CMPT 379
Compilers

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Code Optimization

- There is no fully optimizing compiler *O*
- Let's assume *O* exists: it takes a program P and produces output **Opt**(P) which is the *smallest* possible
- Imagine a program Q that produces no output and never terminates, then **Opt**(Q) could be:
  `L1: goto L1`
- Then to check if a program P never terminates on some inputs, check if **Opt**(P(i)) is equal to **Opt**(Q)
- Full Employment Theorem for Compiler Writers, see Rice(1953)

Optimizations

- Non-Optimizations
- Correctness of optimizations
  - Optimizations must not change the meaning of the program
- Types of optimizations
  - Local optimizations
  - Global dataflow analysis for optimization
  - Static Single Assignment (SSA) Form
- Amdahl's Law

Non-Optimizations

```
enum { GOOD, BAD };
extern int test_condition();

void check() {
 int rc;

 rc = test_condition();
 if (rc != GOOD) {
  exit(rc);
 }
}
```

```
enum { GOOD, BAD };
extern int test_condition();

void check() {
 int rc;

 if ((rc = test_condition())) {
  exit(rc);
 }
}
```

Which version of check runs faster?

Types of Optimizations

- High-level optimizations
  - function inlining
- Machine-dependent optimizations
  - e.g., peephole optimizations, instruction scheduling
- Local optimizations or Transformations
  - within basic block

Types of Optimizations

- Global optimizations or Data flow Analysis
  - across basic blocks
  - within one procedure (*intraprocedural*)
  - whole program (*interprocedural*)
  - pointers (*alias analysis*)

Maintaining Correctness

- What does this program output?

3

Not:

$ decafcc byzero.decaf

Floating exception

```
void main() {
   int x;
   if (false) {
      x = 3/(3-3);
   } else {
      x = 3;
   }
   callout("print_int", x);
}
```

branch delay slot (cf. **load delay** slot)

Peephole Optimization

- Redundant instruction elimination
  - If two instructions perform that same function ***and*** are in the same basic block, remove one
  - Redundant loads and stores

```
li $t0, 3
li $t0, 4
```

  - Remove unreachable code

```
li $t0, 3
goto L2
... (all of this code until next label can be removed)
```

Peephole Optimization

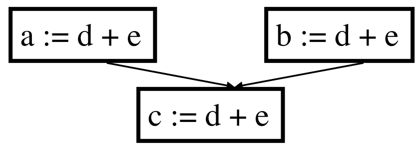
- Flow control optimization
  goto L1
  L1: goto L2
- Algebraic simplification
- Reduction in strength
  - Use faster instructions whenever possible
- Use of Machine Idioms
- Filling delay slots

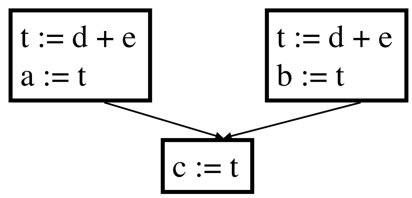
Constant folding & propagation

- Constant folding
  - compute expressions with known values at compile time
- Constant propagation
  - if constant assigned to variable, replace uses of variable with constant unless variable is reassigned

Constant folding & propagation

- Copy Propagation





Transformations

- Structure preserving transformations
- Common subexpression elimination

  a := b + c

  b := a - d

  c := b + c

  d := a - d (⇒ b)

Transformations

- Dead-code elimination (combines copy propogation with removal of unreachable code)

  if (debug) { f(); } /* debug := false (as a constant) */

  if (false) { f(); } /* constant folding */

  using deadcode elimination, code for f() is removed

  x := t3   x := t3

  t4 := x   becomes   t4 := t3

Transformations

- Renaming temporary variables

  t1 := b+c can be changed to t2 := b+c

  replace all instances of t1 with t2

- Interchange of statements

  t1 := b+c   t2 := x+y

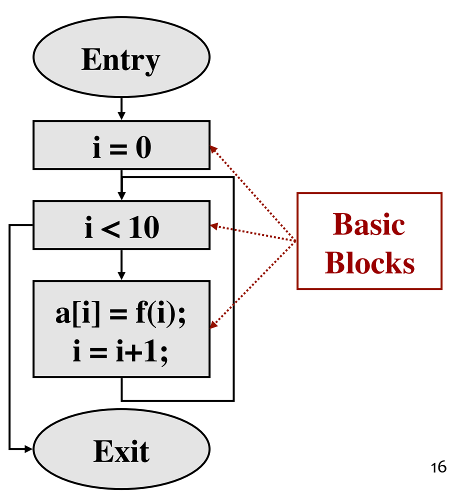
  t2 := x+y   can be converted to t1 := b+c

