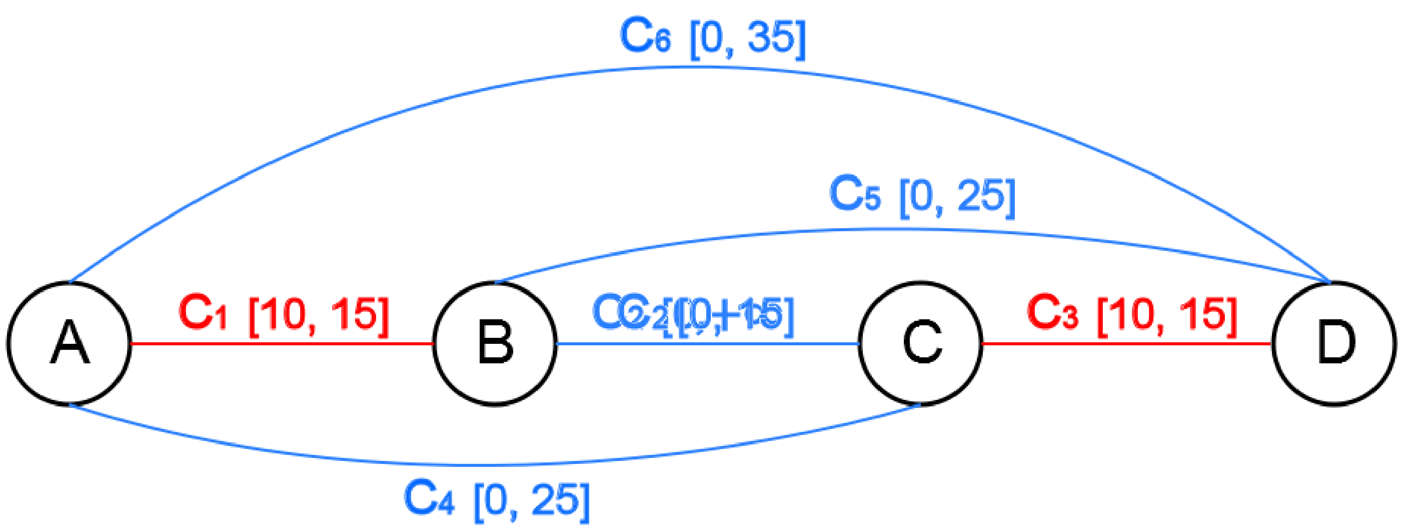
# Continuous Constraint Relaxation

- Previous approaches restore consistency by suspending constraints.
  - All-or-nothing approach.
  - Break the user’s plan.

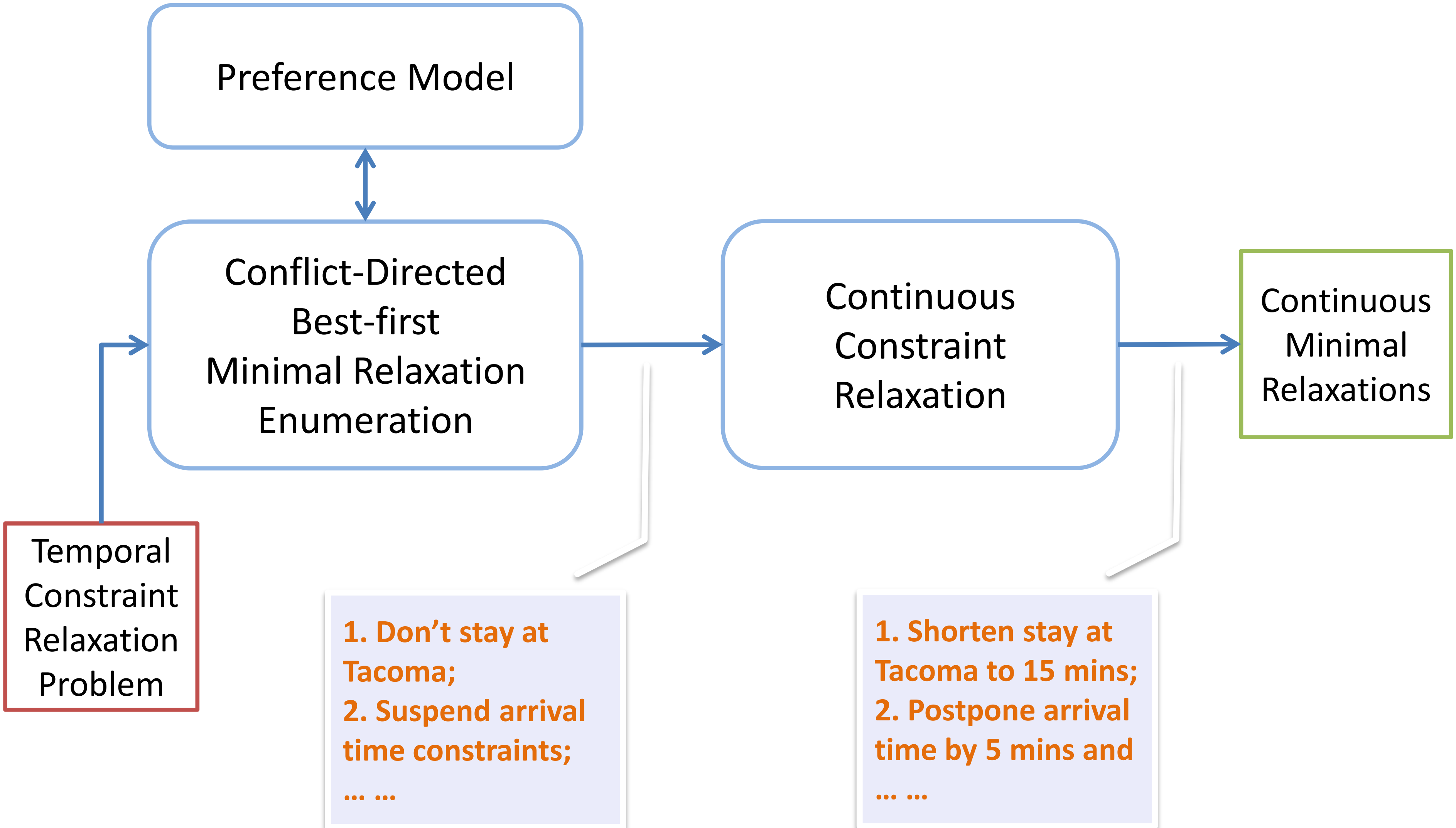
- Continuous Constraint Relaxation preserves all constraints.
  - Restore consistency by updating the temporal bounds .
  - Use Floyd-Warshall algorithm to compute the consistent temporal bounds of suspended constraints.

