Superoptimization

How fast can your code go?

James Pallister
University of Bristol & Embecosm

What is superoptimization?

Unoptimized
code

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Unoptimized
code

Compiler
optimized
code

What is superoptimization?

Unoptimized code

Compiler optimized code

Superoptimized code

Plan for today

What is superoptimization?

Latest developments

The GNU Superoptimizer

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Latest developments

The GNU Superoptimizer

Superoptimization in action

```
int sign(int n)
{
  if(n > 0)
    return 1;
  else if(n < 0)
    return -1;
  else
    return 0;
}
```

Superoptimization in action

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```

```
    cmp.l   d0, 0
    ble     L1
    move.l  d1, 1
    bra     L3
L1:
    bge     L2
    move.l  d1, -1
    bra     L3
L2:
    move.l  d1, 0
L3:
```

Superoptimization in action

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```

```asm
add.l  d0, d0
subx.l d1, d1
negx.l d0
addx.l d1, d1
```

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Superoptimization in action

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```
add.l   d0, d0
subx.l  d1, d1
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addx.l  d1, d1
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How does it work?

```
d0  ← n

add.l  d0, d0
subx.l d1, d1
negx.l d0
addx.l d1, d1

d1  → sign(n)
```

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addx.l  d1, d1

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```

x	d0	d1
0	-3	

x	d0	d1
0	0	

x	d0	d1
0	2	

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How does it work?

```
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add.l  d0, d0
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```

x	d0	d1
0	-3	
1	-6	

x	d0	d1
0	0	
0	0	

x	d0	d1
0	2	
0	4	

How does it work?

```
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add.l  d0, d0
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```

x	d0	d1
0	-3	
1	-6	
0	-6	-1

x	d0	d1
0	0	
0	0	
0	0	0

x	d0	d1
0	2	
0	4	
0	4	0

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1	-6	
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1	6	-1

x	d0	d1
0	0	
0	0	
0	0	0
0	0	0

x	d0	d1
0	2	
0	4	
0	4	0
1	-4	0

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0	6	-1

x	d0	d1
0	0	
0	0	
0	0	0
0	0	0
0	0	0

x	d0	d1
0	2	
0	4	
0	4	0
1	-4	0
0	-4	1

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How does it work?

	x	d0	d1	x	d0	d1	x	d0	d1
`d0 ← n`	0	-3		0	0		0	2	
`add.l d0, d0`	1	-6		0	0		0	4	
`subx.l d1, d1`	0	-6	-1	0	0	0	0	4	0
`negx.l d0`	1	6	-1	0	0	0	1	-4	0
`addx.l d1, d1`	0	6	-1	0	0	0	0	-4	1
`d1 → sign(n)`			-1			0			1

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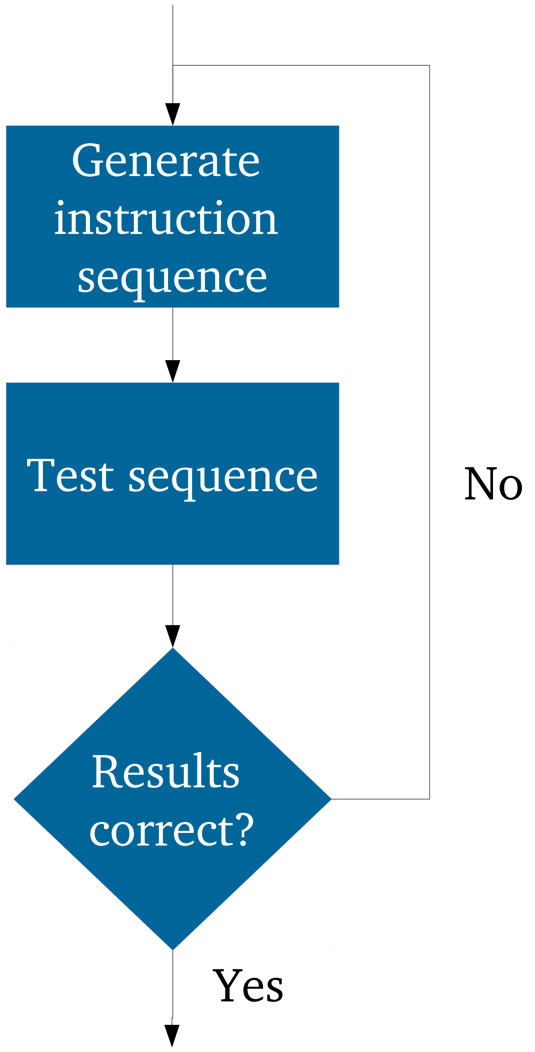
“A look at the smallest program”



Massalin, H. (1987). Superoptimizer - A Look at the Smallest Program. ACM SIGARCH Computer Architecture News, 122–126.

A recent example: Atmel AVR

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Is x a power of 2?

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r = !((x-1) & x) && x;
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Compiled code

```
mov     r20, r24
ldi     r21, 0
mov     r22, r20
mov     r19, r21
subi    r22, 1
sbc     r19, r1
and     r22, r20
and     r19, r21
or      r22, r19
brne    .+0
ldi     r25, 0x01
cpse    r24, 1
rjmp    .+0
ldi     r25, 0
mov     r24, r25
ret
ldi     r24, 0
ret
```

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Is x a power of 2?

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r = !((x-1) & x) && x;
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ldi     r25, 0x01
cpse    r24, 1
rjmp    .+0
ldi     r25, 0
mov     r24, r25
ret
ldi     r24, 0
ret
```

Superoptimized code