Transformations

- Algebraic transformations
  d := a + 0 (⇒ a)
  d := d * 1 (⇒ *eliminate*)
- Reduction of strength
  d := a ** 2 (⇒ a * a)

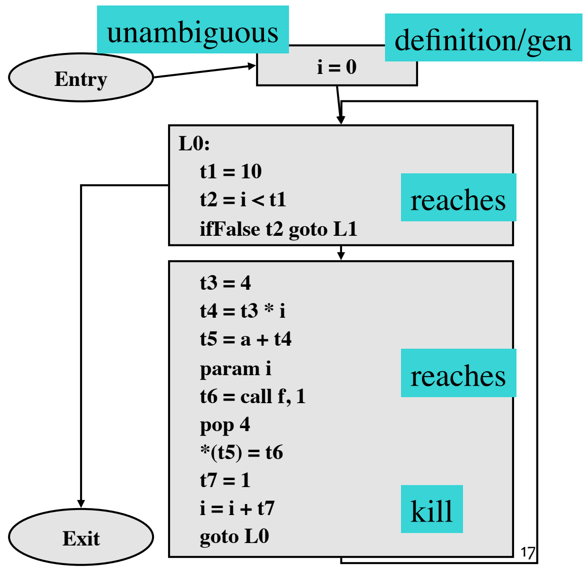
Control Flow Graph (CFG)

```
int main() {
 extern int f(int);
 int i;
 int *a;
 for (i = 0;
        i < 10;
             i = i + 1)
     { a[i] = f(i); }
}
```



Control Flow Graph in TAC

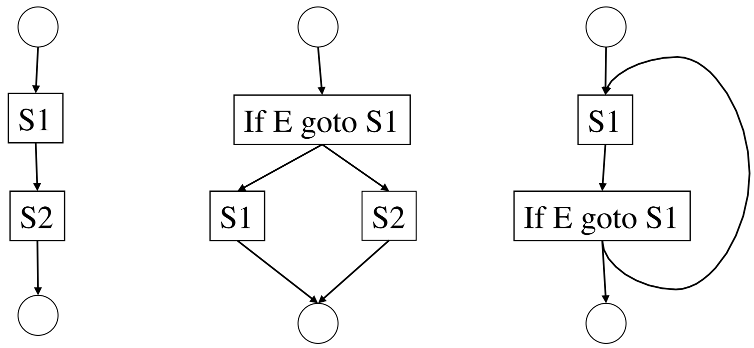
```
main:
  i = 0
L0:
  t1 = 10
  t2 = i < t1
  ifFalse t2 Goto L1
  t3 = 4
  t4 = t3 * i
  t5 = a + t4
  param i
  t6 = call f, 1
  pop 4
  *(t5) = t6
  t7 = 1
  i = i + t7
  goto L0
L1:
  return
```



Dataflow Analysis

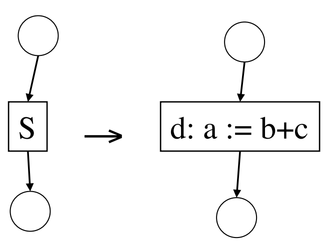
- S → id := E
- S → S ; S
- S → if E then S else S
- S → do S while E
- E → id + id
- E → id

Dataflow Analysis



S ; S   if E then S else S   do S while E

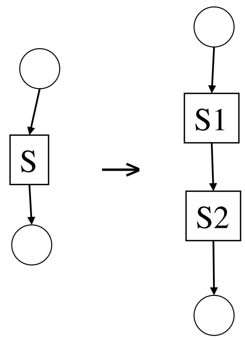
Reaching definitions



gen[S] = { d }
kill[S] = def(a) - { d }

out[S] = gen[S] ∪ (in[S] - kill[S])