# Continuous Constraint Relaxation

- Step 1 generates a minimal relaxation: {Suspending C2}.
- CCR relaxes the temporal bound of C2 to restore consistency.
  - Reset C2 to [0, +∞].
  - Run Floyd-Warshall to update C2 with the tightest bound.
  - Extract the new temporal bound, [0, 15].

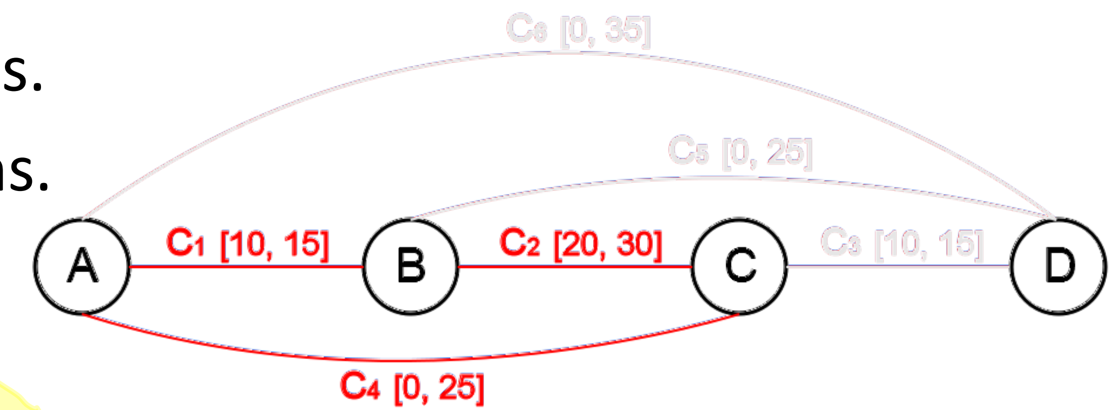


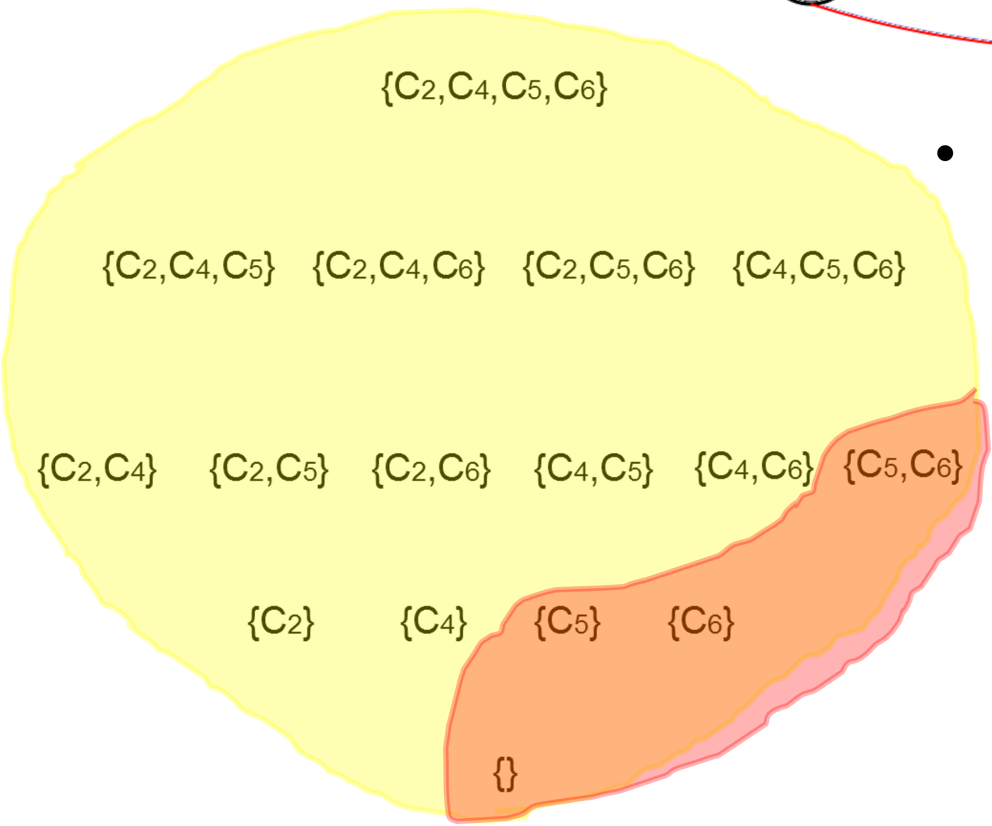
# Conflict-Directed Temporal Relaxation



# Enumerate Minimal Relaxations

- 4 relaxable constraints.
- 16 possible relaxations.
- Q = {C2=sus},{C4=sus}




- Start with {}.
  - Covers all relaxations.

Test {C2=act,C4=act,C5=act,C6=act}.

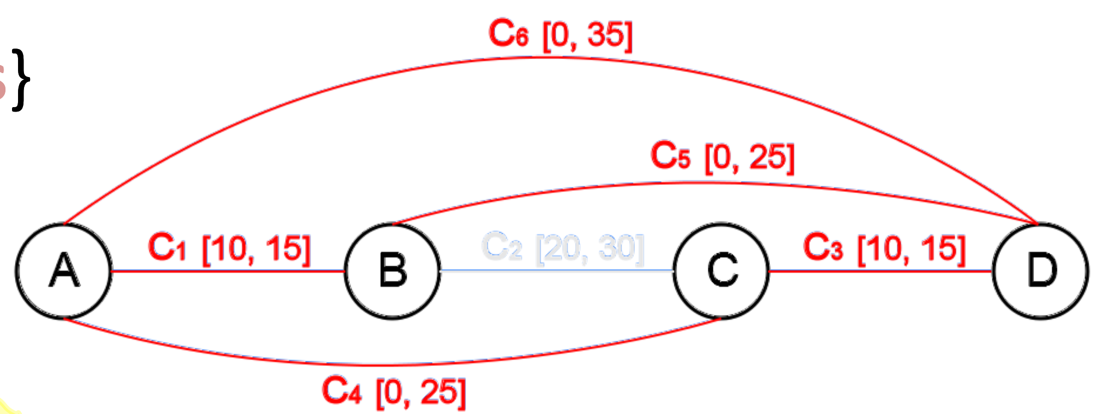
- Inconsistent!
- Extract **least cost** minimal conflict