```
mov     r1,r0
dec     r1
eor     r0,r1
sub     r1,r0
adc     r1,r1
and     r1,r0
ret
```

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Superoptimization fundamentals: Enumeration

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Generating the sequences of instructions

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- But doing them *all* takes far too long

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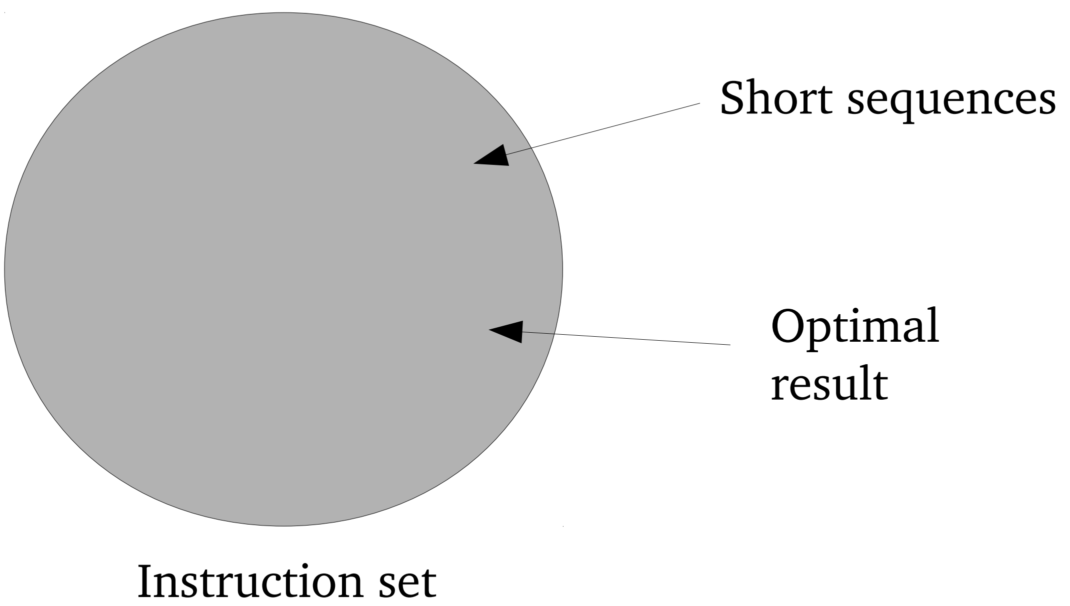

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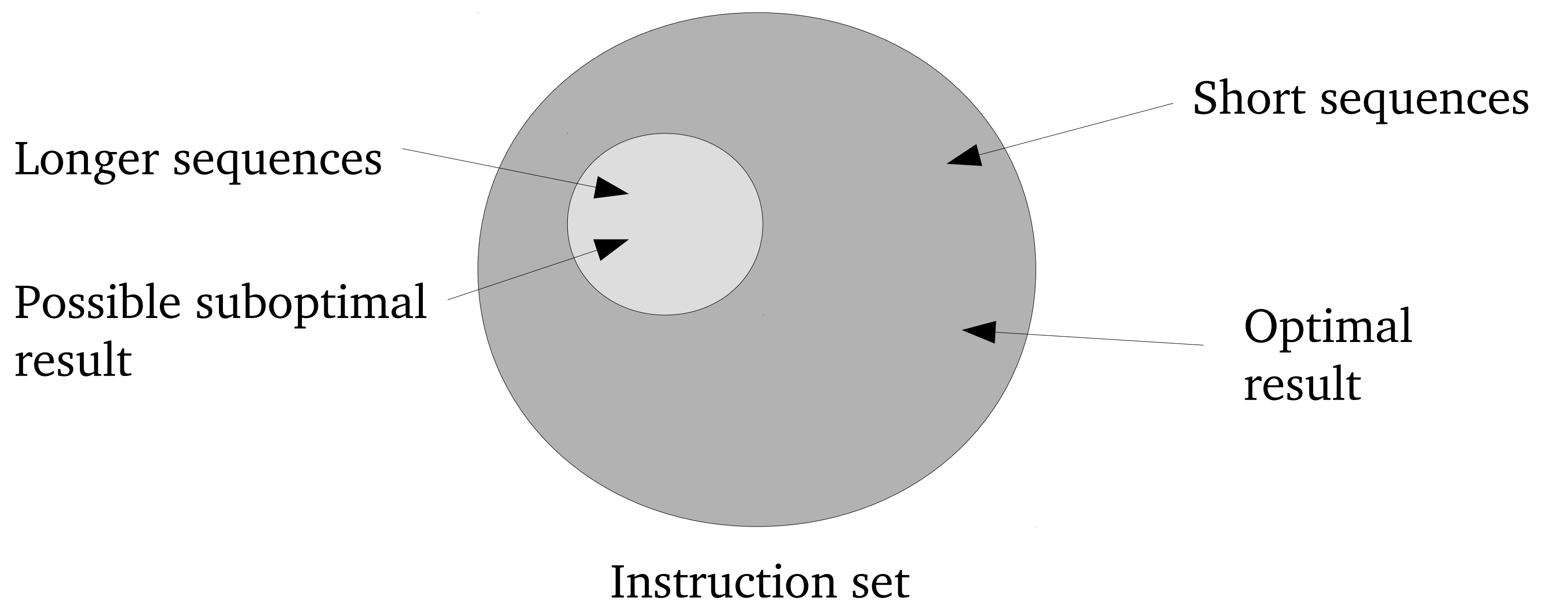

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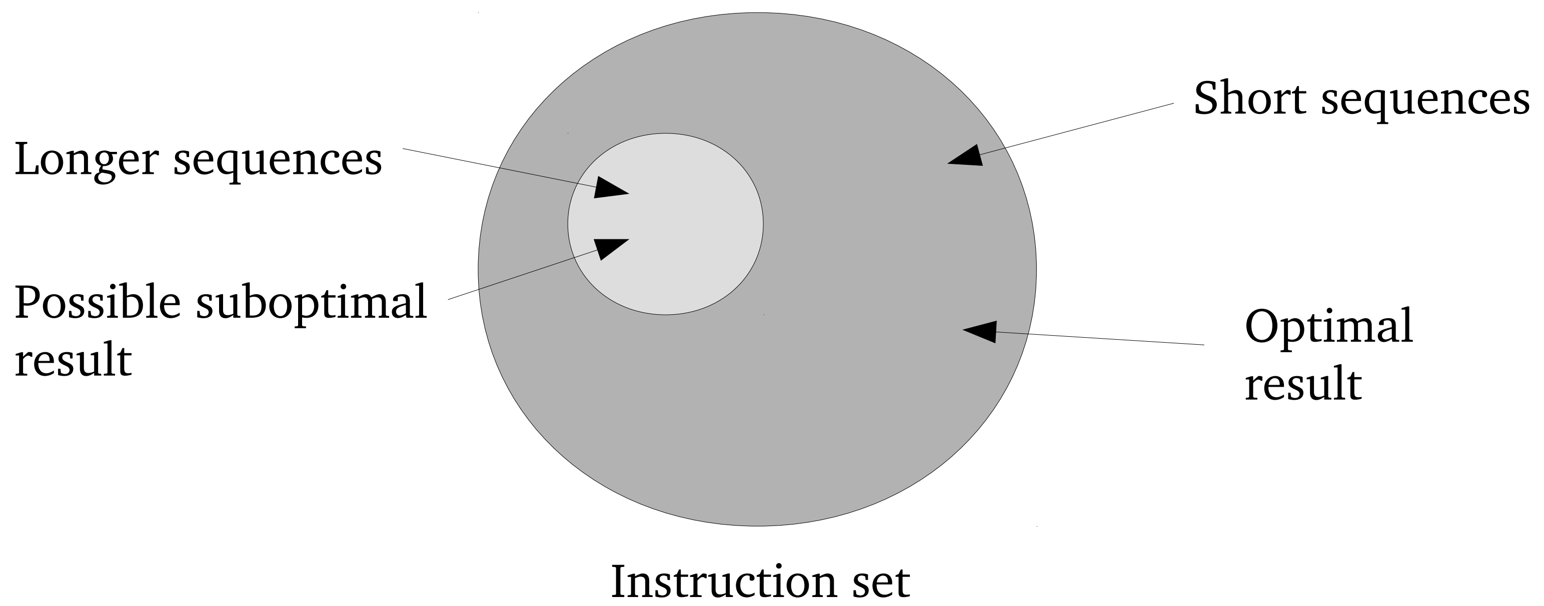
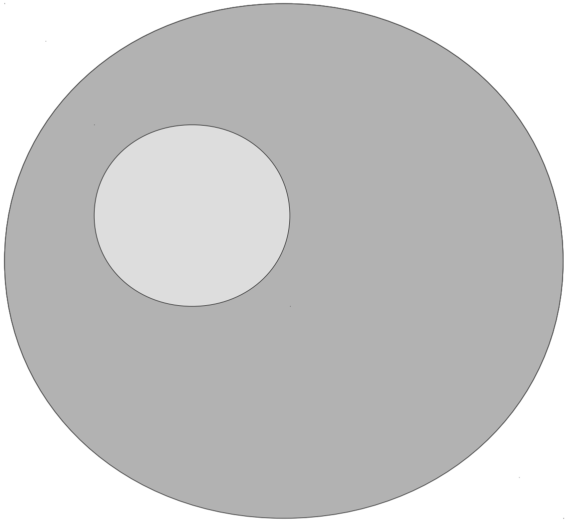


How to select the sequences of instructions?

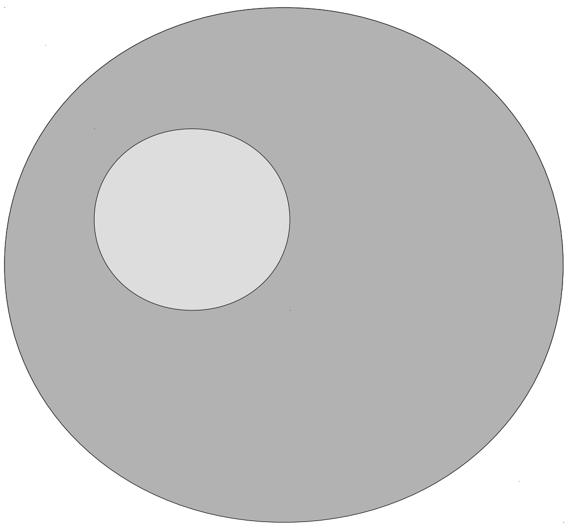
Superoptimization fundamentals: Pruning



Instruction set

Superoptimization fundamentals: Pruning

Not all instruction sequences are valid.



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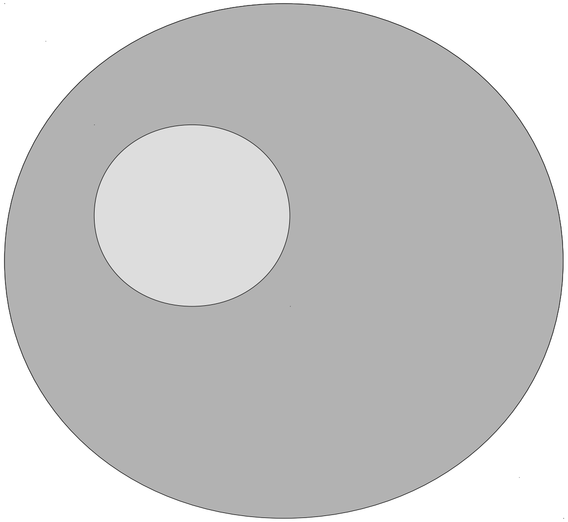
Superoptimization fundamentals: Pruning

Not all instruction sequences are valid.

How do we quickly ignore bad sequences?



Instruction set

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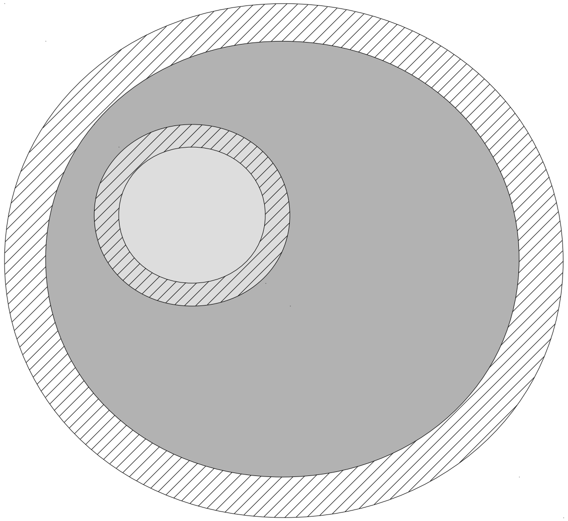

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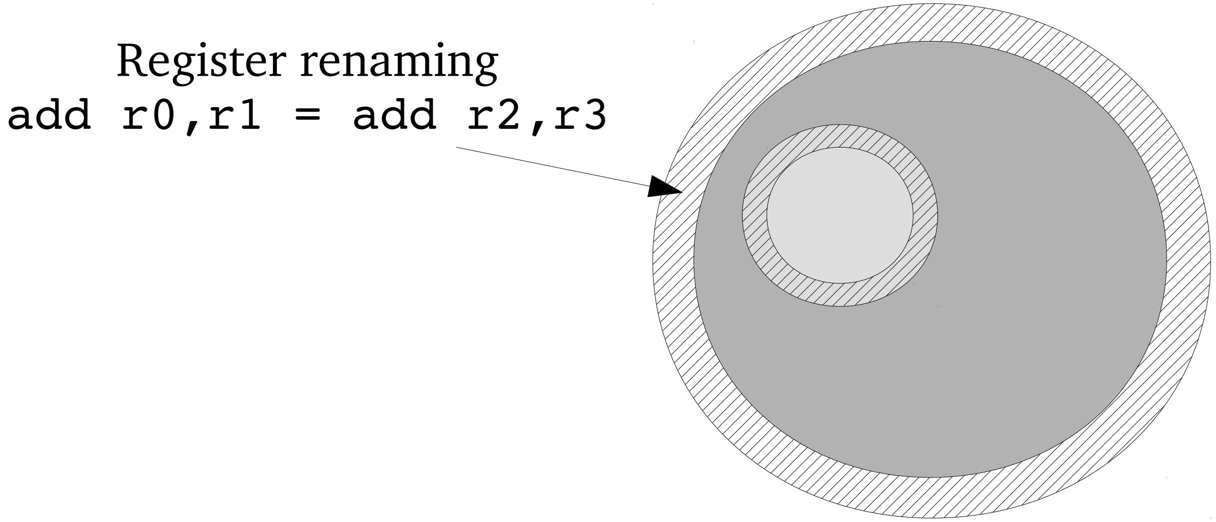

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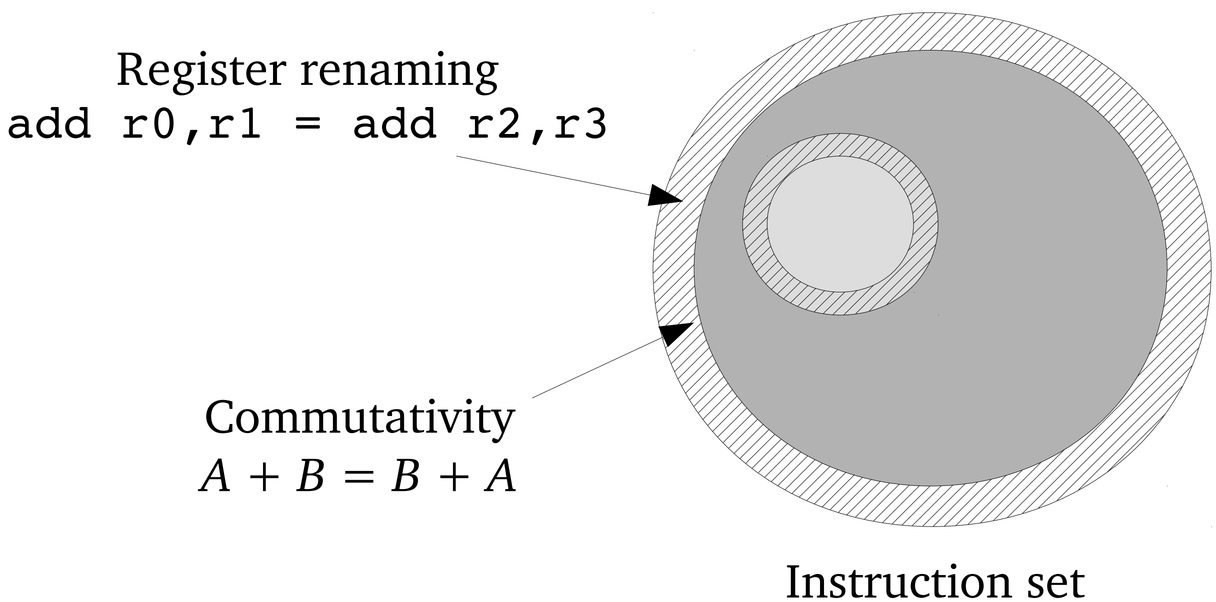

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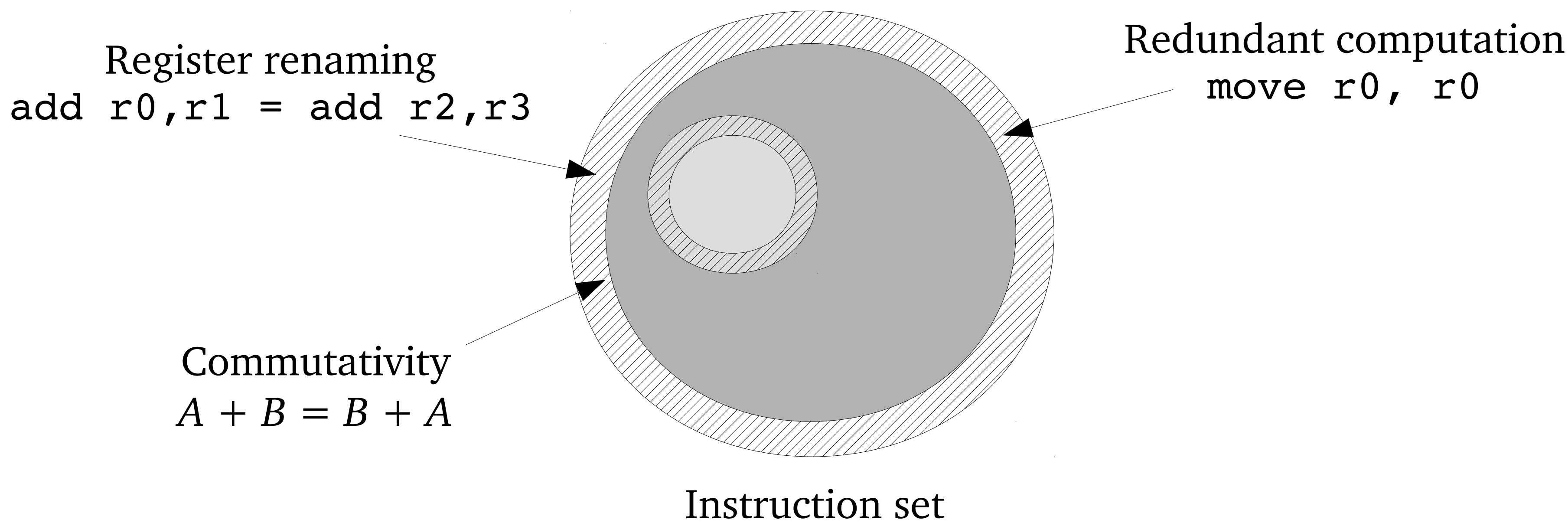

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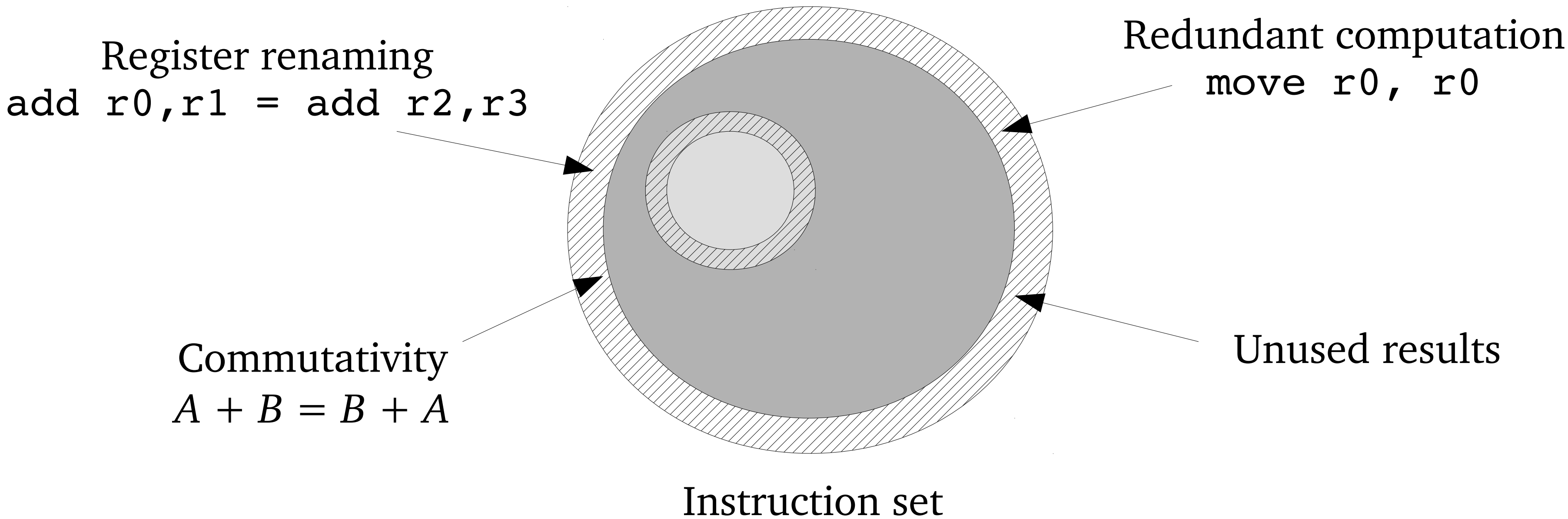

Superoptimization fundamentals: Testing

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Is the sequence correct?

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Testing
(simulation)

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Testing
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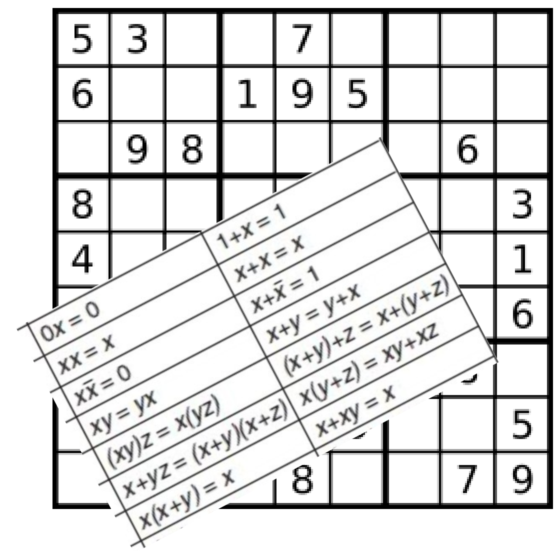
Mathematical proof
(symbolic solving)



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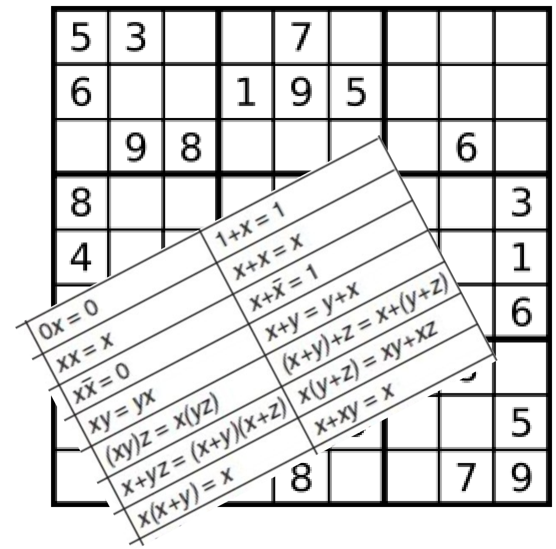
Superoptimization fundamentals: Testing

Is the sequence correct?

Testing
(simulation)

1. Choose some input
2. Run/simulate
3. Check output

Mathematical proof
(symbolic solving)



Superoptimization fundamentals: Testing

Is the sequence correct?

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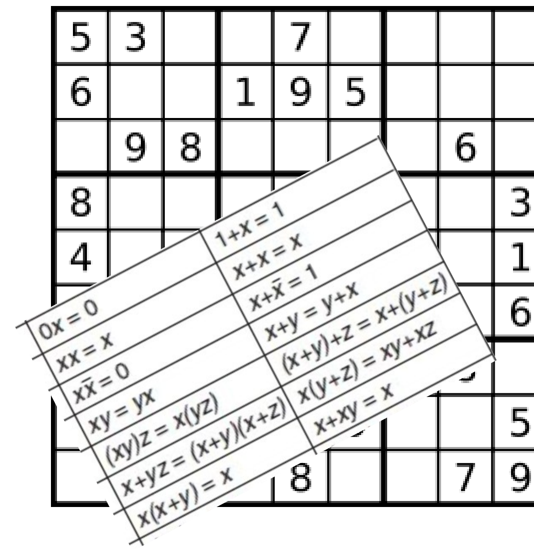


Formal verification
Proves the sequence correct
Slow

Superoptimization fundamentals: Testing

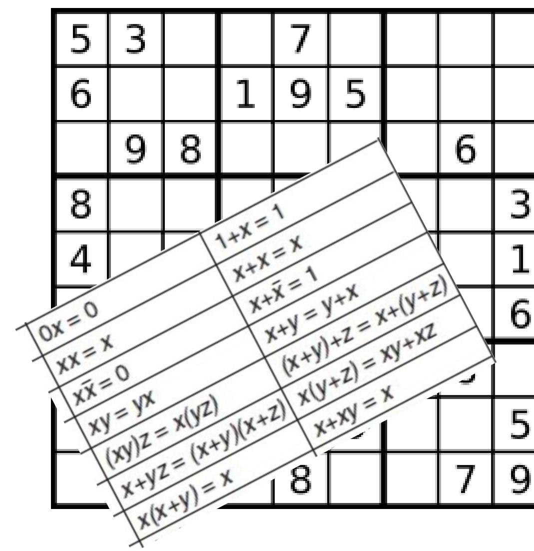
Is the sequence correct?

Testing
(simulation)

1. Choose some input
2. Run/simulate
3. Check output

Use Both

Mathematical proof
(symbolic solving)



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Superoptimization fundamentals: Costing

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Which sequence is the best?

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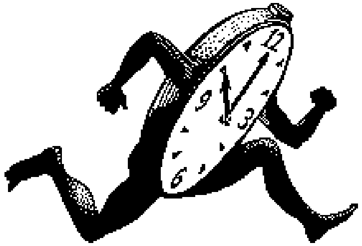
Execution time



Superoptimization fundamentals: Costing

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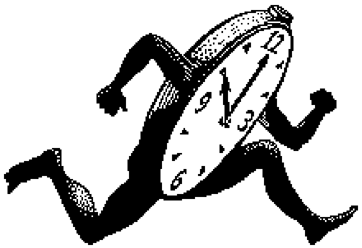
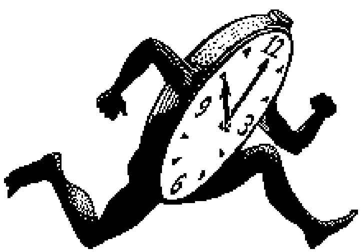


Code size

Superoptimization fundamentals: Costing

Which sequence is the best?

Execution time



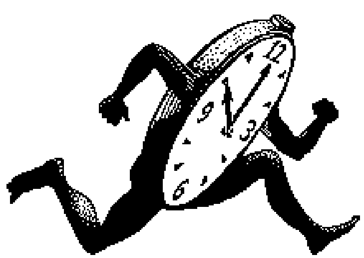
Code size

Energy consumption

Superoptimization fundamentals: Costing

Which sequence is the best?

Execution time



Code size

Energy consumption

If you can enumerate the instructions in cost order, the first correct sequence is the optimal sequence.

Plan for today

What is superoptimization?

Latest developments

The GNU Superoptimizer

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Search space pruning

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Restrict parameters

- Registers
  - 50% of instruction sequences of length 8 use less than 4 registers
- Immediate constants
  - Frequently used constants: -16 to +16, 2^n, 2^n-1

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Canonical form

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`mov r1, r0` has many equivalent versions

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Rename each register so they appear in sequence:

```
mov r1, r0   →
mov r4, r2   →   mov r1, r0
mov r2, r8   →
```

Canonical form

`mov r1, r0` has many equivalent versions

Rename each register so they appear in sequence:

```
mov r1, r0
mov r4, r2    →    mov r1, r0
mov r2, r8
```

With 16 registers this replaces 16*15 equivalent versions

Canonical form

```
add r4, r8, r1            add r2, r1, r0
orr r8, r4, #1    --->    orr r1, r2, #1
sub r1, r2, #8            sub r0, r3, #8
```

Canonical form

```
add r4, r8, r1
orr r8, r4, #1
sub r1, r2, #8
```

→

```
add r2, r1, r0
orr r1, r2, #1
sub r0, r3, #8
```

Single three operand instruction:

```
add rX, rX, rX
```

5 unique forms

→

```
add r0, r0, r0
add r0, r0, r1
add r0, r1, r0
add r0, r1, r1
add r0, r1, r2
```

Canonical form – reduction

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Data processing instructions

- 16 ops, each using 3 of 16 possible registers.
- E.g.

```
add r0, r1, r2
sub r3, r4, r5
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Instructions	Normal	Canonical	Canonical (4 registers)
1	65,536	80	80
2	4,294,967,296	51,968	47,872
3	281,474,976,710,656	4,157,669,376	45,264,896
4	18,446,744,073,709,551,616	276,142,292,992	45,880,115,200

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@200,000 tests/second   2.9 million years

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@200,000 tests/second — 2.9 million years (Normal, 4 instructions); 16 days (Canonical, 4 instructions)

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@200,000 tests/second — 2.9 million years (Normal, 4 instructions); 16 days (Canonical); <3 days (Canonical, 4 registers)

Instruction costing

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Sequence cost is simple if code size is to be minimised

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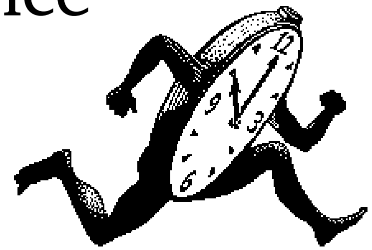
Difficult to accurately measure the performance of short sequences of instructions.