Reaching definitions



$gen[S] = gen[S2] \cup (gen[S1] - kill[S2])$
$kill[S] = kill[S2] \cup (kill[S1] - gen[S2])$

$in[S1] = in[S]$
$in[S2] = out[S1]$
$out[S] = out[S2]$

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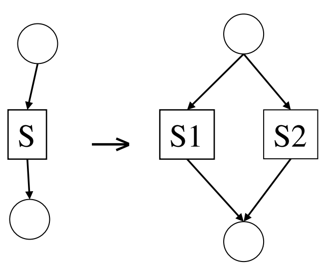
Reaching definitions



$gen[S] = gen[S1] \cup gen[S2]$
$kill[S] = kill[S1] \cap (kill[S1] - gen[S2])$

$in[S1] = in[S]$
$in[S2] = in[S]$
$out[S] = out[S1] \cup out[S2]$

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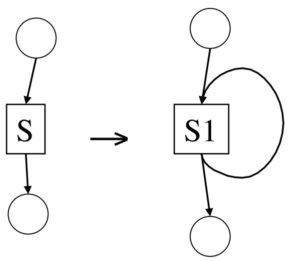
Reaching definitions



gen[S] = gen[S1]
kill[S] = kill[S1]

in[S1] = in[S] ∪ gen[S1]
out[S] = out[S1]

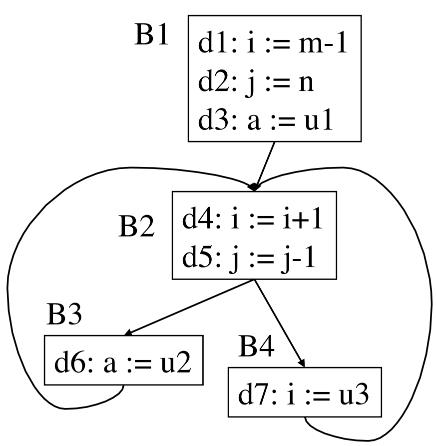
Iteratively find out[S] (fixed point)

out = synthesized attribute

in = inherited attribute

out[S1] = gen[S1] ∪ (in[S1] - kill[S1])

Reaching definitions



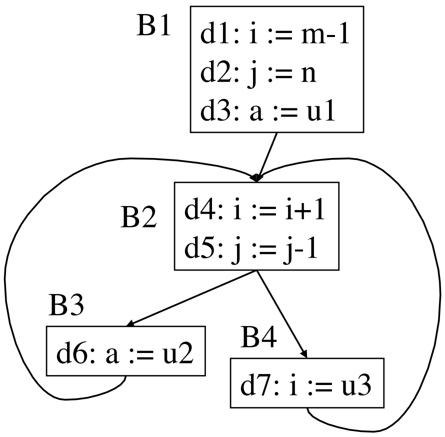
gen[B1] = { d1, d2, d3 }
kill[B1] = { d4, d5, d6, d7 }

gen[B2] = { d4, d5 }
kill[B2] = { d1, d2, d7 }

gen[B3] = { d6 }
kill[B3] = { d3 }

gen[B4] = { d7 }
kill[B4] = { d1, d4 }

Reaching definitions



gen[B1] = { d1, d2, d3 }
kill[B1] = { d4, d5, d6, d7 }

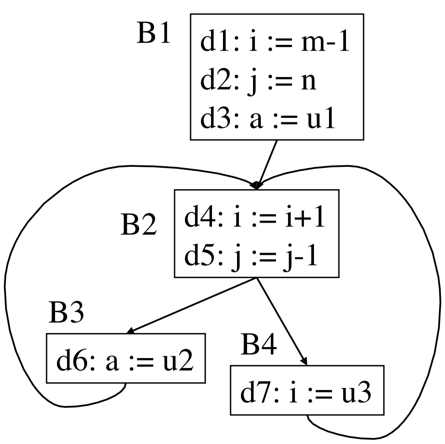
gen[B2] = { d4, d5 }
kill[B2] = { d1, d2, d7 }

gen[B3] = { d6 }
kill[B3] = { d3 }

gen[B4] = { d7 }
kill[B4] = { d1, d4 }

in[B2] = out[B1] ∪ out[B3] ∪ out[B4]