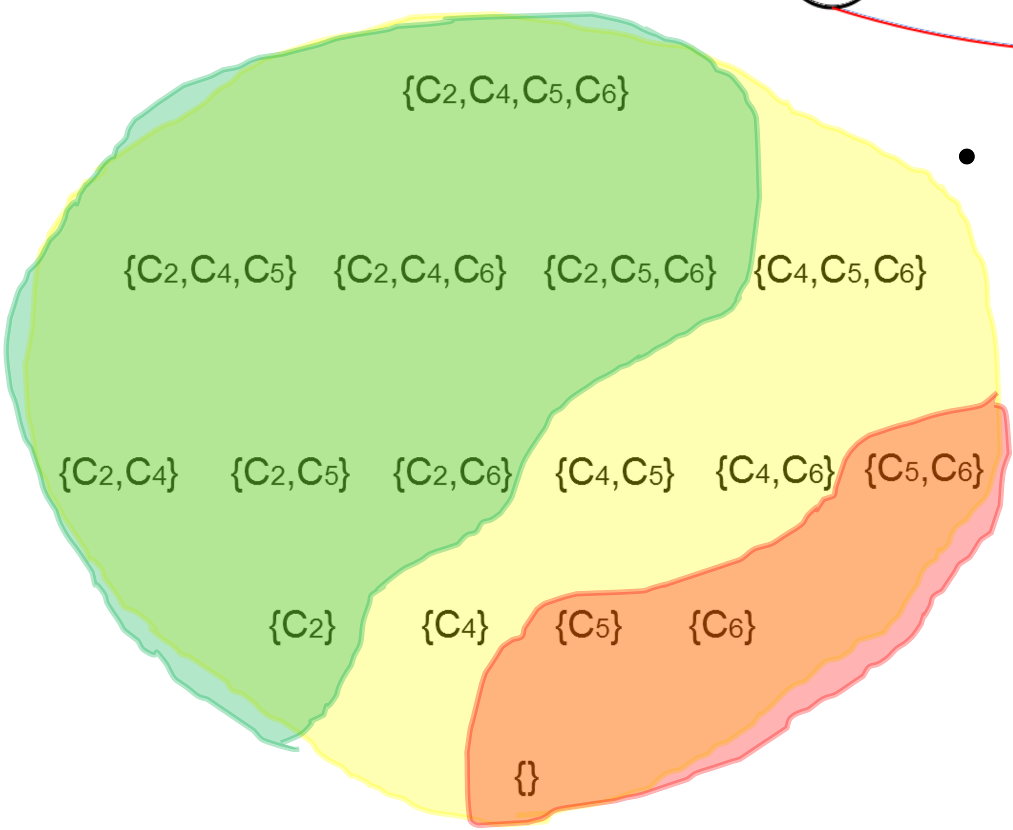
{C1=act,C2=act,C4=act}.

- Candidate **minimal** relaxations: {C2=sus},{C4=sus}.

# Enumerate Minimal Relaxations

- Q = {C2=sus},{C4=sus}



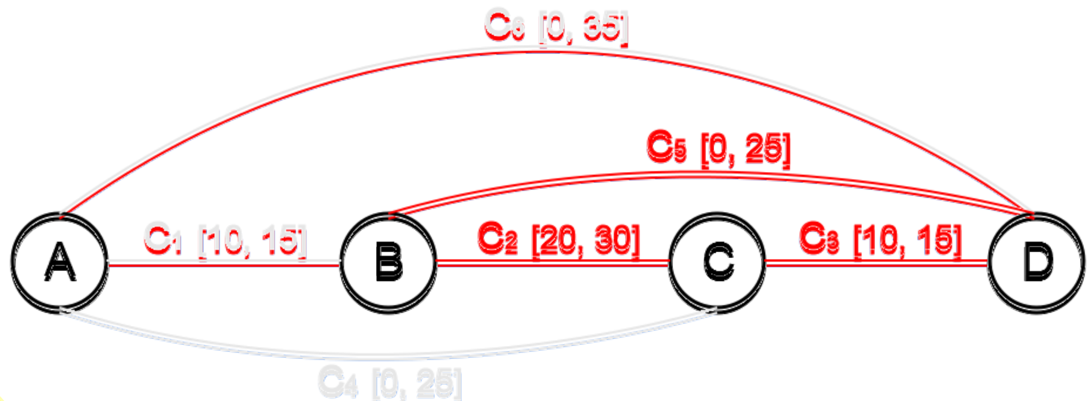



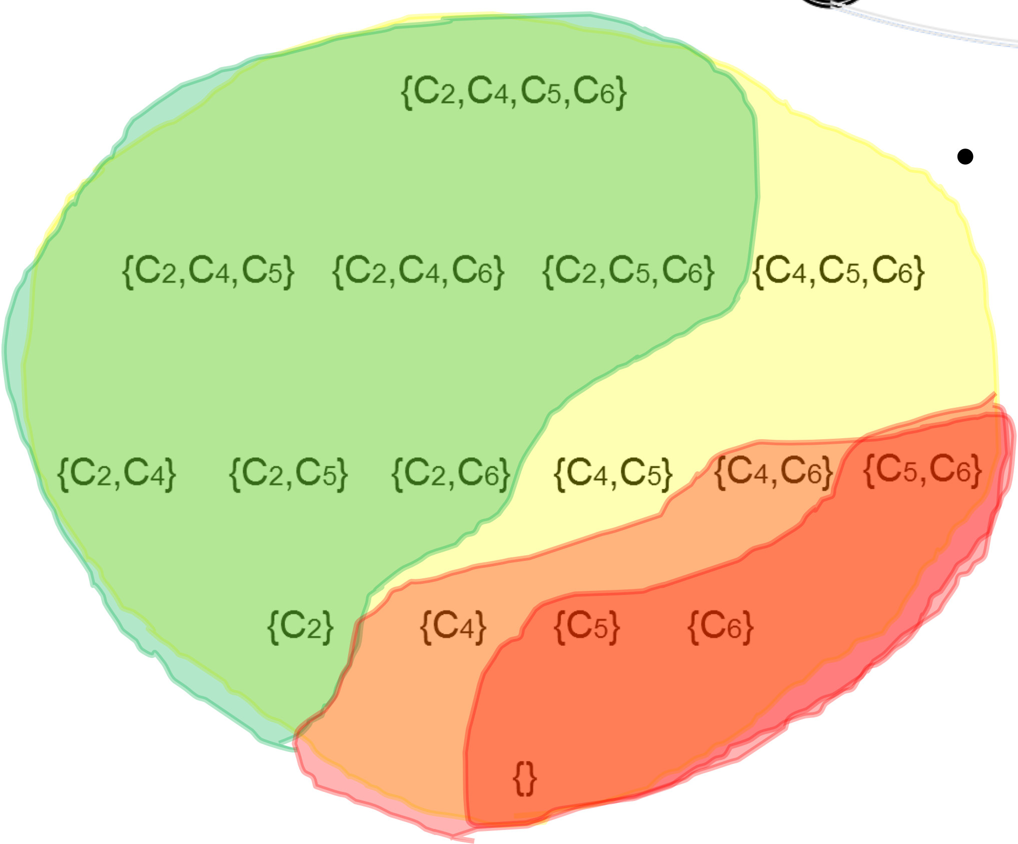

- Check {C2=sus}
  - Test {C2=sus,C4=act,C5=act,C6=act}.
  - Consistent!
  - All supersets of {C2=sus} are valid relaxations.

