## Programming Languages and Compilers (CS 421)


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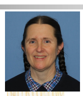

https://courses.engr.illinois.edu/cs421/sp2023

Based in part on slides by Mattox Beckman, as updated by Vikram Adve and Gul Agha



## Background for Unification

- Terms made from constructors and variables (for the simple first order case)
- Constructors may be applied to arguments (other terms) to make new terms
- Variables and constructors with no arguments are base cases
- Constructors applied to different number of arguments (arity) considered different
- Substitution of terms for variables



## Unification Problem

Given a set of pairs of terms ("equations")

$$\{(s_1, t_1), (s_2, t_2), \ldots, (s_n, t_n)\}$$

(the *unification problem*) does there exist a substitution $\sigma$ (the *unification solution*) of terms for variables such that

$$\sigma(s_i) = \sigma(t_i),$$

for all $i = 1, \ldots, n$?



## Unification Algorithm

- Let $S = \{(s_1 = t_1), (s_2 = t_2), \ldots, (s_n = t_n)\}$ be a unification problem.
- Case $S = \{\ \}$: $\mathrm{Unif}(S)$ = Identity function (i.e., no substitution)
- Case $S = \{(s, t)\} \cup S'$ : Four main steps



## Unification Algorithm

- Delete: if $s = t$ (they are the same term) then $\mathrm{Unif}(S) = \mathrm{Unif}(S')$
- Decompose: if $s = f(q_1, \ldots, q_m)$ and $t = g(r_1, \ldots, r_n)$ if $f = g$, $m = n$, then $\mathrm{Unif}(S) = \mathrm{Unif}(\{(q_1, r_1), \ldots, (q_m, r_m)\} \cup S')$ else **fail**!
- Orient: if $t = x$ is a variable, and $s$ is not a variable, $\mathrm{Unif}(S) = \mathrm{Unif}(\{(x = s)\} \cup S')$



## Unification Algorithm

- Eliminate: if $s = x$ is a variable, then if $x$ does not occur in $t$ (the occurs check), then
  - Let $\varphi = \{x \to t\}$
    - $\mathrm{Unif}(S) = \mathrm{Unif}(\varphi(S'))\ o\ \{x \to t\}$
  - Let $\psi = \mathrm{Unif}(\varphi(S'))$
  - $\mathrm{Unif}(S) = \{x \to \psi(t)\}\ o\ \psi$
    - Note: $\{x \to a\}\ o\ \{y \to b\} = \{y \to (\{x \to a\}(b))\}\ o\ \{x \to a\}$ if $y$ not in $a$

  else **fail** (because of occurs check failure)

## Example

- $x,y,z$ variables, $f,g$ constructors
- Unify $\{(f(x) = f(g(f(z),y))), (g(y,y) = x)\}$ = ?



## Example

- $x,y,z$ variables, $f,g$ constructors
- $S = \{(f(x) = f(g(f(z),y))), (g(y,y) = x)\}$ is nonempty
- Unify $\{(f(x) = f(g(f(z),y))), (g(y,y) = x)\}$ = ?



## Example

- $x,y,z$ variables, $f,g$ constructors
- Pick a pair: $(g(y,y) = x)$
- Unify $\{(f(x) = f(g(f(z),y))), (g(y,y) = x)\}$ = ?



## Example

- $x,y,z$ variables, $f,g$ constructors
- Pick a pair: $(g(y,y)) = x)$
- Orient: $(x = g(y,y))$
- Unify $\{(f(x) = f(g(f(z),y))), (g(y,y) = x)\}$ =
  Unify $\{(f(x) = f(g(f(z),y))), (x = g(y,y))\}$

by Orient



## Example

- $x,y,z$ variables, $f,g$ constructors
- Unify $\{(f(x) = f(g(f(z),y))), (x = g(y,y))\}$ = ?



## Example

- $x,y,z$ variables, $f,g$ constructors
- $\{(f(x) = f(g(f(z),y))), (x = g(y,y))\}$ is non-empty
- Unify $\{(f(x) = f(g(f(z),y))), (x = g(y,y))\}$ = ?

## Example

- x,y,z variables, f,g constructors
- Pick a pair: (x = g(y,y))

- Unify {(f(x) = f(g(f(z),y))), (x = g(y,y))} = ?



## Example

- x,y,z variables, f,g constructors
- Pick a pair: (x = g(y,y))
- Eliminate x with substitution {x→ g(y,y)}
  - Check: x not in g(y,y)
- Unify {(f(x) = f(g(f(z),y))), (x = g(y,y))} = ?



## Example

- x,y,z variables, f,g constructors
- Pick a pair: (x = g(y,y))
- Eliminate x with substitution {x→ g(y,y)}

- Unify {(f(x) = f(g(f(z),y))), (x = g(y,y))} =
  Unify {(f(g(y,y)) = f(g(f(z),y)))}
  o {x→ g(y,y)}



## Example

- x,y,z variables, f,g constructors

- Unify {(f(g(y,y)) = f(g(f(z),y)))}
  o {x→ g(y,y)} = ?