Reaching definitions



gen[B1] = { d1, d2, d3 }
kill[B1] = { d4, d5, d6, d7 }

gen[B2] = { d4, d5 }
kill[B2] = { d1, d2, d7 }

gen[B3] = { d6 }
kill[B3] = { d3 }

gen[B4] = { d7 }
kill[B4] = { d1, d4 }

out[B2] = gen[B2] ∪ (in[B3] - kill[B2])
out[B2] = gen[B2] ∪ (in[B4] - kill[B2])

Dataflow Analysis

- Compute Dataflow Equations over Control Flow Graph
  - Reaching Definitions (Forward)
    out[BB] := gen[BB] ∪ (in[BB] – kill[BB])
    in[BB] := ∪ out[s] : forall s ∈ pred[BB]
  - Liveness Analysis (Backward)
    in[BB] := use[BB] ∪ (out[BB] – def[BB])
    out[BB] := ∪ in[s] : forall s ∈ succ[BB]
- Computation by fixed-point analysis

SSA Form

- *def-use* chains keep track of where variables were defined and where they were used
- Consider the case where each variable has only one definition in the intermediate representation
- One static definition, accessed many times
- Static Single Assignment Form (SSA)

SSA Form

- SSA is useful because
  – Dataflow analysis and optimization is simpler when each variable has only one definition
  – If a variable has N uses and M definitions (which use N+M instructions) it takes N*M to represent def-use chains
  – Complexity is the same for SSA but in practice it is usually linear in number of definitions
  – SSA simplifies the register interference graph

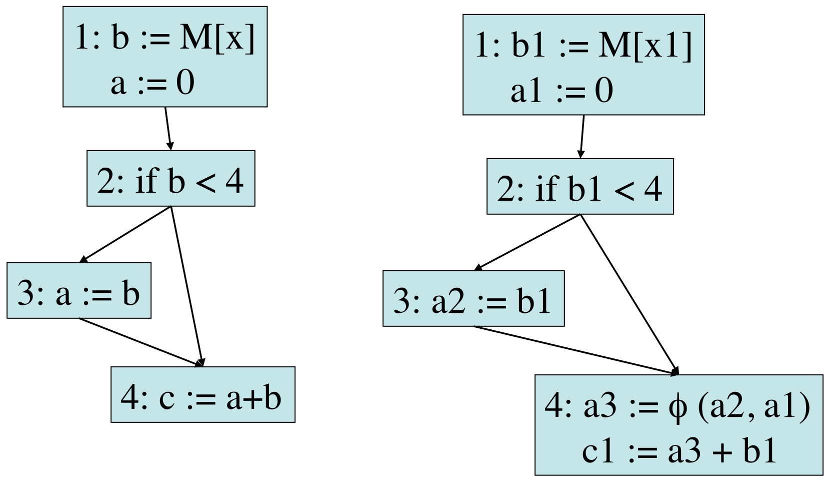
SSA Form

- Original Program
- SSA Form

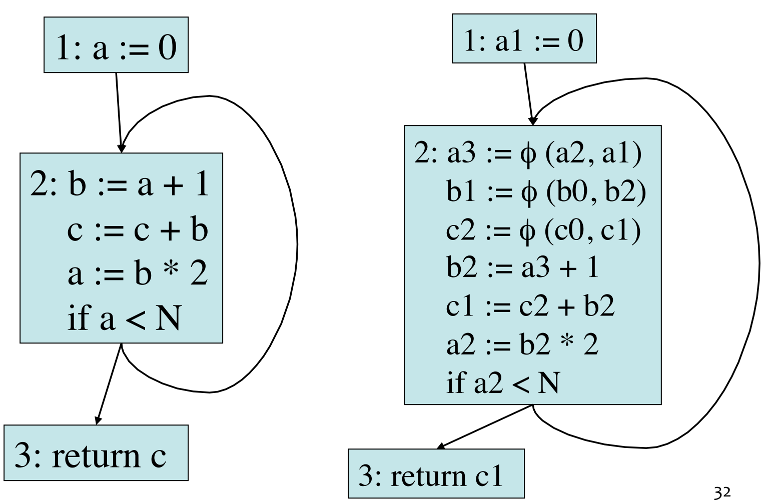
Original Program	SSA Form
a := x + y	a1 := x + y
b := a - 1	b1 := a1 - 1
a := y + b	a2 := y + b1
b := x * 4	b2 := x * 4
a := a + b	a3 := a2 + b2

what about conditional branches?