# Enumerate Minimal Relaxations

- Q = {C4=sus}

  {C4=sus,C5=sus}



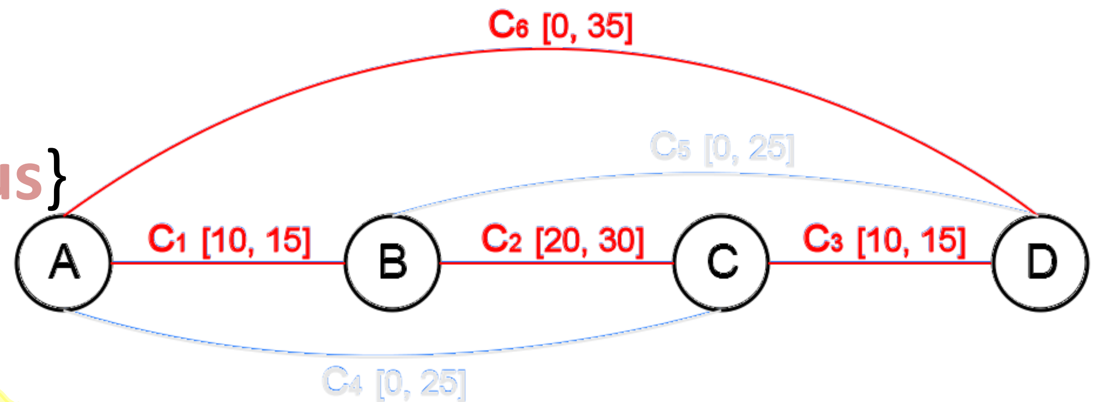



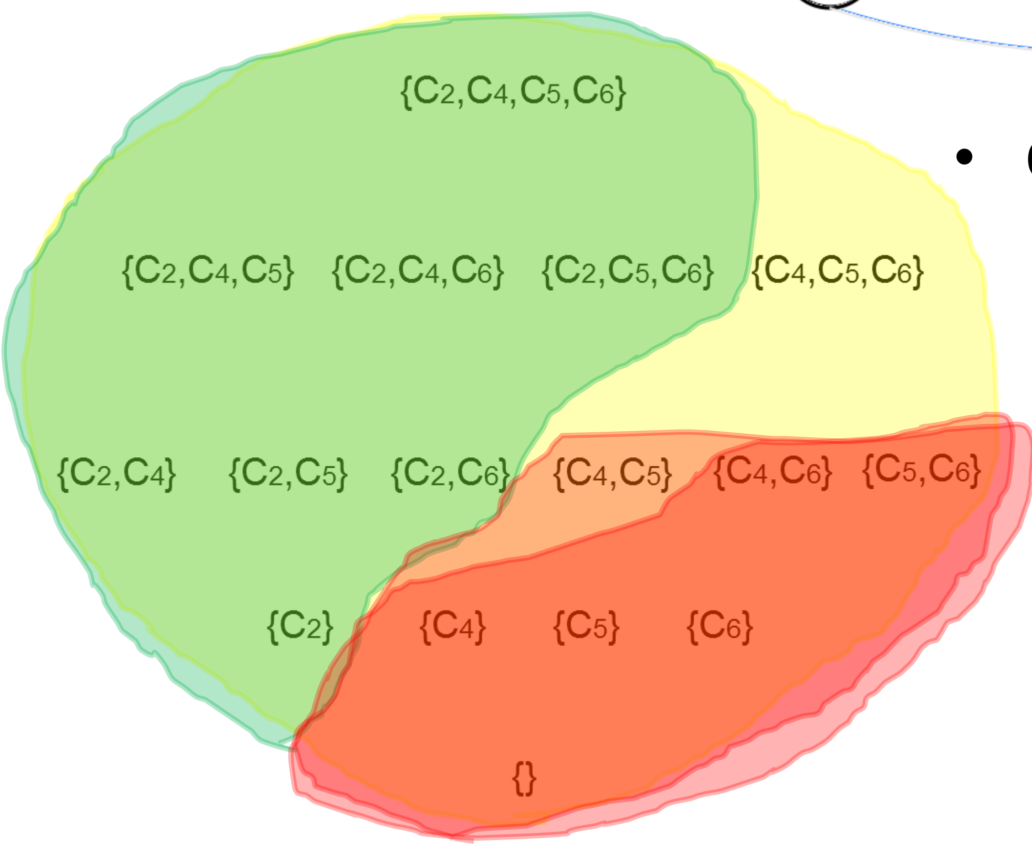

- Check {C4=sus}
  - Test
  
    {C2=act,C4=sus,C5=act,C6=act}.
  - Inconsistent!
  - Extract least cost minimal conflicts {C2=act,C3=act,C5=act}, {C1=act,C2=act,C4=act}.
  - Candidate minimal relaxations: {C4=sus, C5=sus}.