- Pipeline modelling
- Cycle accurate simulation

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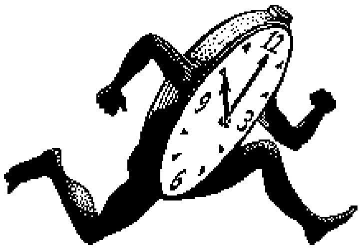

Energy

- Total Software Energy and Reporting (TSERO)

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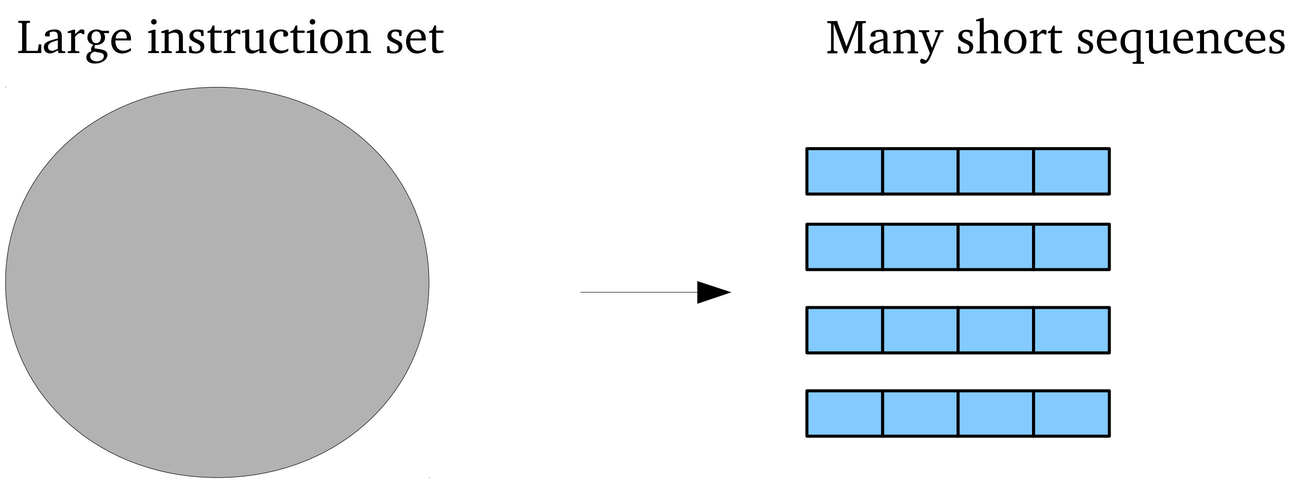

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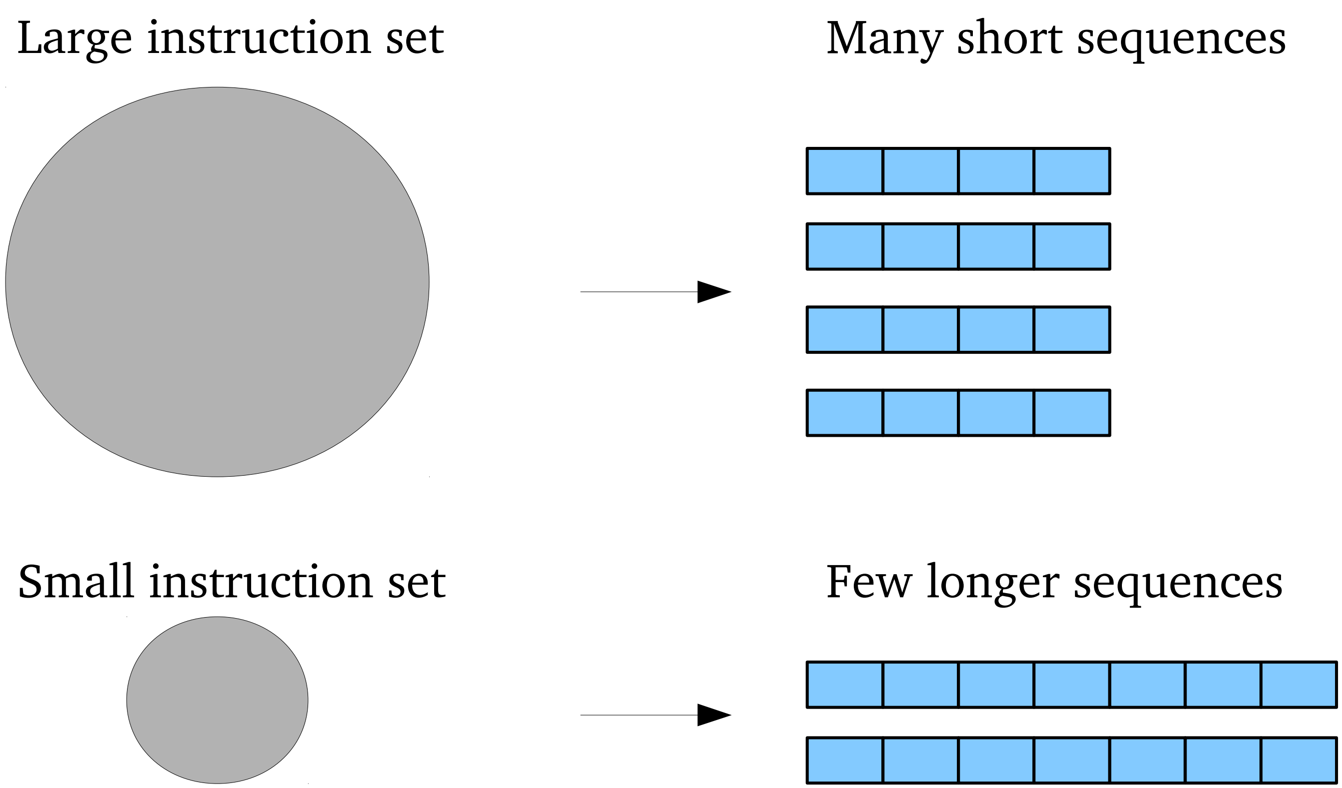

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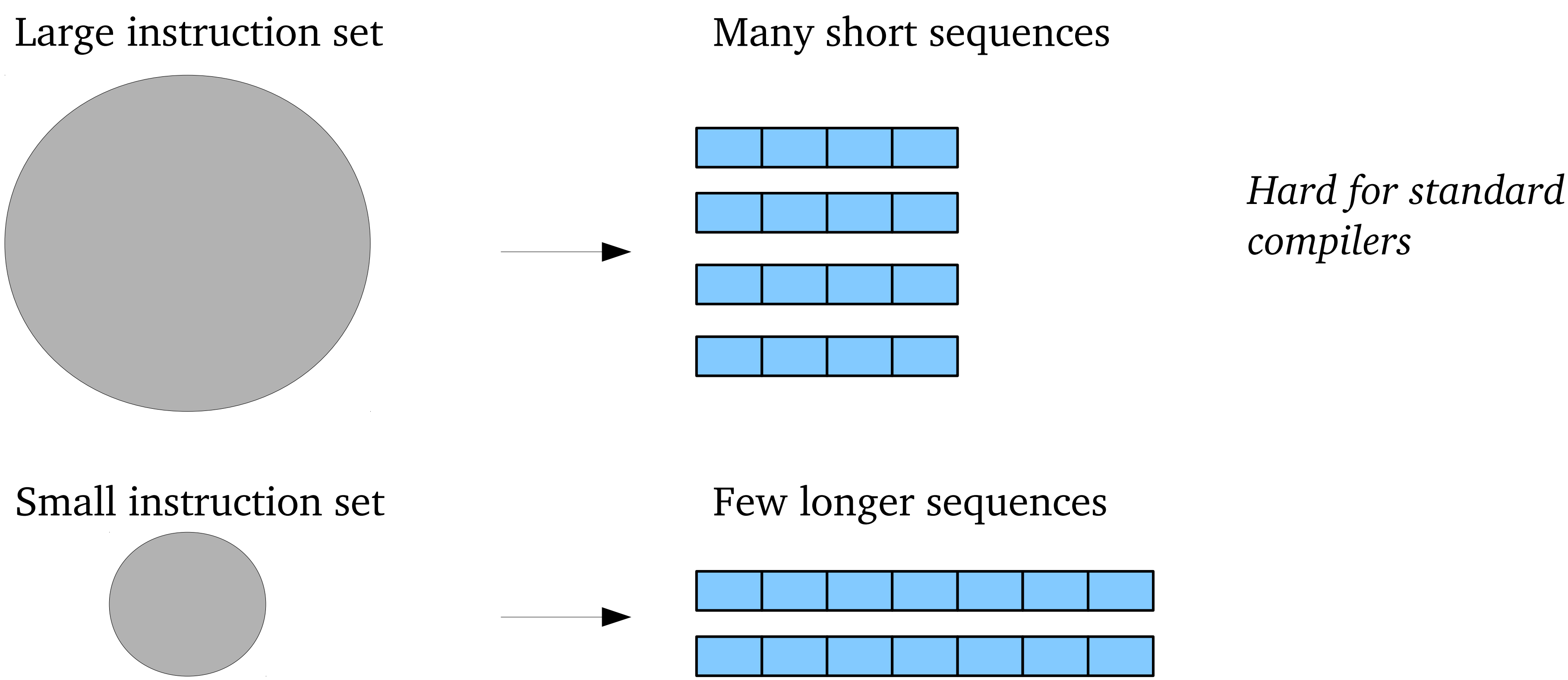

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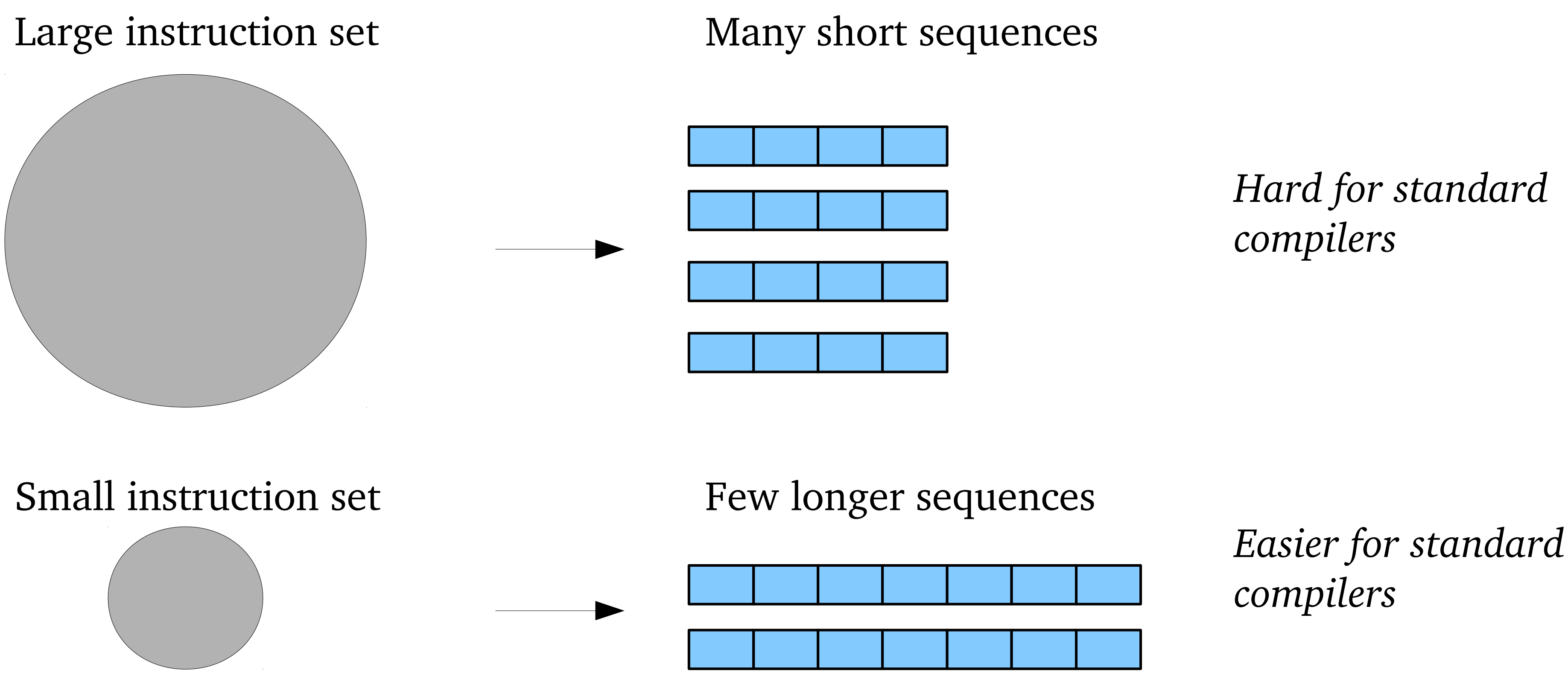

Superoptimizers

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Superoptimizers

GNU SuperOptimizer (GSO)

Superoptimizers

GNU SuperOptimizer (GSO)

Denali

Superoptimizers

GNU SuperOptimizer (GSO)

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Peephole Superoptimizer

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Stochastic Superoptimization

Superoptimizers

- GNU SuperOptimizer (GSO)
- Denali
- Peephole Superoptimizer
- Stochastic Superoptimization
- Other
  - A Hacker's Assistant (similar to GSO)
  - TOAST (similar to Denali)

GNU SuperOptimizer

Focuses on elimination of short basic blocks

Granlund, T., & Kenner, R. (1992). Eliminating branches using a superoptimizer and the GNU C compiler. PLDI '92 Proceedings of the ACM SIGPLAN 1992 conference on Programming language design and implementation.