SSA Form



SSA Form



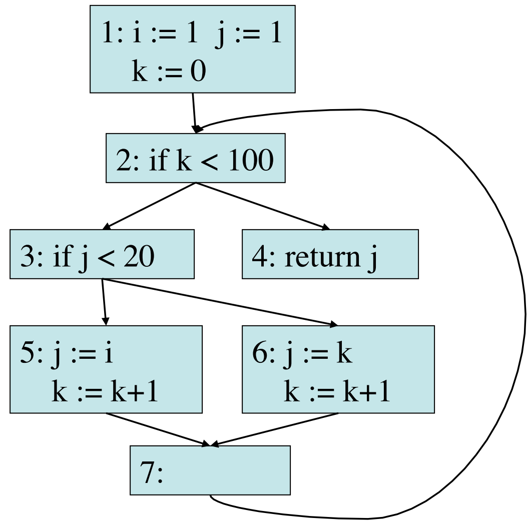
Optimizations using SSA

- SSA form contains *statements*, *basic blocks* and *variables*
- Dead-code elimination
  - if there is a variable v with no *uses* and *def* of v has no side-effects, delete statement defining v
  - if $z := \phi(x, y)$ then eliminate this stmt if no *defs* for x, y

Optimizations using SSA

- Constant Propagation
  - if $v := c$ for some constant c then replace v with c for all uses of v
  - $v := \phi(c1, c2, \ldots, cn)$ where all c_i are equal to c can be replaced by $v := c$

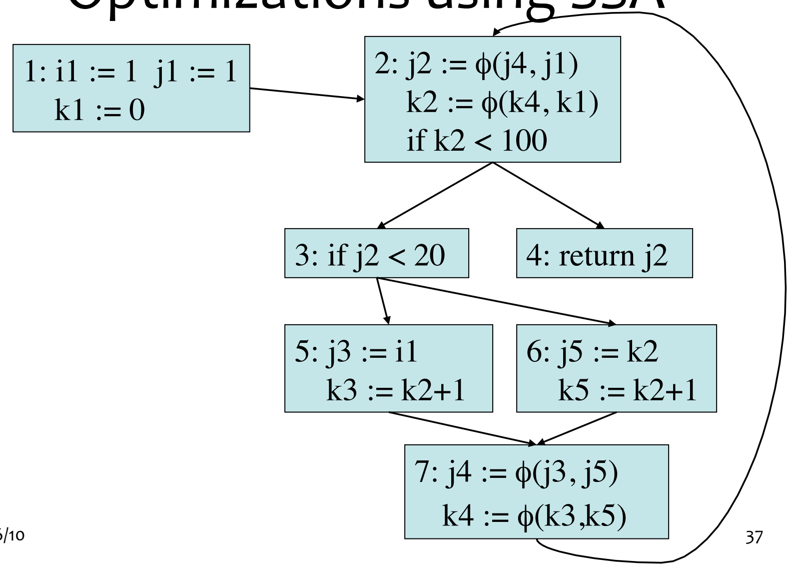
Optimizations using SSA



Optimizations using SSA

- Conditional Constant Propagation
  - In previous flow graph, is j always equal to 1?
  - If j = 1 always, then block 6 will never execute and so j := i and j := 1 always
  - If j > 20 then block 6 will execute, and j := k will be executed so that eventually j > 20
  - Which will happen? Using SSA we can find the answer.

Optimizations using SSA



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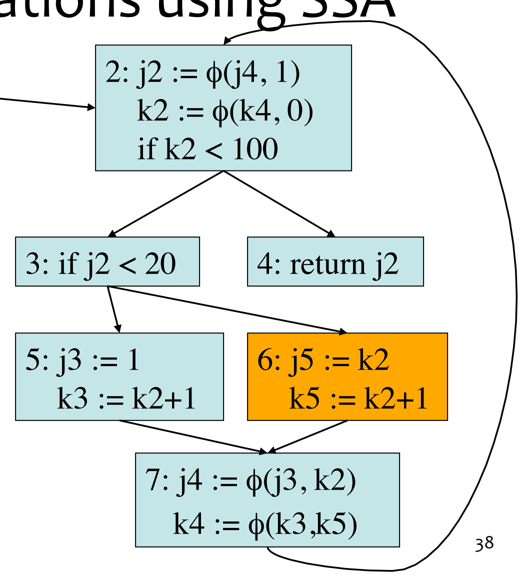
Optimizations using SSA