# Enumerate Minimal Relaxations

- Q = {C4=sus,C5=sus}

{C4=sus, C5=sus, C6=sus}

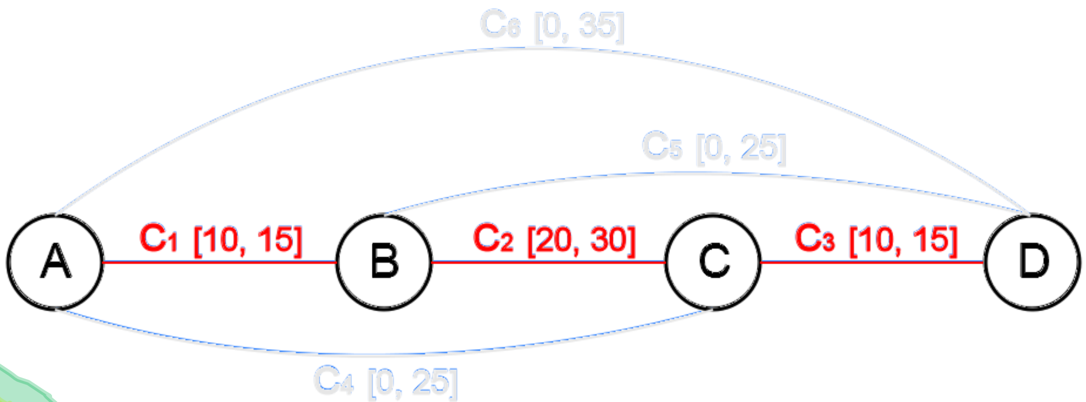


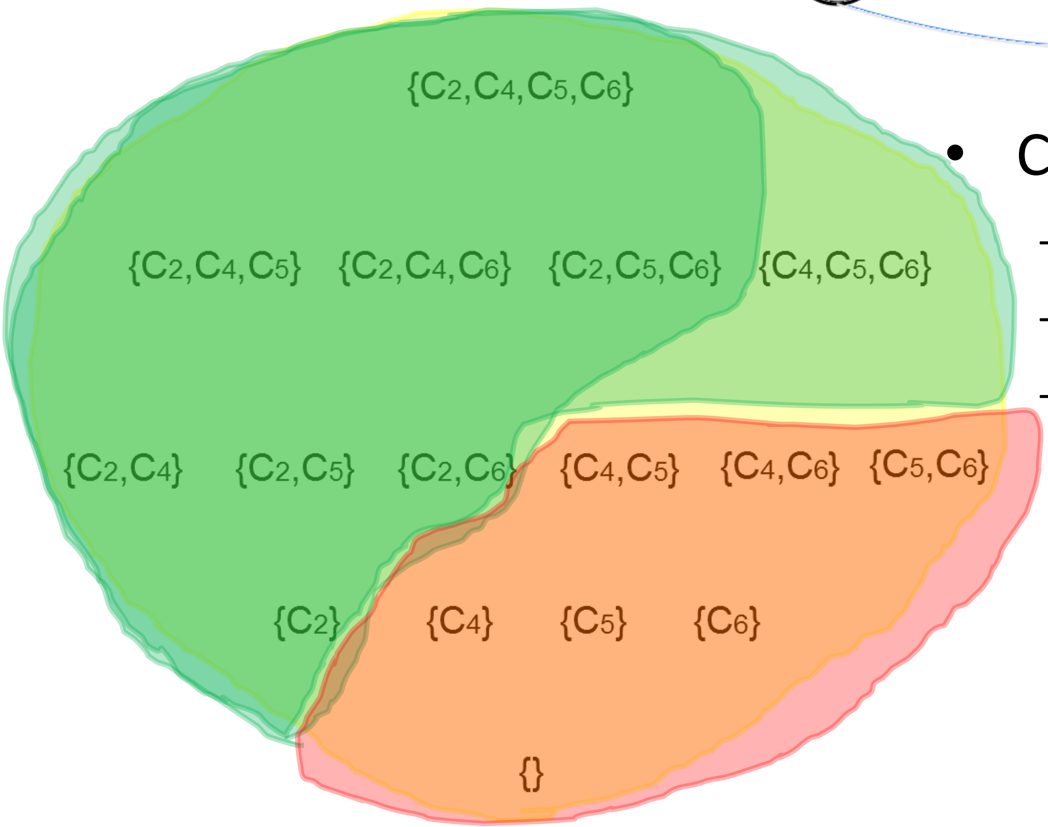




- Check {C4=sus,C5=sus}
  - Test {C2=act,C4=sus,C5=sus,C6=act}.
  - Inconsistent!
  - Extract conflicts {C1=act, C2=act, C3=act, C6=act}.
  - Candidate minimal relaxations: {C4=sus, C5=sus, C6=sus}.

# Enumerate Minimal Relaxations

- Q = {C4=sus, C5=sus, C6=sus}

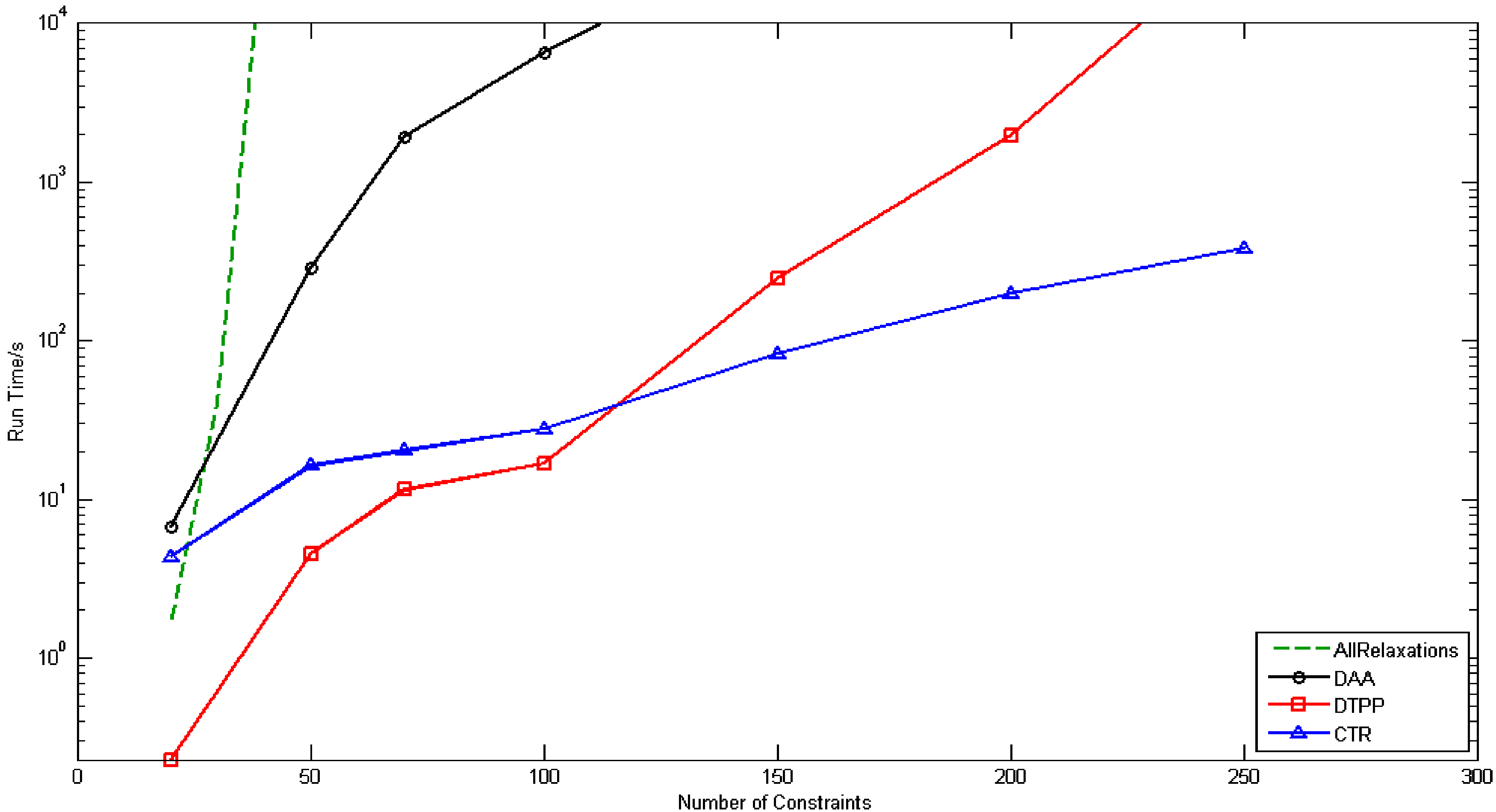



- Check {C4=sus,C5=sus,C6=sus}
  - Test {C2=act,C4=sus,C5=sus,C6=sus}.
  - Consistent!
  - No more candidate relaxations left, search complete!