GNU SuperOptimizer

Focuses on elimination of short basic blocks

```c
unsigned a, b, c;

if(a < b)
    c++;
```

→

```
    cmp     eax, ebx
    jge     L1
    add     ecx, #1
L1:
    ...
```

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GNU SuperOptimizer

Focuses on elimination of short basic blocks

```
unsigned a, b, c;

if(a < b)                      cmp   eax, ebx
    c++;             →         jge   L1
                               add   ecx, #1
                           L1:
                               ...

c = (a < b) + c;     →         subl  eax, edx
                               adcl  ecx, #0
```

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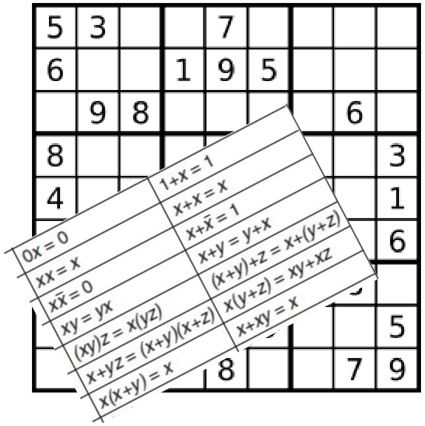
Denali



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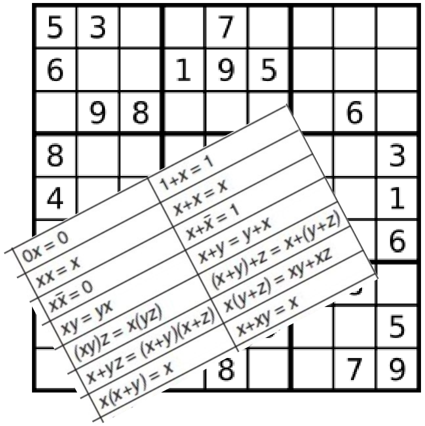
Denali

Rule based program generation:



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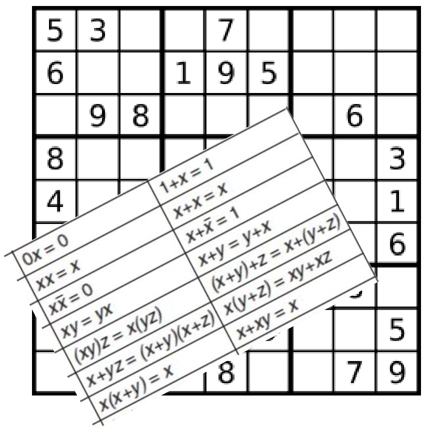
Denali

Rule based program generation:

- Prove the condition: there exists no instruction sequence that solves F(x) in < K cycles



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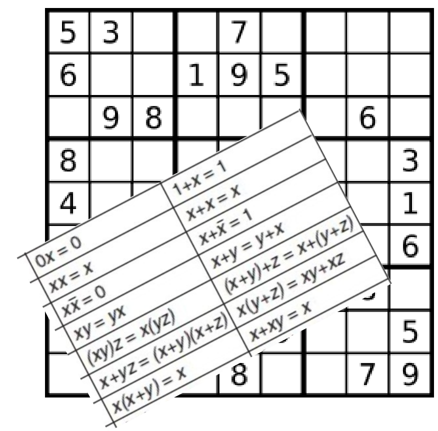
Denali

Rule based program generation:

- Prove the condition: there exists no instruction sequence that solves F(x) in < K cycles
- Failure yields an example sequence



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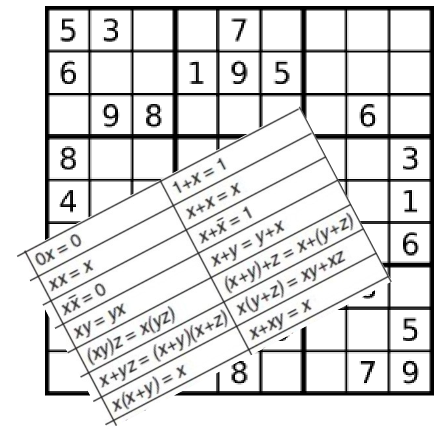
Denali

Rule based program generation:

- Prove the condition: there exists no instruction sequence that solves F(x) in < K cycles
- Failure yields an example sequence
- Use hand-written transformation rules




```
x * 2  ↔  x << 1
 a + b  ↔  b + a
```

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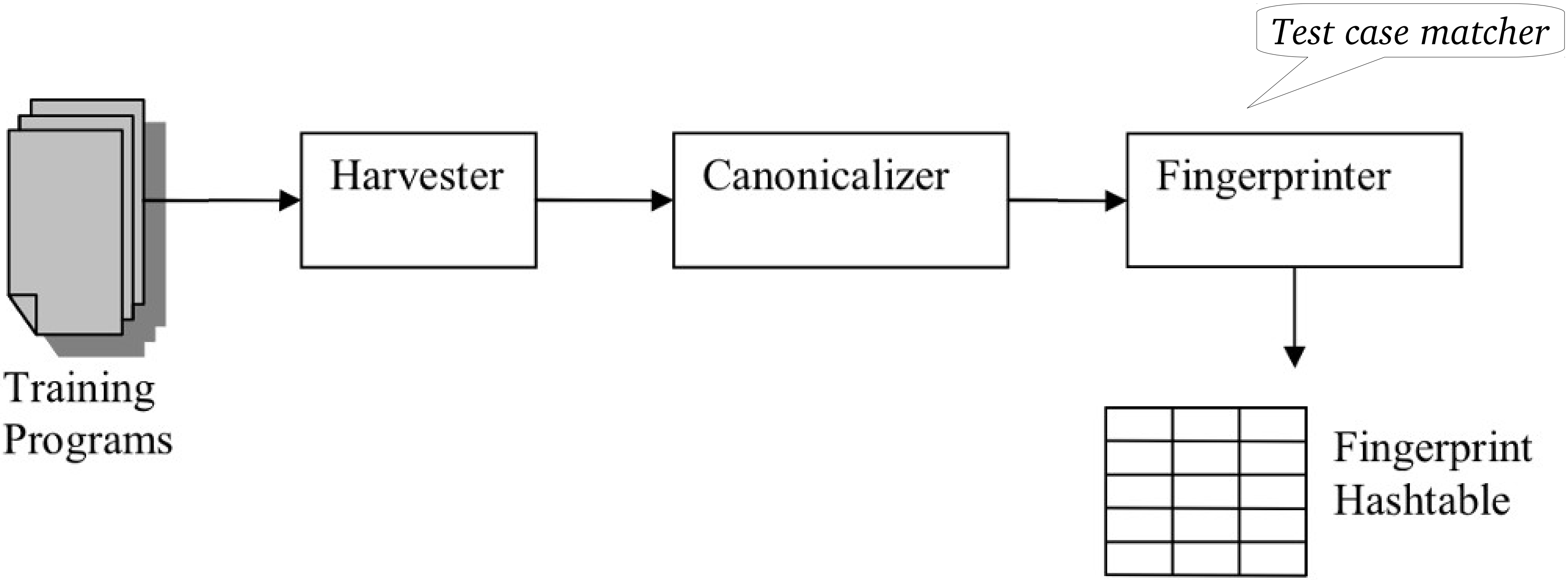
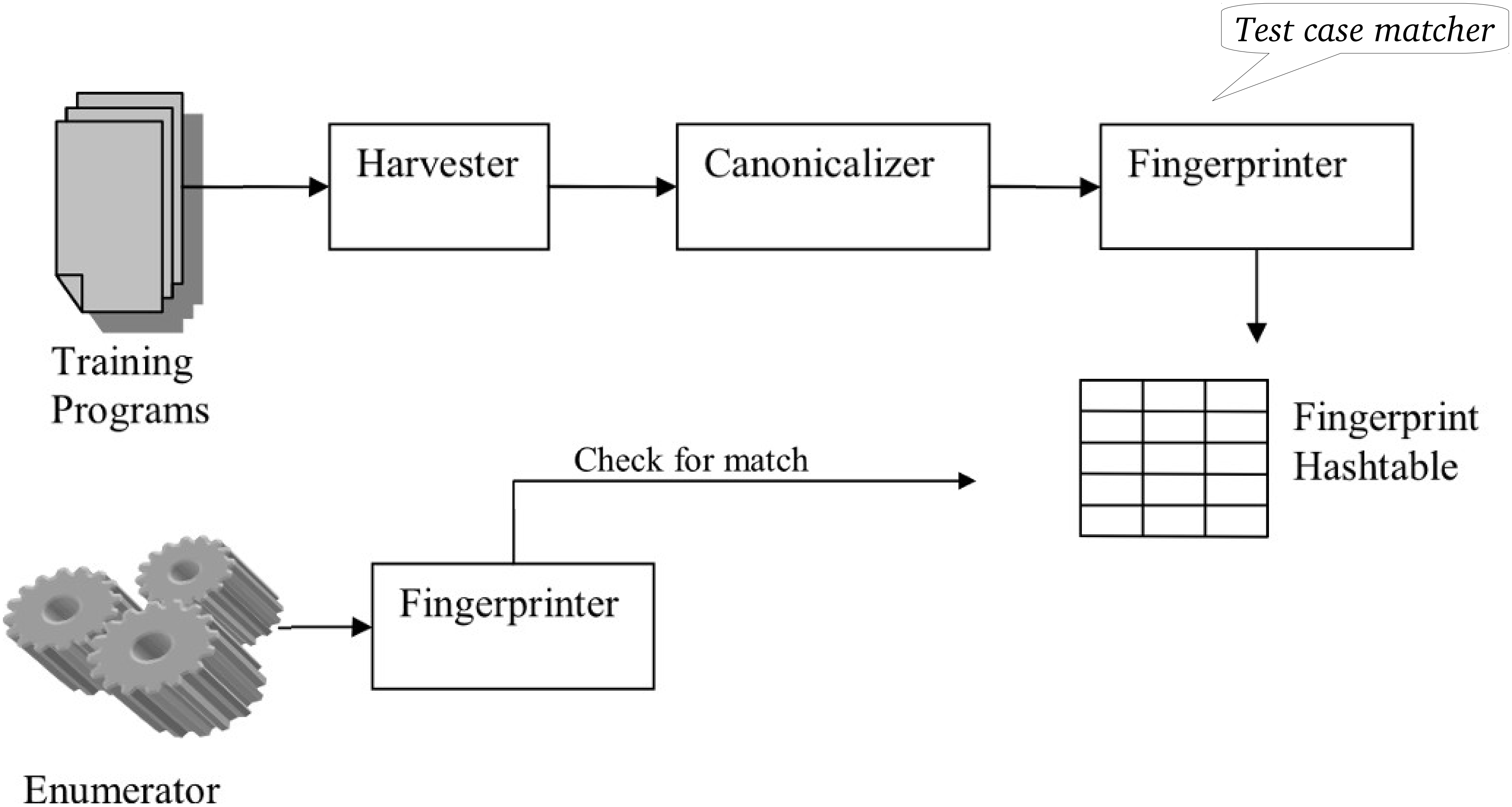
Peephole Superoptimizers