## Example

- x,y,z variables, f,g constructors
- {(f(g(y,y)) = f(g(f(z),y)))} is non-empty

- Unify {(f(g(y,y)) = f(g(f(z),y)))}
  o {x→ g(y,y)} = ?



## Example

- x,y,z variables, f,g constructors
- Pick a pair: (f(g(y,y)) = f(g(f(z),y)))

- Unify {(f(g(y,y)) = f(g(f(z),y)))}
  o {x→ g(y,y)} = ?

## Example

- x,y,z variables, f,g constructors
- Pick a pair: (f(g(y,y)) = f(g(f(z),y)))
- Decompose:(f(g(y,y)) = f(g(f(z),y))) becomes {(g(y,y) = g(f(z),y))}
- Unify {(f(g(y,y)) = f(g(f(z),y)))} o {x→ g(y,y)} =

  Unify {(g(y,y) = g(f(z),y))} o {x→ g(y,y)}



## Example

- x,y,z variables, f,g constructors
- {(g(y,y) = g(f(z),y))} is non-empty
- Unify {(g(y,y) = g(f(z),y))} o {x→ g(y,y)} = ?



## Example

- x,y,z variables, f,g constructors
- Pick a pair: (g(y,y) = g(f(z),y))
- Unify {(g(y,y) = g(f(z),y))} o {x→ g(y,y)} = ?



## Example

- x,y,z variables, f,g constructors
- Pick a pair: (f(g(y,y)) = f(g(f(z),y)))
- Decompose: (g(y,y)) = g(f(z),y)) becomes {(y = f(z)); (y = y)}
- Unify {(g(y,y) = g(f(z),y))} o {x→ g(y,y)} = Unify {(y = f(z)); (y = y)} o {x→ g(y,y)}



## Example

- x,y,z variables, f,g constructors
- Unify {(y = f(z)); (y = y)} o {x→ g(y,y)} = ?



## Example

- x,y,z variables, f,g constructors
- {(y = f(z)); (y = y)} o {x→ g(y,y) is non-empty
- Unify {(y = f(z)); (y = y)} o {x→ g(y,y)} = ?

## Example

- x,y,z variables, f,g constructors
- Pick a pair: (y = f(z))
- Unify {(y = f(z)); (y = y)} o {x→ g(y,y)} = ?



## Example

- x,y,z variables, f,g constructors
- Pick a pair: (y = f(z))
- Eliminate y with {y → f(z)}
- Unify {(y = f(z)); (y = y)} o {x→ g(y,y)} = Unify {(f(z) = f(z))} o ({y → f(z)} o {x→ g(y,y)})= Unify {(f(z) = f(z))} o {y → f(z); x→ g(f(z), f(z))}



## Example

- x,y,z variables, f,g constructors
- Unify {(f(z) = f(z))} o {y → f(z); x→ g(f(z), f(z))} = ?



## Example

- x,y,z variables, f,g constructors
- {(f(z) = f(z))} is non-empty
- Unify {(f(z) = f(z))} o {y → f(z); x→ g(f(z), f(z))} = ?



## Example

- x,y,z variables, f,g constructors
- Pick a pair: (f(z) = f(z))
- Unify {(f(z) = f(z))} o {y → f(z); x→ g(f(z), f(z))} = ?



## Example

- x,y,z variables, f,g constructors
- Pick a pair: (f(z) = f(z))
- Delete
- Unify {(f(z) = f(z))} o {y → f(z); x→ g(f(z), f(z))} = Unify {} o {y → f(z); x→ g(f(z), f(z))}

## Example

- x,y,z variables, f,g constructors
- Unify {} o {y → f(z); x→ g(f(z), f(z))} = ?



## Example

- x,y,z variables, f,g constructors
- {} is empty
- Unify {} = identity function
- Unify {} o {y → f(z); x→ g(f(z), f(z))} = {y → f(z); x→ g(f(z), f(z))}



## Example

- Unify {(f(x) = f(g(f(z),y))), (g(y,y) = x)} = {y → f(z); x→ g(f(z), f(z))}

f( x ) = f(g(f(z), y ))
→ f(g(f(z), f(z))) = f(g(f(z), f(z)))

g( y , y ) = x
→ g(f(z),f(z)) = g(f(z), f(z))



## Example of Failure: Decompose

- Unify{(f(x,g(y)) = f(h(y),x))}
- Decompose: (f(x,g(y)) = f(h(y),x))
- = Unify {(x = h(y)), (g(y) = x)}
- Orient: (g(y) = x)
- = Unify {(x = h(y)), (x = g(y))}
- Eliminate: (x = h(y))
- Unify {(h(y) = g(y))} o {x → h(y)}
- Decompose only rule in this case, but Decompose fails!



## Example of Failure: Occurs Check

- Unify{(f(x,g(x)) = f(h(x),x))}
- Decompose: (f(x,g(x)) = f(h(x),x))
- = Unify {(x = h(x)), (g(x) = x)}
- Orient: (g(x) = x)
- = Unify {(x = h(x)), (x = g(x))}
- Eliminate only rule that applies in this case, but Eliminate fails because the occurs check fails.