

Automated Theorem Proving

Lecture 11: Completion

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4.6 Knuth–Bendix Completion

Completion:

Goal: Given a set E of equations, transform E into an equivalent convergent set R of rewrite rules.

(If R is finite: decision procedure for E .)

Knuth–Bendix Completion: Idea

How to ensure termination?

Fix a reduction ordering \succ and construct R in such a way that $\rightarrow_R \subseteq \succ$ (i.e., $l \succ r$ for every $l \rightarrow r \in R$).

How to ensure confluence?

Check that all critical pairs are joinable.

Note: Every critical pair $\langle s, t \rangle$ can be *made* joinable by adding $s \rightarrow t$ or $t \rightarrow s$ to R .

(Actually, we first add $s \approx t$ to E and later try to turn it into a rule that is contained in \succ ; this gives us more freedom.)

Knuth–Bendix Completion: Inference Rules

The completion procedure is presented as a set of inference rules working on a set of equations E and a set of rules R :

$$E_0, R_0 \vdash E_1, R_1 \vdash E_2, R_2 \vdash \dots$$

At the beginning, $E = E_0$ is the input set and $R = R_0$ is empty.

At the end, E should be empty; then R is the result.

For each step $E, R \vdash E', R'$, the equational theories of $E \cup R$ and $E' \cup R'$ agree: $\approx_{E \cup R} = \approx_{E' \cup R'}$.

Knuth–Bendix Completion: Inference Rules

Notations:

The formula $s \overset{\cdot}{\approx} t$ denotes either $s \approx t$ or $t \approx s$.

$CP(R)$ denotes the set of all critical pairs between rules in R .

Knuth–Bendix Completion: Inference Rules

Orient:

$$\frac{E \cup \{s \approx t\}, R}{E, R \cup \{s \rightarrow t\}} \quad \text{if } s \succ t$$

Note: There are equations $s \approx t$ that cannot be oriented, i.e., neither $s \succ t$ nor $t \succ s$.

Knuth–Bendix Completion: Inference Rules

Trivial equations cannot be oriented—but we do not need them anyway:

Delete:

$$\frac{E \cup \{s \approx s\}, R}{E, R}$$

Knuth–Bendix Completion: Inference Rules

Critical pairs between rules in R are turned into additional equations:

Deduce:

$$\frac{E, R}{E \cup \{s \approx t\}, R} \quad \text{if } \langle s, t \rangle \in \text{CP}(R).$$

Note: If $\langle s, t \rangle \in \text{CP}(R)$, then $s \leftarrow_R u \rightarrow_R t$ and hence $R \models s \approx t$.

Knuth–Bendix Completion: Inference Rules

The following inference rules are not strictly necessary, but are very useful (e.g., to cope with equations that cannot be oriented):

Simplify-Eq:

$$\frac{E \cup \{s \approx t\}, R}{E \cup \{u \approx t\}, R} \quad \text{if } s \rightarrow_R u.$$

Knuth–Bendix Completion: Inference Rules

Simplification of the right-hand side of a rule is unproblematic:

R-Simplify-Rule:

$$\frac{E, R \cup \{s \rightarrow t\}}{E, R \cup \{s \rightarrow u\}} \quad \text{if } t \rightarrow_R u.$$

Simplification of the left-hand side may influence orientability and orientation. Therefore, it yields an *equation*:

L-Simplify-Rule:

$$\frac{E, R \cup \{s \rightarrow t\}}{E \cup \{u \approx t\}, R} \quad \text{if } s \rightarrow_R u \text{ using a rule } l \rightarrow r \in R \text{ such that } s \sqsupset l \text{ (see next slide).}$$

Knuth–Bendix Completion: Inference Rules

For technical reasons, the lhs of $s \rightarrow t$ may only be simplified using a rule $l \rightarrow r$ if $l \rightarrow r$ cannot be simplified using $s \rightarrow t$, that is, if $s \sqsupset l$, where the **encompassment quasi-ordering** \sqsupseteq is defined by

$$s \sqsupseteq l \text{ if } s|_p = l\sigma \text{ for some } p \text{ and } \sigma$$

and $\sqsupset = \sqsupseteq \setminus \sqsubseteq$ is the strict part of \sqsupseteq .