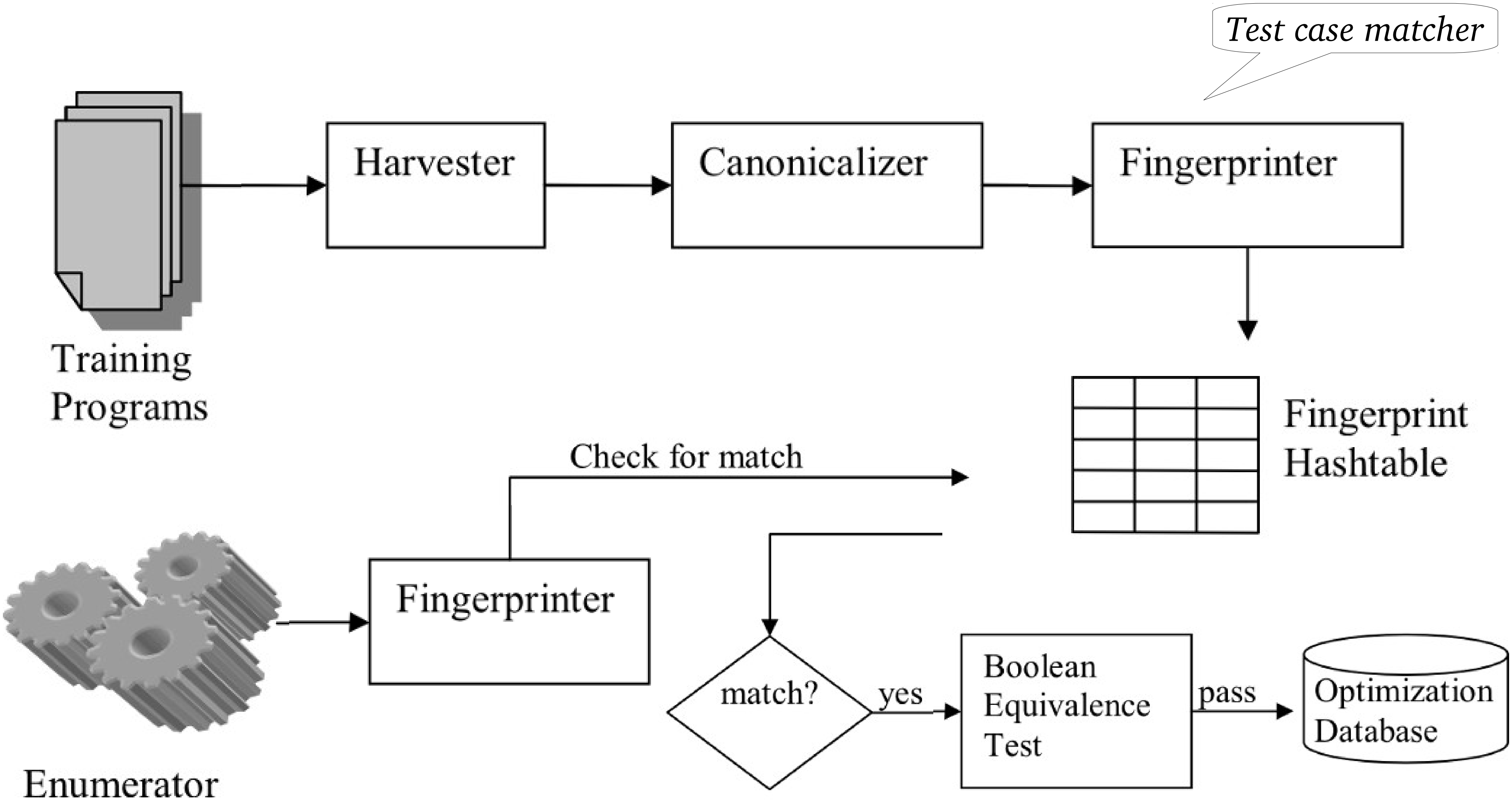
Peephole Superoptimizers



Peephole Superoptimizers



Peephole Superoptimizers



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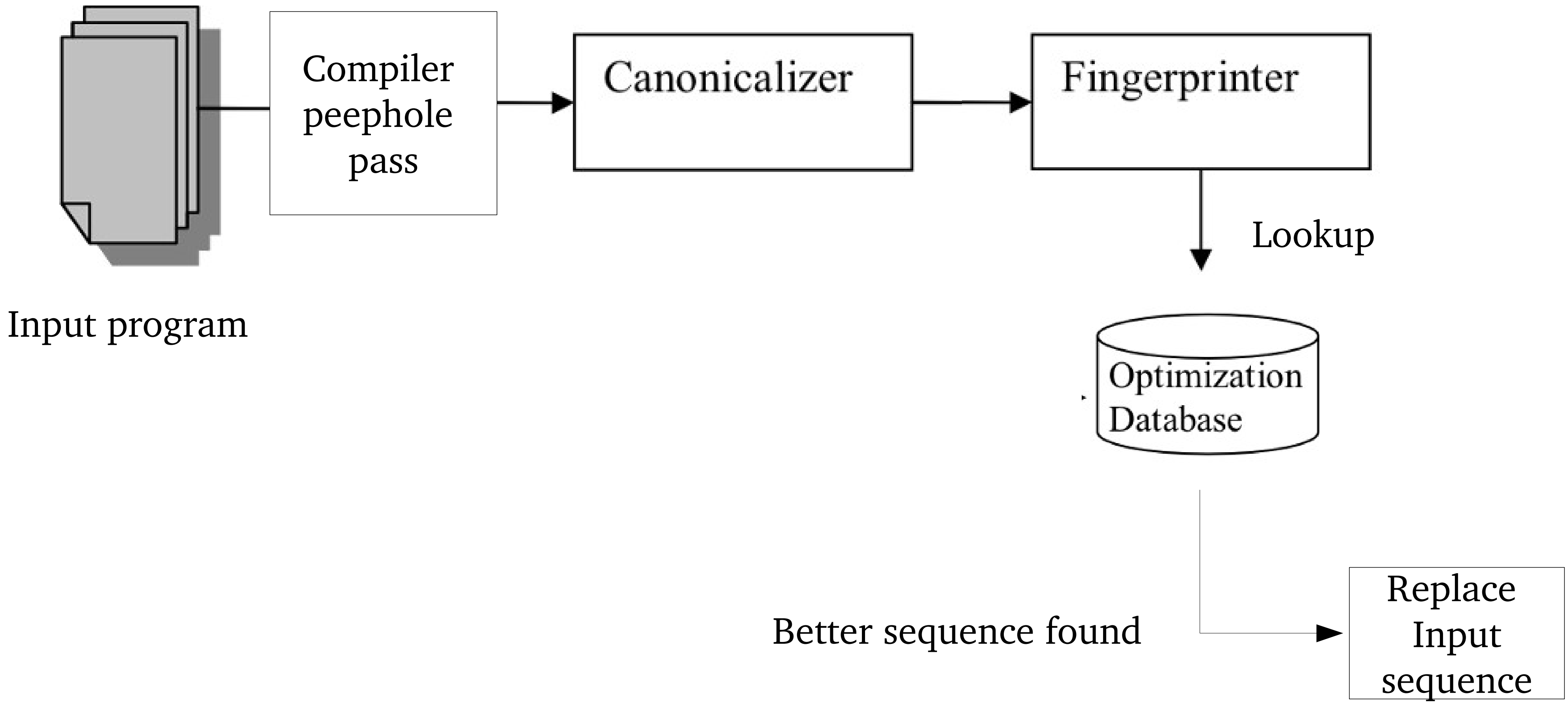
Peephole Superoptimizers



Stochastic superoptimization

Schkufza, E., Sharma, R., & Aiken, A. (2013). Stochastic superoptimization. Architectural Support for Programming Languages and Operating Systems, 305.

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Stochastic superoptimization

A different approach to instruction sequence enumeration

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Stochastic superoptimization

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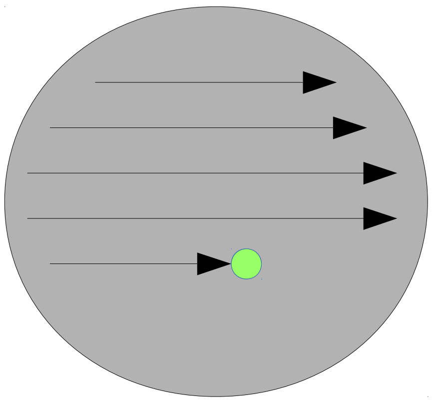

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Stochastic superoptimization

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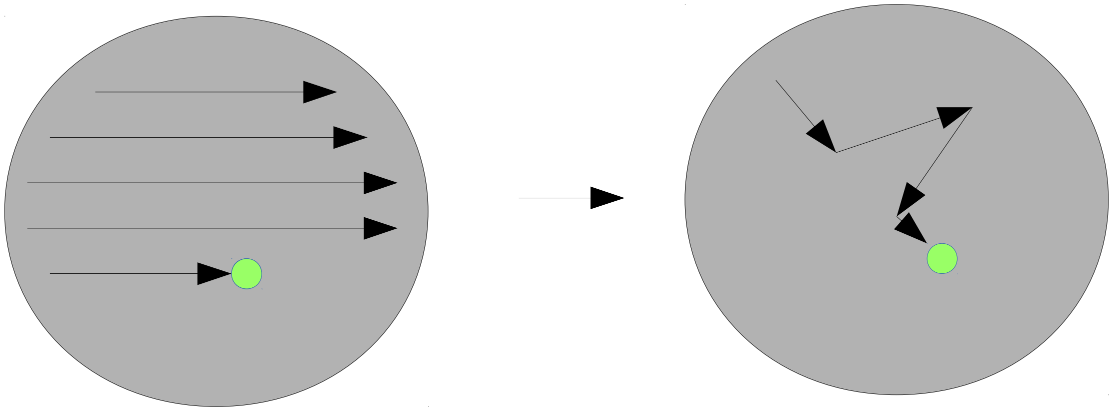

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Stochastic superoptimization

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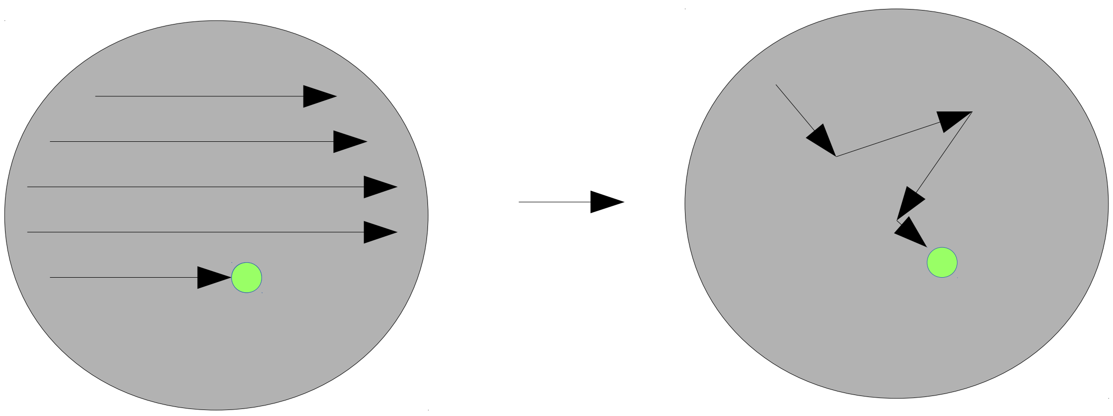