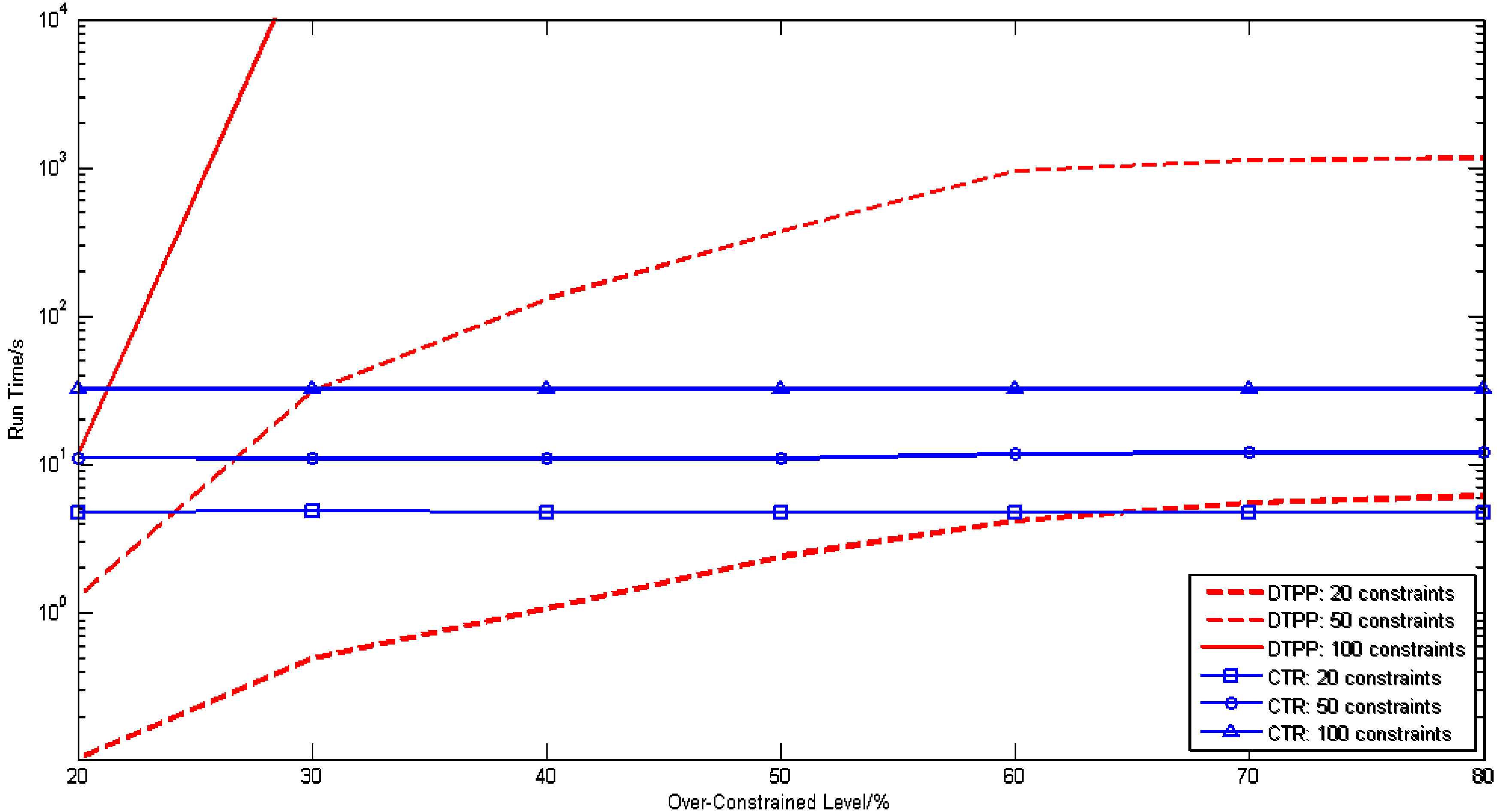
# Performance: Run-time

- All Relaxation, Dualize & Advance, DTPP, and CTR.



# Performance: Run-time

- Better performance on hard problems:
  - DTPP and CTR.



# Future Work

- A work together model:
  - For a larger set of applications, such as manufacturing, where human and robots are working together.
- Generative explanation:
  - Propose alternative plans with new constraints and actions in addition to suspending/relaxing existing constraints.
- A more natural user interface:
  - Shared knowledge model.
  - Efficient description of spatial and temporal commands.

# Achievements

- An algorithm to efficiently resolve over-constrained temporal problems.

- New features provided:
  - Best-first minimal relaxation enumeration.
  - Continuous constraint relaxation.
  - Relaxation enumeration with qualitative preferences.

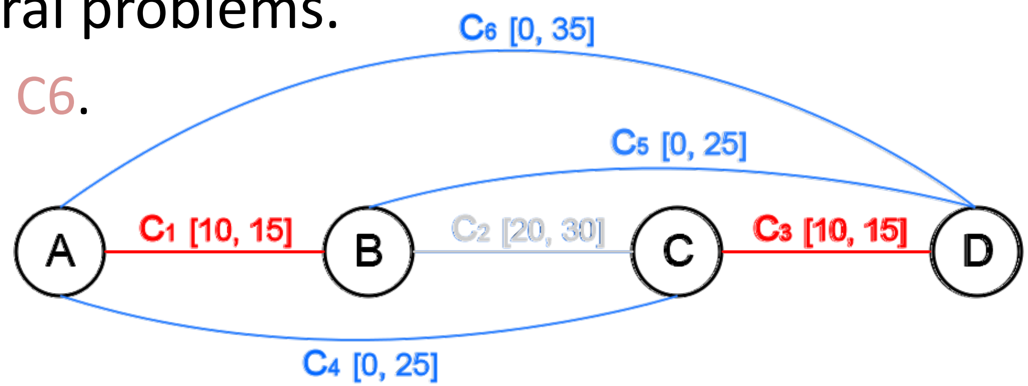
- Improvements:
  - Faster relaxations generation compare to state-of-the-art methods.