Lemma 4.6.1:

\sqsupset is a well-founded strict partial ordering.

Knuth–Bendix Completion: Inference Rules

Lemma 4.6.2:

If $E, R \vdash E', R'$, then $\approx_{E \cup R} = \approx_{E' \cup R'}$.

Lemma 4.6.3:

If $E, R \vdash E', R'$ and $\rightarrow_R \subseteq \succ$, then $\rightarrow_{R'} \subseteq \succ$.

Knuth–Bendix Completion: Inference Rules

Note: Like in ordered resolution, simplification should be preferred to deduction:

- Simplify/delete whenever possible.
- Otherwise, orient an equation if possible.
- Last resort: compute critical pairs.

Knuth–Bendix Completion: Example

We apply the Knuth–Bendix procedure to the set of equations

$$\mathit{add}(\mathit{zero}, \mathit{zero}) \approx \mathit{zero} \quad (1) \quad \mathit{add}(x, \mathit{succ}(y)) \approx \mathit{succ}(\mathit{add}(x, y)) \quad (2)$$

$$\mathit{add}(\mathit{succ}(x), y) \approx \mathit{succ}(\mathit{add}(x, y)) \quad (3)$$

using the lpo with the precedence $\mathit{add} \succ \mathit{succ} \succ \mathit{zero}$.

We first apply “Orient” to (1)–(3), resulting in the rewrite rules

$$\mathit{add}(\mathit{zero}, \mathit{zero}) \rightarrow \mathit{zero} \quad (4) \quad \mathit{add}(x, \mathit{succ}(y)) \rightarrow \mathit{succ}(\mathit{add}(x, y)) \quad (5)$$

$$\mathit{add}(\mathit{succ}(x), y) \rightarrow \mathit{succ}(\mathit{add}(x, y)) \quad (6)$$

Knuth–Bendix Completion: Example

$$add(\text{zero}, \text{zero}) \rightarrow \text{zero} \quad (4) \quad add(x, succ(y)) \rightarrow succ(add(x, y)) \quad (5)$$

$$add(succ(x), y) \rightarrow succ(add(x, y)) \quad (6)$$

Then we apply “Deduce” between (5) and a renamed copy of (6):

$$succ(add(succ(x), y)) \approx succ(add(x, succ(y))) \quad (7)$$

We can now apply “Simplify-Eq” to both sides of (7) using (6) and (5):

$$succ(succ(add(x, y))) \approx succ(succ(add(x, y))) \quad (8)$$

This last equation is trivial and can be deleted using “Delete.”

All critical pairs have been checked.

The resulting term rewrite system is $\{(4), (5), (6)\}$.

Knuth–Bendix Completion: Correctness Proof

What can happen if we run the completion procedure on a set E of equations?

- (1) We reach a state where no more inference rules are applicable and E is not empty.
⇒ Failure (try again with another ordering?)
- (2) We reach a state where E is empty and all critical pairs between the rules in the current R have been checked.
- (3) The procedure runs forever.

To treat these cases simultaneously, we need some definitions.

Knuth–Bendix Completion: Correctness Proof

A (finite or infinite sequence) $E_0, R_0 \vdash E_1, R_1 \vdash E_2, R_2 \vdash \dots$ with $R_0 = \emptyset$ is called a **run** of the completion procedure with input E_0 and \succ .

For a run, $E_{\cup} = \bigcup_{i \geq 0} E_i$ and $R_{\cup} = \bigcup_{i \geq 0} R_i$.

The sets of **persistent equations or rules** of the run are $E_{\infty} = \bigcup_{i \geq 0} \bigcap_{j \geq i} E_j$ and $R_{\infty} = \bigcup_{i \geq 0} \bigcap_{j \geq i} R_j$.

Note: If the run is finite and ends with E_n, R_n , then $E_{\infty} = E_n$ and $R_{\infty} = R_n$.

Knuth–Bendix Completion: Correctness Proof

A run is called **fair** if $CP(R_\infty) \subseteq E_U$

(i.e., if every critical pair between persisting rules is computed at some step of the derivation).