Longer sequences of instructions

- Sequences of >14 instructions were considered

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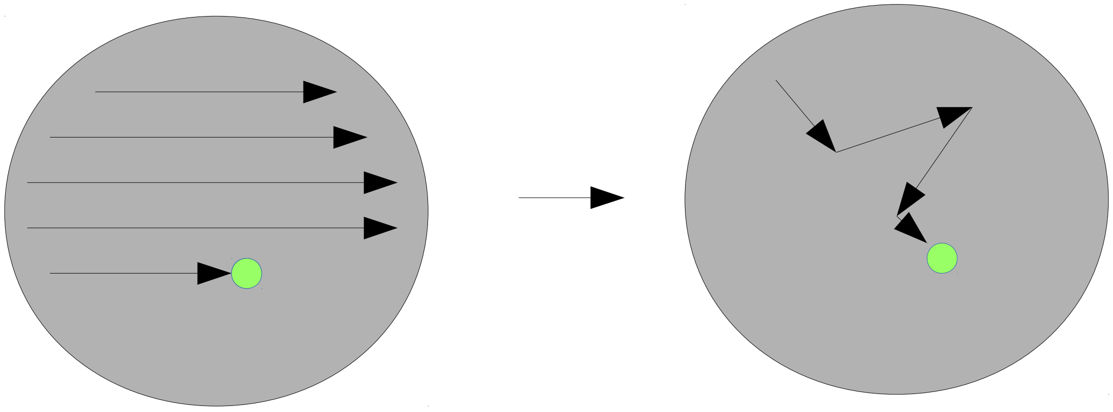

Longer sequences of instructions

- Sequences of >14 instructions were considered
- E.g. OpenSSL Montgomery multiplication 60% faster

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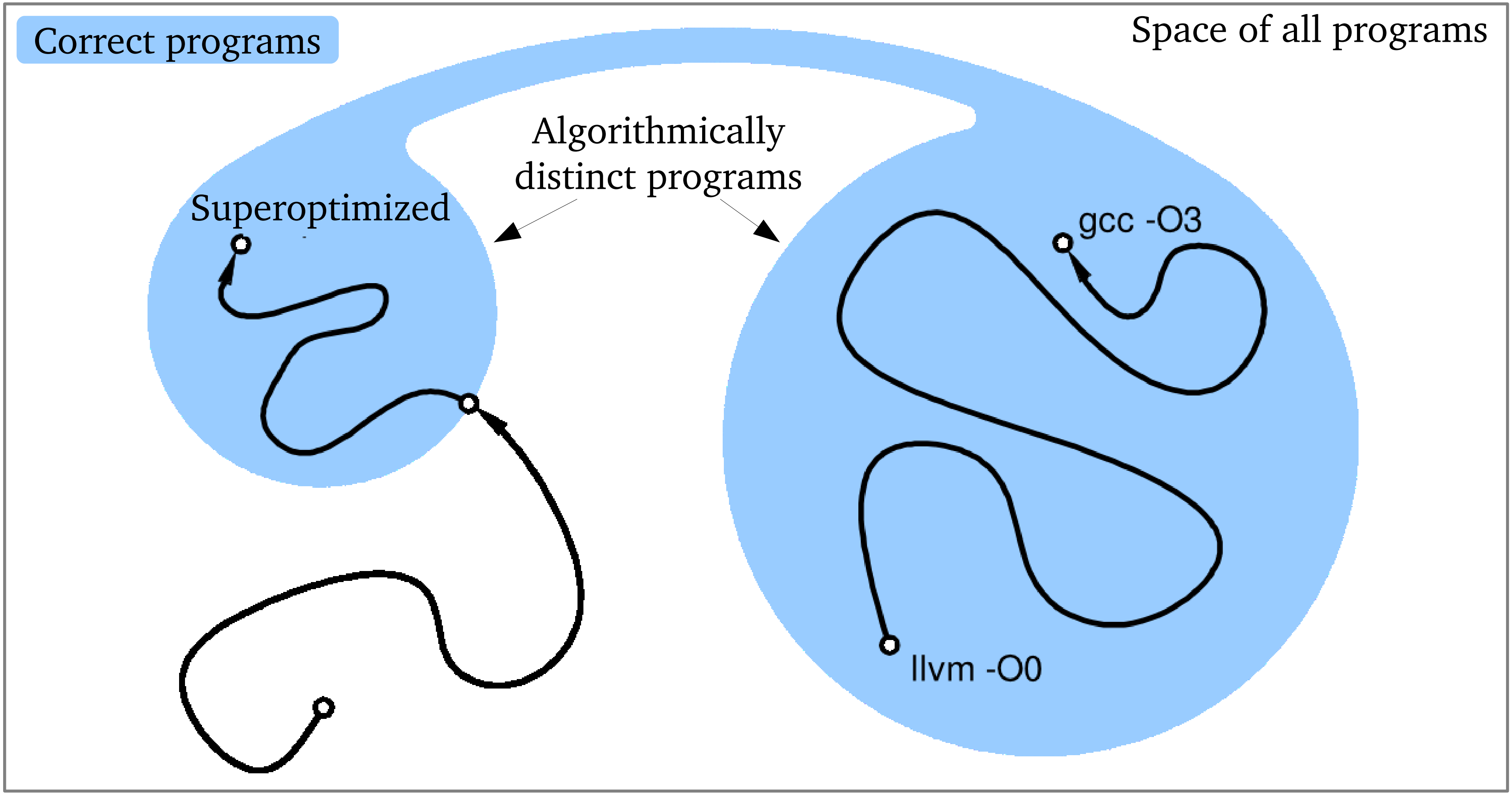
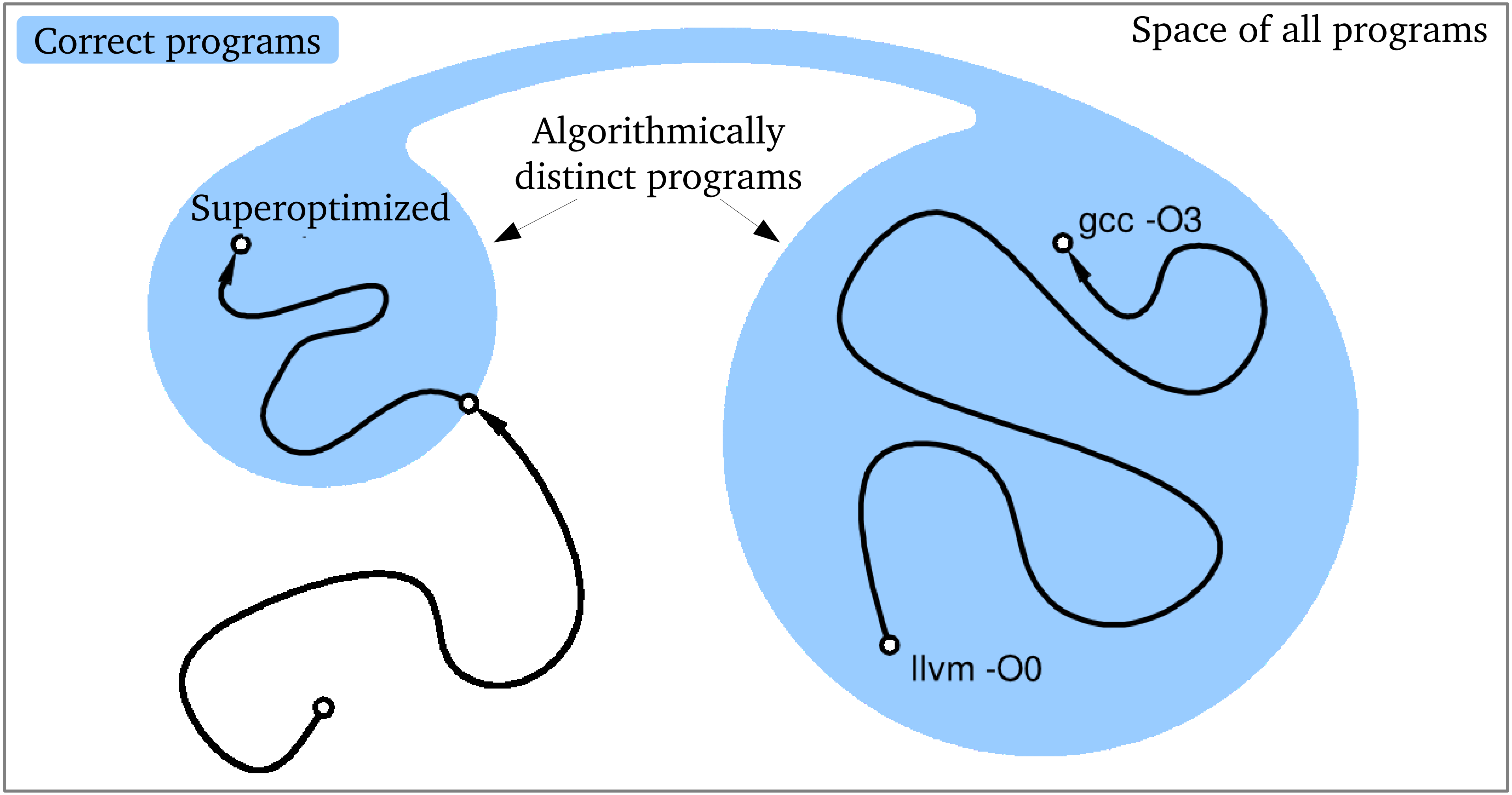
Discovering new algorithms

Discovering new algorithms



Discovering new algorithms



Stochastic superoptimization's longer sequences make this more likely

Plan for today

What is superoptimization?

Latest developments **NEW**

The GNU SuperOptimizer

GSO: What can it do?

The sign function, AVR:

```
cp    r1, r24
brlt .+14
ldi   r25, 0x01
cpse r24, r1
rjmp .+2
ldi   r25, 0x00
mov   r24, r25
neg   r24
rjmp .+2
ldi   r24, 0x01
```

```
add r0, r0
mov r1, r0
sbc r1, r0
sub r1, r0
adc r1, r0
```

Compiler (-Os)
- 11 instructions
- 4-10 cycles (if r1 initialised to 0)

Superoptimizer:
- 5 instructions
- 5 cycles

How does it work?

Iterative deepening depth first search

- 1 instruction

How does it work?

Iterative deepening depth first search

- 1 instruction

add r0, r0 → Check

How does it work?

Iterative deepening depth first search

1 instruction

add r0, r0 → Check
sub r0, r0 → Check

How does it work?

Iterative deepening depth first search

1 instruction

add r0, r0 → Check
sub r0, r0 → Check
mul r0, r0 → Check

How does it work?

- Iterative deepening depth first search
  - 2 instructions

How does it work?

Iterative deepening depth first search

- 2 instructions

```
add r0, r0
```

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add r0, r0 → add r0, r0 → Check

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Iterative deepening depth first search

2 instructions

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sub r0, r0

add r0, r0 → Check
sub r0, r0 → Check
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How does it work?

Iterative deepening depth first search

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sub r0, r0 → Check
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add r0, r0 → Check

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...

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How does it work?

- Iterative deepening depth first search
  - 3 instructions

How does it work?

Iterative deepening depth first search

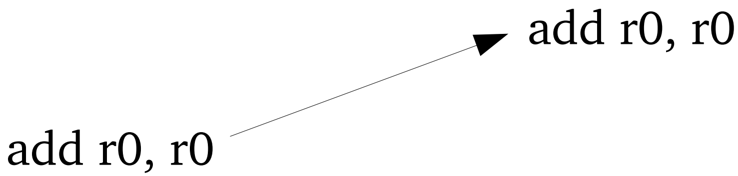
- 3 instructions

```
add r0, r0
```

How does it work?

