

Foundations of Artificial Intelligence

D5. Constraint Satisfaction Problems: Path Consistency

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D5.1 Beyond Arc Consistency

D5.2 Path Consistency

D5.3 Summary

Constraint Satisfaction Problems: Overview

Chapter overview: constraint satisfaction problems

- ▶ D1–D2. Introduction
- ▶ D3–D5. Basic Algorithms
 - ▶ D3. Backtracking
 - ▶ D4. Arc Consistency
 - ▶ D5. Path Consistency
- ▶ D6–D7. Problem Structure

D5.1 Beyond Arc Consistency

Beyond Arc Consistency: Path Consistency

idea of arc consistency:

- ▶ For every assignment to a variable u there must be a suitable assignment to every other variable v .
- ▶ If not: remove values of u for which no suitable “partner” assignment to v exists.

↪ tighter **unary constraint** on u

This idea can be extended to three variables (**path consistency**):

- ▶ For every joint assignment to variables u, v there must be a suitable assignment to every third variable w .
- ▶ If not: remove pairs of values of u and v for which no suitable “partner” assignment to w exists.

↪ tighter **binary constraint** on u and v

German: Pfadkonsistenz

Beyond Arc Consistency: i -Consistency

general concept of i -consistency for $i \geq 2$:

- ▶ For every joint assignment to variables v_1, \dots, v_{i-1} there must be a suitable assignment to every i -th variable v_i .
- ▶ If not: remove value tuples of v_1, \dots, v_{i-1} for which no suitable “partner” assignment for v_i exists.
- ↪ tighter $(i - 1)$ -ary constraint on v_1, \dots, v_{i-1}
 - ▶ 2-consistency = arc consistency
 - ▶ 3-consistency = path consistency (*)

We do not consider general i -consistency further as larger values than $i = 3$ are rarely used and we restrict ourselves to binary constraints in this course.

(*) usual definitions of 3-consistency vs. path consistency differ when ternary constraints are allowed

D5.2 Path Consistency

Path Consistency: Definition

Definition (path consistent)

Let $\mathcal{C} = \langle V, \text{dom}, (R_{uv}) \rangle$ be a constraint network.

- 1 Two different variables $u, v \in V$ are **path consistent** with respect to a third variable $w \in V$ if for all values $d_u \in \text{dom}(u), d_v \in \text{dom}(v)$ with $\langle d_u, d_v \rangle \in R_{uv}$ there is a value $d_w \in \text{dom}(w)$ with $\langle d_u, d_w \rangle \in R_{uw}$ and $\langle d_v, d_w \rangle \in R_{vw}$.
- 2 The constraint network \mathcal{C} is **path consistent** if for all triples of different variables u, v, w , the variables u and v are path consistent with respect to w .

Path Consistency on Running Example

Running Example

$$R_{wz} = \{\langle 1, 2 \rangle, \langle 1, 3 \rangle, \langle 2, 3 \rangle\}$$

$$R_{yz} = \{\langle 2, 1 \rangle, \langle 3, 1 \rangle, \langle 3, 2 \rangle, \langle 4, 1 \rangle, \langle 4, 2 \rangle, \langle 4, 3 \rangle\}$$

$$R_{wy} = \{\langle 1, 1 \rangle, \langle 1, 2 \rangle, \langle 1, 3 \rangle, \langle 1, 4 \rangle, \\ \langle 2, 1 \rangle, \langle 2, 2 \rangle, \langle 2, 3 \rangle, \langle 2, 4 \rangle, \\ \langle 3, 1 \rangle, \langle 3, 2 \rangle, \langle 3, 3 \rangle, \langle 3, 4 \rangle, \\ \langle 4, 1 \rangle, \langle 4, 2 \rangle, \langle 4, 3 \rangle, \langle 4, 4 \rangle\}$$