Goal:

Show: If a run is fair and E_∞ is empty,
then R_∞ is convergent and equivalent to E_0 .

In particular: If a run is fair and E_∞ is empty,
then $\approx_{E_0} = \approx_{E_U \cup R_U} = \leftrightarrow_{E_U \cup R_U}^* = \downarrow R_\infty$.

Knuth–Bendix Completion: Correctness Proof

General assumptions from now on:

$E_0, R_0 \vdash E_1, R_1 \vdash E_2, R_2 \vdash \dots$ is a fair run.

R_0 and E_∞ are empty.

Knuth–Bendix Completion: Correctness Proof

A **proof** of $s \approx t$ in $E_U \cup R_U$ is a finite sequence (s_0, \dots, s_n) such that $s = s_0$, $t = s_n$, and for all $i \in \{1, \dots, n\}$:

(1) $s_{i-1} \leftrightarrow_{E_U} s_i$, or

(2) $s_{i-1} \rightarrow_{R_U} s_i$, or

(3) $s_{i-1} \leftarrow_{R_U} s_i$.

The pairs (s_{i-1}, s_i) are called **proof steps**.

A proof is called a **rewrite proof in R_∞**

if there is a $k \in \{0, \dots, n\}$ such that $s_{i-1} \rightarrow_{R_\infty} s_i$ for $1 \leq i \leq k$

and $s_{i-1} \leftarrow_{R_\infty} s_i$ for $k + 1 \leq i \leq n$

Knuth–Bendix Completion: Correctness Proof

Idea (Bachmair, Dershowitz, Hsiang):

Define a well-founded ordering on proofs such that for every proof that is not a rewrite proof in R_∞ there is an equivalent smaller proof.

Consequence: For every proof there is an equivalent rewrite proof in R_∞ .

Knuth–Bendix Completion: Correctness Proof

We associate a **cost** $c(s_{i-1}, s_i)$ with every proof step as follows:

- (1) If $s_{i-1} \leftrightarrow_{E \cup} s_i$, then $c(s_{i-1}, s_i) = (\{s_{i-1}, s_i\}, -, -)$,
where the first component is a multiset of terms and $-$ denotes an arbitrary (irrelevant) term.
- (2) If $s_{i-1} \rightarrow_{R \cup} s_i$ using $l \rightarrow r$, then $c(s_{i-1}, s_i) = (\{s_{i-1}\}, l, s_i)$.
- (3) If $s_{i-1} \leftarrow_{R \cup} s_i$ using $l \rightarrow r$, then $c(s_{i-1}, s_i) = (\{s_i\}, l, s_{i-1})$.

Proof steps are compared using the lexicographic combination of the multiset extension of the reduction ordering \succ , the encompassment ordering \sqsupseteq , and the reduction ordering \succ .

Knuth–Bendix Completion: Correctness Proof

The cost $c(P)$ of a proof P is the multiset of the costs of its proof steps.

The **proof ordering** \succ_c compares the costs of proofs using the multiset extension of the proof step ordering.

Lemma 4.6.4:

\succ_c is a well-founded ordering.

Knuth–Bendix Completion: Correctness Proof

Lemma 4.6.5:

Let P be a proof in $E_{\cup} \cup R_{\cup}$. If P is not a rewrite proof in R_{∞} , then there exists an equivalent proof P' in $E_{\cup} \cup R_{\cup}$ such that $P \succ_c P'$.

Proof:

If P is not a rewrite proof in R_{∞} , then it contains

- (a) a proof step that is in E_{\cup} , or
- (b) a proof step that is in $R_{\cup} \setminus R_{\infty}$, or
- (c) a subproof $s_{i-1} \leftarrow_{R_{\infty}} s_i \rightarrow_{R_{\infty}} s_{i+1}$ (peak).

We show that in all three cases, the proof step or subproof can be replaced by a smaller subproof.

Knuth–Bendix Completion: Correctness Proof

Case (a): A proof step using an equation $s \dot{\approx} t$ is in E_U .
This equation must be deleted during the run.