After Constant Propagation

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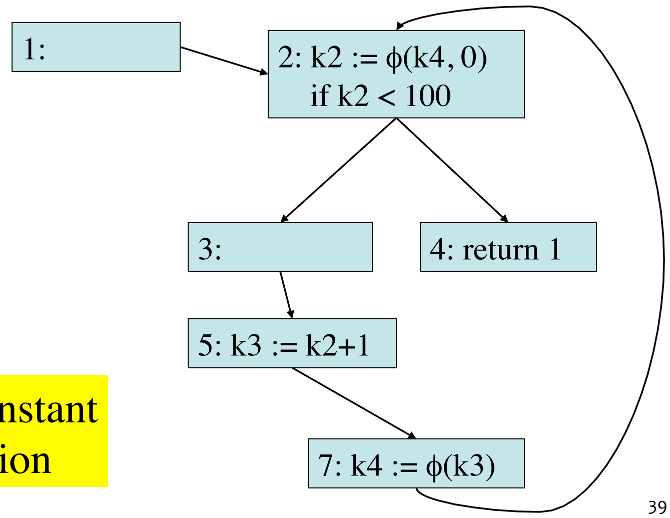
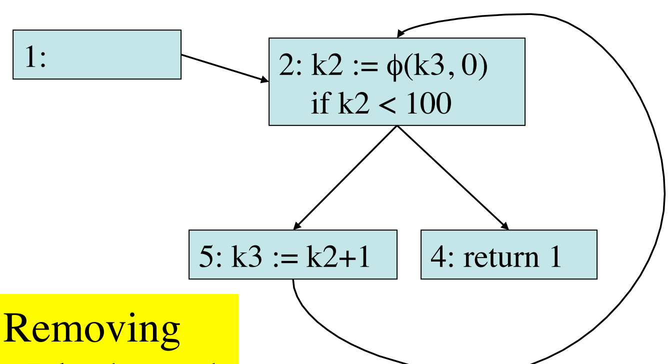
Optimizations using SSA



After Constant Propagation

Optimizations using SSA



After Removing Empty Blocks and 1-arg ϕ functions

Optimizations using SSA

- Arrays, Pointers and Memory
  - For more complex programs, we need *dependencies*: how does statement B depend on statement A?
  - **Read after write**: A defines variable *v*, then B uses *v*
  - **Write after write**: A defines *v*, then B defines *v*
  - **Write after read**: A uses *v*, then B defines *v*
  - **Control**: A controls whether B executes

Optimizations using SSA

- Memory dependence

  M[i] := 4

  x := M[j]

  M[k] := j
- We cannot tell if *i, j, k* are all the same value which makes any optimization difficult
- Similar problems with Control dependence
- SSA does not offer an easy solution to these problems

SSA Form

- Conversion from a Control Flow Graph (created from TAC) into SSA Form is not trivial
- Two famous algorithms:
  - Lengauer-Tarjan algorithm (see the Tiger book by Andrew W. Appel for more details)
  - Harel algorithm

More on Optimization

- *Advanced Compiler Design and Implementation* by Steven S. Muchnick

- Control Flow Analysis
- Data Flow Analysis
- Dependence Analysis
- Alias Analysis
- Early Optimizations
- Redundancy Elimination
- Loop Optimizations
- Procedure Optimizations
- Code Scheduling (pipelining)
- Low-level Optimizations
- Interprocedural Analysis

Amdahl's Law

- $Speedup_{total}$ = $((1 - Time_{Fractionoptimized}) + Time_{Fractionoptimized} / Speedup_{optimized})^{-1}$
- Optimize the common case, 90/10 rule
- Requires quantitative approach
  - Profiling + Benchmarking
- Problem: Compiler writer doesn't know the application beforehand

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Summary

- Optimizations can improve speed, while maintaining correctness
- Various early optimization steps
- Global optimizations = dataflow analysis
- Reachability and Liveness analysis provides dataflow analysis
- Static Single-Assignment Form (SSA)

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