# Backup Slides

# Minimal relaxation

- Relaxation:
  - A set of relaxed constraints that resolve the inconsistency of over constrained temporal problems.
    - Suspending C4, C5 and C6.
    - Suspending C2, C6.
    - Suspending C2.

    … …




  - All supersets of a relaxation are valid relaxations, too.
- Minimal relaxation:
  - A valid relaxation.
  - None of its proper subsets are valid relaxations.
    - {C2=sus} vs. {C2=sus, C6=sus} .

# Best-First

- Cost of relaxations:
  - Suspending constraints will incur costs:

$$f : C_i \rightarrow \mathbb{R}$$

  - Assigned by the user: C1 → 1, C2 → 2, C3 → 3 … …
  - {C2=**sus**, C5=**sus**}: Cost 7; {C2=**sus**, C4=**sus**}: Cost 6.

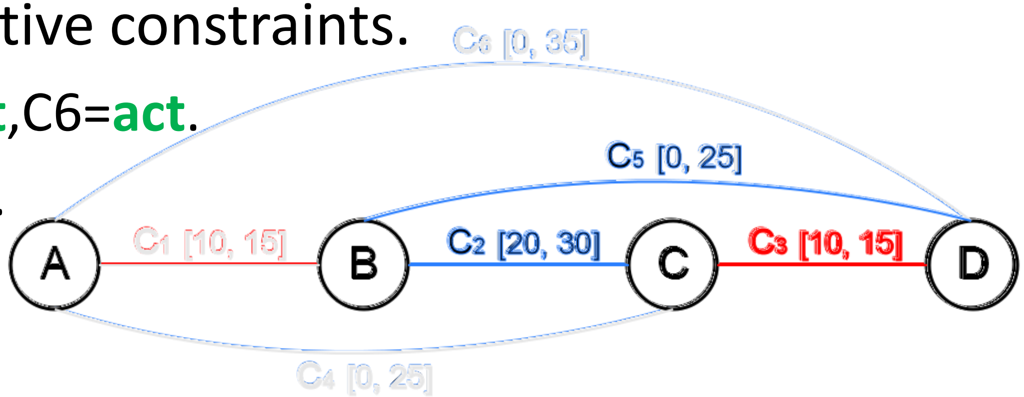
- Conflicts with lower cost will be extracted first.
  - {C1=**act**,C2=**act**,C4=**act**} vs. {C2=**act**,C3=**act**,C5=**act**}.

- Candidate relaxations with lower cost will be tested first.
  - {C2=**sus**} vs. {C4=**sus**, C5=**sus**, C6=**sus**}.

# Conflict-Directed

- What is a conflict?
  - A set of inconsistent active constraints.
    - C1=**act**,C2=**act**,C3=**act**,C6=**act**.
    - C1, C2, C3, C4, C5, C6.
    - C2, C3, C5.

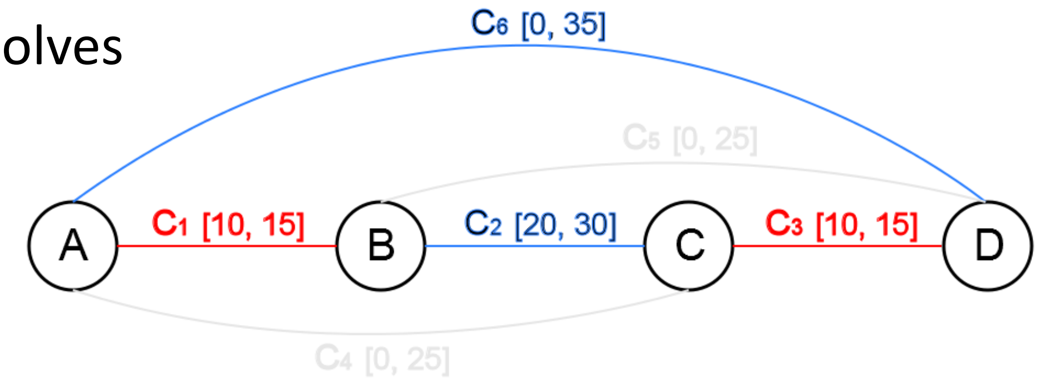
    … …




- Minimal conflicts.
  - A conflict whose proper subsets are not in conflict.
    - C2=**act**, C3=**act**, C5=**act**.
    - C1=**act**, C2=**act**, C3=**act**, C6=**act**.
    - C1=**act**, C2=**act**, C4=**act**.

# Conflict-Directed, cont.

- Conflicts vs. Relaxations.
  - Relaxing one constraint can resolve a minimal conflict.
    - Suspending C6 resolves {C1=**act**, C2=**act**, C3=**act**, C6=**act**}.




  - A relaxation suspends at least one constraint in each minimal conflict (a covering set).
  - Minimal relaxations are minimal covering sets of minimal conflicts.

| | |
|---|---|
| {C2=**act**, C3=**act**, C5=**act**}. | {C2=**sus**, C1=**sus**, C4=**sus**}. |
| {C1=**act**, C2=**act**, C3=**act**, C6=**act**}. | |
| {C1=**act**, C2=**act**, C4=**act**}. | {C2=**sus**}. |
| | … … |

# Generate Least Cost Conflicts

- Least cost conflicts:
  - Minimal conflicts with the least cost constraints.
- Procedure:
  - Prioritize the set of constraints in conflict.
  - Iterate through the set, starting with high cost constraints.
    - Remove the current constraint and check the consistency of the set.
    - If inconsistent, keep the constraint removed.
    - Otherwise, put it back to the set.

{C1,C2,C3,C4,C5,C6} → {C1,C2,C4}

# Generate Random Temporal Problems

- Given number of constraints, N:
  - Randomly generate:
    - Number of decisions: D;
    - Number of constraints per branch: Ci;

  such that

$$N = \sum_{i=1}^{D} C_i.$$

- Given the over-constrained level, O:
  - Manually add constraints to create conflicts.
  - Use the ratio, #conflicts/#constraints, to estimate O.