Are w and y path consistent with respect to z ? **No!**

Path Consistency on Running Example

Running Example

$$R_{wz} = \{\langle 1, 2 \rangle, \langle 1, 3 \rangle, \langle 2, 3 \rangle\}$$

$$R_{yz} = \{\langle 2, 1 \rangle, \langle 3, 1 \rangle, \langle 3, 2 \rangle, \langle 4, 1 \rangle, \langle 4, 2 \rangle, \langle 4, 3 \rangle\}$$

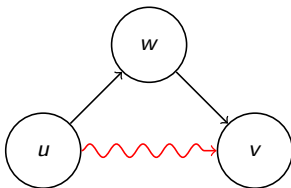
$$R_{wy} = \{\langle 1, 3 \rangle, \langle 1, 4 \rangle, \langle 2, 4 \rangle\}$$

Are w and y path consistent with respect to z ? **Yes!**

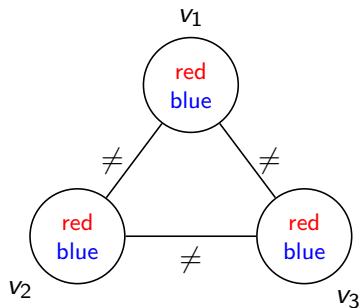
Path Consistency: Remarks

remarks:

- ▶ Even if the constraint R_{uv} is trivial, path consistency can infer nontrivial constraints between u and v .
- ▶ name “path consistency”:
path $u \rightarrow w \rightarrow v$ leads to new information on $u \rightarrow v$



Path Consistency: Example



arc consistent, but not path consistent

Processing Variable Triples: revise-3

analogous to **revise** for arc consistency:

function revise-3(\mathcal{C}, u, v, w):

$\langle V, \text{dom}, (R_{uv}) \rangle := \mathcal{C}$

for each $\langle d_u, d_v \rangle \in R_{uv}$:

if there is no $d_w \in \text{dom}(w)$ with

$\langle d_u, d_w \rangle \in R_{uw}$ **and** $\langle d_v, d_w \rangle \in R_{vw}$:

remove $\langle d_u, d_v \rangle$ from R_{uv}

input: constraint network \mathcal{C} and three variables u, v, w of \mathcal{C}

effect: u, v path consistent with respect to w .

All violating pairs are removed from R_{uv} .

time complexity: $O(k^3)$ where k is maximal domain size

Enforcing Path Consistency: PC-2

analogous to AC-3 for arc consistency:

function PC-2(\mathcal{C}):

$\langle V, \text{dom}, (R_{uv}) \rangle := \mathcal{C}$

queue := \emptyset

for each set of two variables $\{u, v\}$:

for each $w \in V \setminus \{u, v\}$:

 insert $\langle u, v, w \rangle$ into *queue*

while *queue* $\neq \emptyset$:

 remove any element $\langle u, v, w \rangle$ from *queue*

 revise-3(\mathcal{C}, u, v, w)

if R_{uv} changed in the call to revise-3:

for each $w' \in V \setminus \{u, v\}$:

 insert $\langle w', u, v \rangle$ into *queue*

 insert $\langle w', v, u \rangle$ into *queue*

PC-2: Discussion

The comments for AC-3 hold analogously.

- ▶ PC-2 enforces path consistency
- ▶ **proof idea:** invariant of the **while** loop:
if $\langle u, v, w \rangle \notin \text{queue}$, then u, v path consistent
with respect to w
- ▶ time complexity $O(n^3 k^5)$ for n variables and maximal domain
size k (**Why?**)

D5.3 Summary

Summary

- ▶ generalization of
arc consistency (considers pairs of variables)
to path consistency (considers triples of variables)
and i -consistency (considers i -tuples of variables)
- ▶ arc consistency tightens unary constraints
- ▶ path consistency tightens binary constraints
- ▶ i -consistency tightens $(i - 1)$ -ary constraints
- ▶ higher levels of consistency more powerful
but more expensive than arc consistency