If $s \dot{\approx} t$ is deleted using *Orient*:

$$\dots S_{i-1} \leftrightarrow_{E_U} S_i \dots \implies \dots S_{i-1} \rightarrow_{R_U} S_i \dots$$

If $s \dot{\approx} t$ is deleted using *Delete*:

$$\dots S_{i-1} \leftrightarrow_{E_U} S_{i-1} \dots \implies \dots S_{i-1} \dots$$

If $s \dot{\approx} t$ is deleted using *Simplify-Eq*:

$$\dots S_{i-1} \leftrightarrow_{E_U} S_i \dots \implies \dots S_{i-1} \rightarrow_{R_U} S' \leftrightarrow_{E_U} S_i \dots$$

Knuth–Bendix Completion: Correctness Proof

Case (b): A proof step using a rule $s \rightarrow t$ is in $R_U \setminus R_\infty$.

This rule must be deleted during the run.

If $s \rightarrow t$ is deleted using *R-Simplify-Rule*:

$$\dots s_{i-1} \rightarrow_{R_U} s_i \dots \implies \dots s_{i-1} \rightarrow_{R_U} s' \leftarrow_{R_U} s_i \dots$$

If $s \rightarrow t$ is deleted using *L-Simplify-Rule*:

$$\dots s_{i-1} \rightarrow_{R_U} s_i \dots \implies \dots s_{i-1} \rightarrow_{R_U} s' \leftrightarrow_{E_U} s_i \dots$$

Knuth–Bendix Completion: Correctness Proof

Case (c): A subproof has the form $s_{i-1} \leftarrow_{R_\infty} s_i \rightarrow_{R_\infty} s_{i+1}$.

If there is no overlap or a noncritical overlap:

$$\dots s_{i-1} \leftarrow_{R_\infty} s_i \rightarrow_{R_\infty} s_{i+1} \dots \implies \dots s_{i-1} \rightarrow_{R_\infty}^* s' \leftarrow_{R_\infty}^* s_{i+1} \dots$$

If there is a critical pair that has been added using “Deduce”:

$$\dots s_{i-1} \leftarrow_{R_\infty} s_i \rightarrow_{R_\infty} s_{i+1} \dots \implies \dots s_{i-1} \leftrightarrow_{E_U} s_{i+1} \dots$$

In all cases, checking that the replacement subproof is smaller than the replaced subproof is routine. □

Knuth–Bendix Completion: Correctness Proof

Theorem 4.6.6:

Let $E_0, R_0 \vdash E_1, R_1 \vdash E_2, R_2 \vdash \dots$ be a fair run and let R_0 and E_∞ be empty. Then

- (1) every proof in $E_\cup \cup R_\cup$ is equivalent to a rewrite proof in R_∞ ,
- (2) R_∞ is equivalent to E_0 , and
- (3) R_∞ is convergent.

Knuth–Bendix Completion: Correctness Proof

Proof:

(1) By well-founded induction on \succ_c using the previous lemma.

(2) Clearly $\approx_{E \cup R_U} = \approx_{E_0}$.

Since $R_\infty \subseteq R_U$, we get $\approx_{R_\infty} \subseteq \approx_{E \cup R_U}$.

On the other hand, by (1), $\approx_{E \cup R_U} \subseteq \approx_{R_\infty}$.

(3) Since $\rightarrow_{R_\infty} \subseteq \succ$, R_∞ is terminating.

By (1), R_∞ is confluent. □

4.7 Unfailing Completion

Classical Knuth–Bendix completion:

Try to transform a set E of equations into an equivalent convergent TRS.

Fail if an equation can be neither oriented nor deleted.

Unfailing completion (Bachmair, Dershowitz, and Plaisted):

If an equation cannot be oriented, we can still use *orientable instances* for rewriting.

Note: If \succ is total on ground terms, then every *ground instance* of an equation is trivial or can be oriented.

Goal: Derive a *ground convergent* set of equations.

Unfailing Completion

Outlook:

Combine ordered resolution and unfailing completion to get a calculus for equational clauses.

⇒ Superposition calculus.