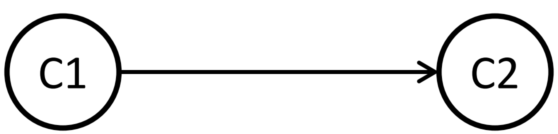
# Qualitative Preference Model: CP-nets

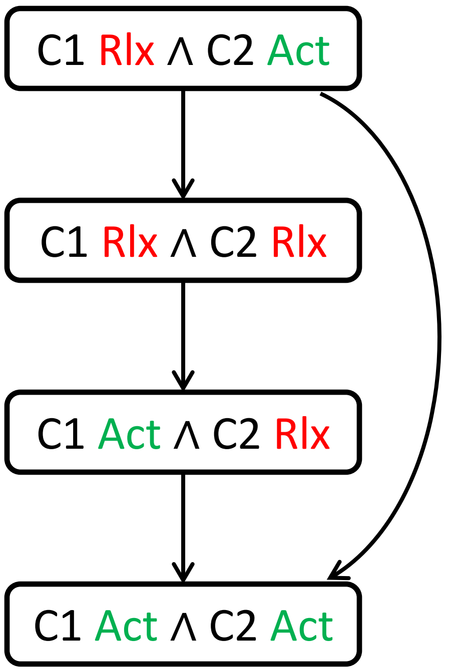
- Conditional Preference Networks:
  - Binary comparison over the decision outcomes with conditional independence assumption.
  - Assume relative importance between variables.
  - Compact and intuitive graphical representation.

- CP-Nets and relaxation problems:
  - Variables: relaxable constraints.
  - Outcomes: {Relax, Active}.

C1: Active $\succ$ Relax

C1 Active: Active $\succ$ Relax
C1 Relax: Relax $\succ$ Active

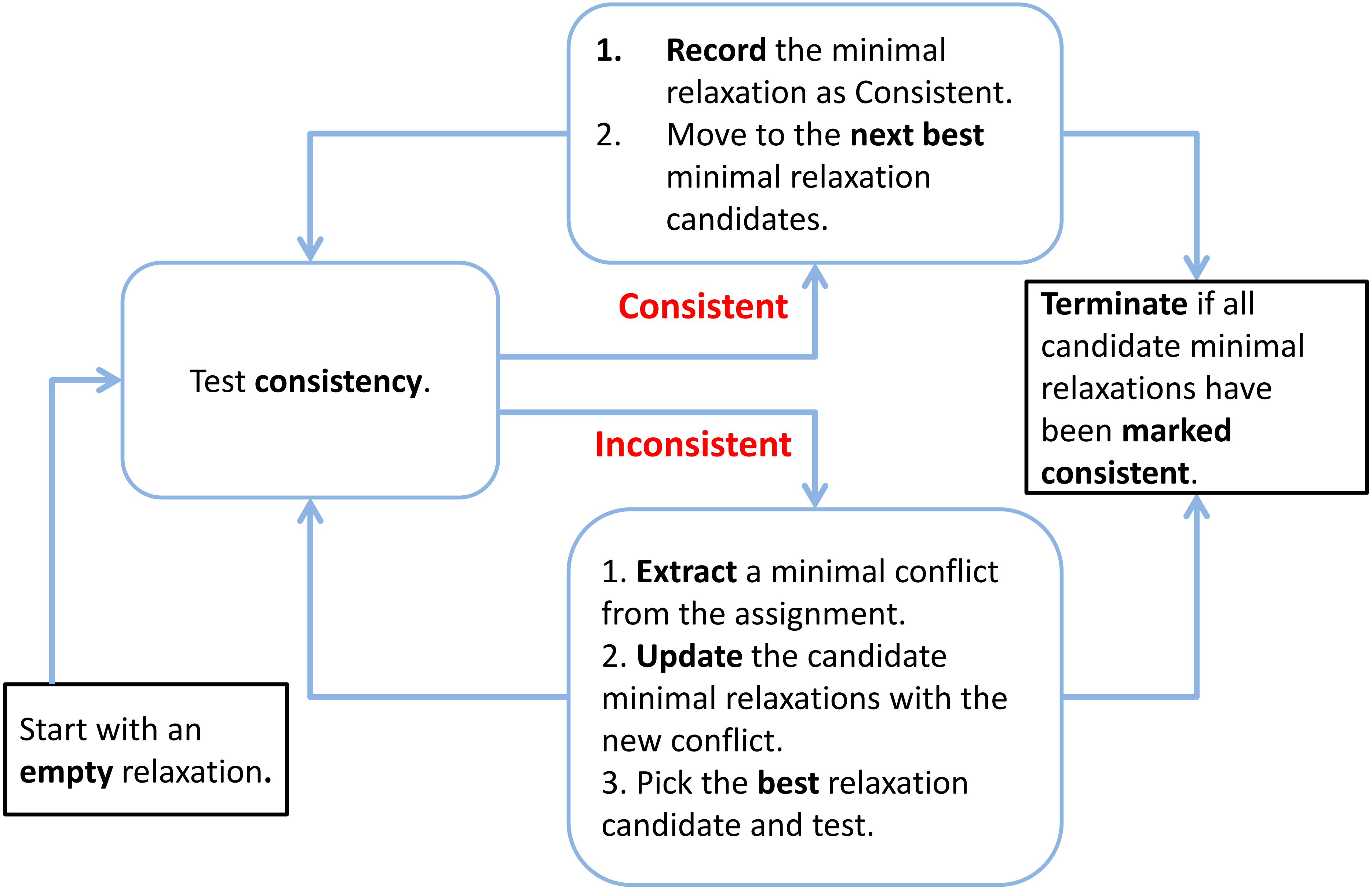


# Main Components

- Conflict-Directed Best-First Minimal Relaxation enumeration.
  - Leveraged from Conflict-Directed A* and Dualize & Advance.
- Continuous Constraint Relaxation.
  - Update the temporal bounds of suspended constraints to restore consistency.
- Conditional Preference Networks as Qualitative Preference Model.

# Procedure: Enumerate Minimal Relaxation



# Solving Relaxation Problem with MILP

- Relaxation cost: C1, C2,…,Cn.
- To Be Relaxed?: R1, R2,…,Rn ∈ {0,1}.
- Events: E1, E2,…,En.
- Constraints: a1 < Ei – Ej < b1; a2 < Em – En < b2;…

- Objective: Minimize $\sum_{i=1}^{n} C_i * R_i$;

  s.t. a1 – a1*R1 < Ei – Ej < b1 + M*R1;

  a2 – a2*R2 < Em – Em < b2 + M*R2;

  … …

- Generates the preferred full relaxations, but not minimal relaxations.

# All vs. Minimal relaxations: More compact results

| Number of Constraints | 20 | 50 | 70 | 100 | 150 | 200 | 250 |
|---|---|---|---|---|---|---|---|
| All Relaxations | 3984 | 1.02e10 | 1.62e17 | 2.43e23 | 1.89e34 | 4.54e47 | 4.01e58 |
| Minimal Relaxations | 90 | 1680 | 9520 | 24200 | 2.97e6 | 3.84e8 | 5.14e10 |

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