Iterative deepening depth first search

- 3 instructions



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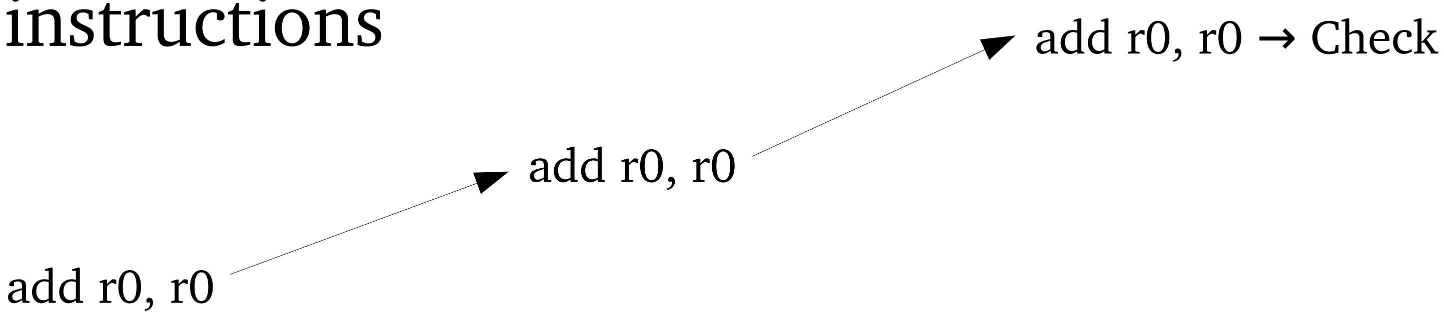

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add r0, r0 → add r0, r0 → add r0, r0 → Check

sub r0, r0 → Check

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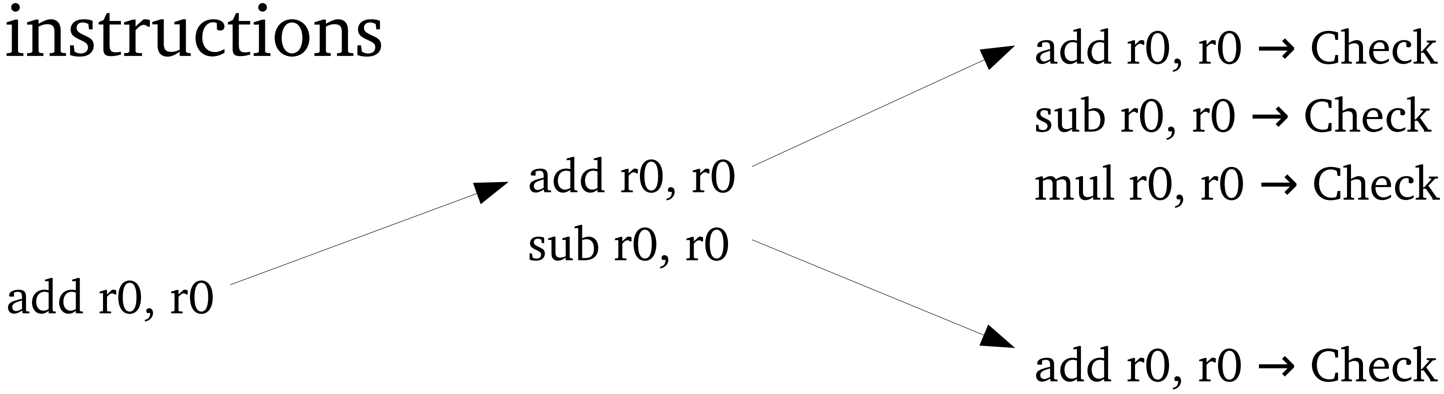

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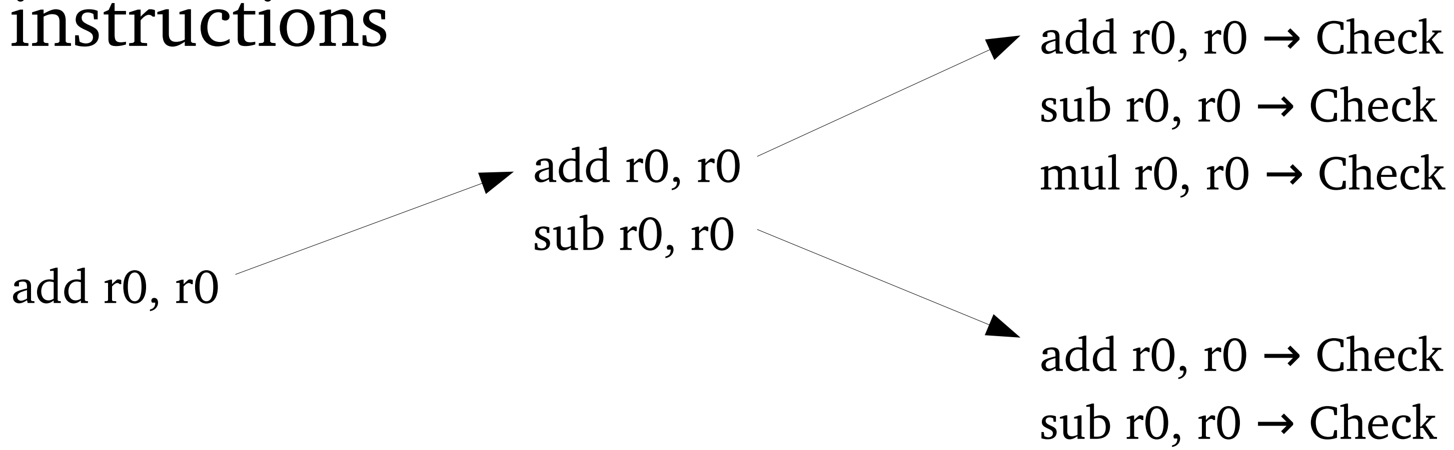

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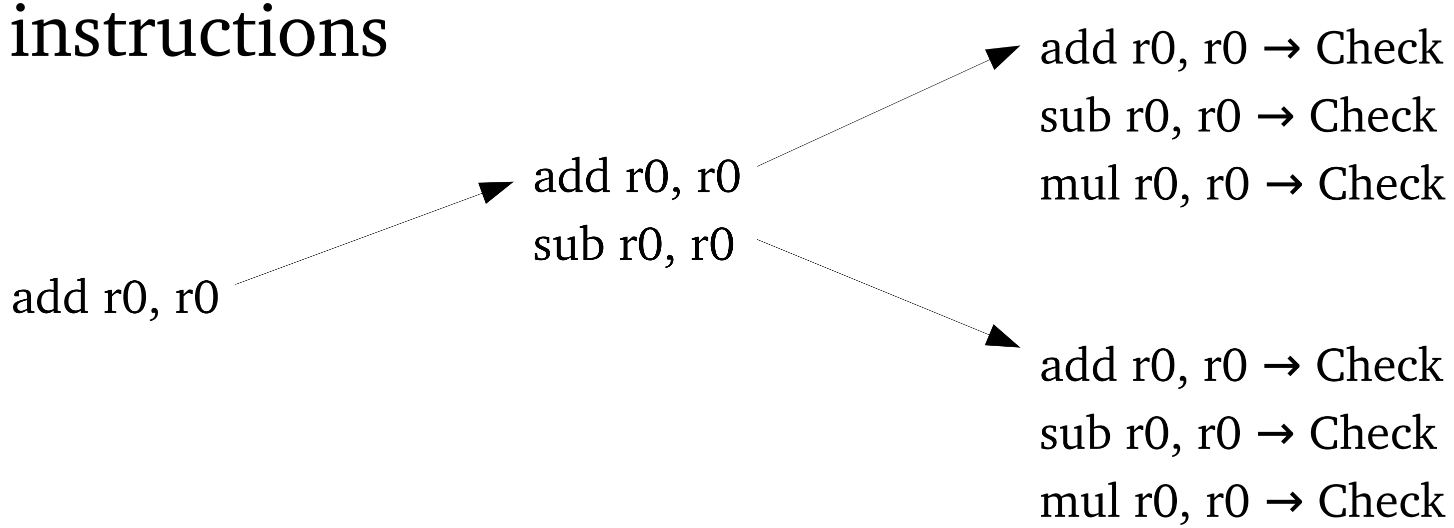

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Iterative deepening depth first search

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- add r0, r0
  - add r0, r0
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    - sub r0, r0 → Check
    - mul r0, r0 → Check
  - sub r0, r0
    - add r0, r0 → Check
    - sub r0, r0 → Check
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  - mul r0, r0

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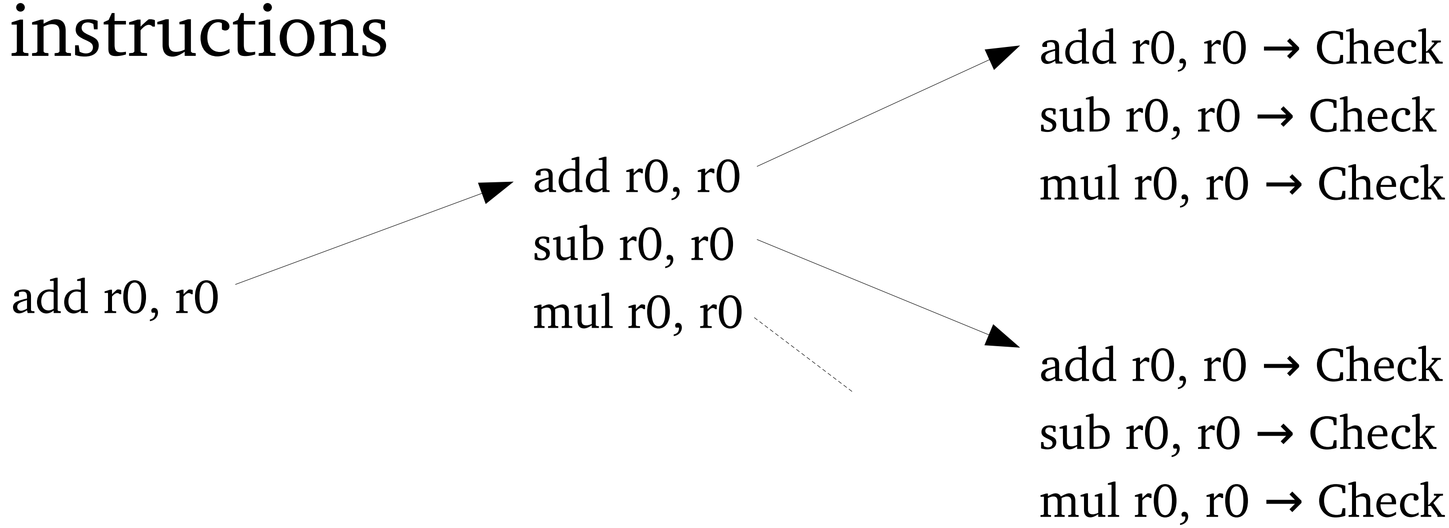

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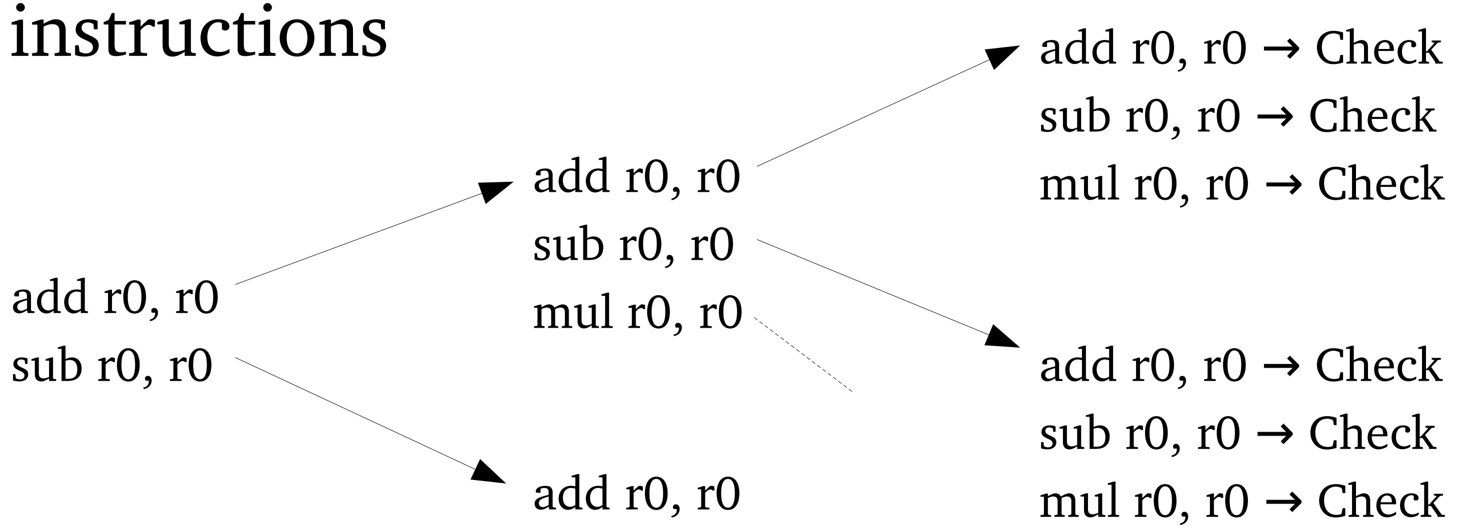

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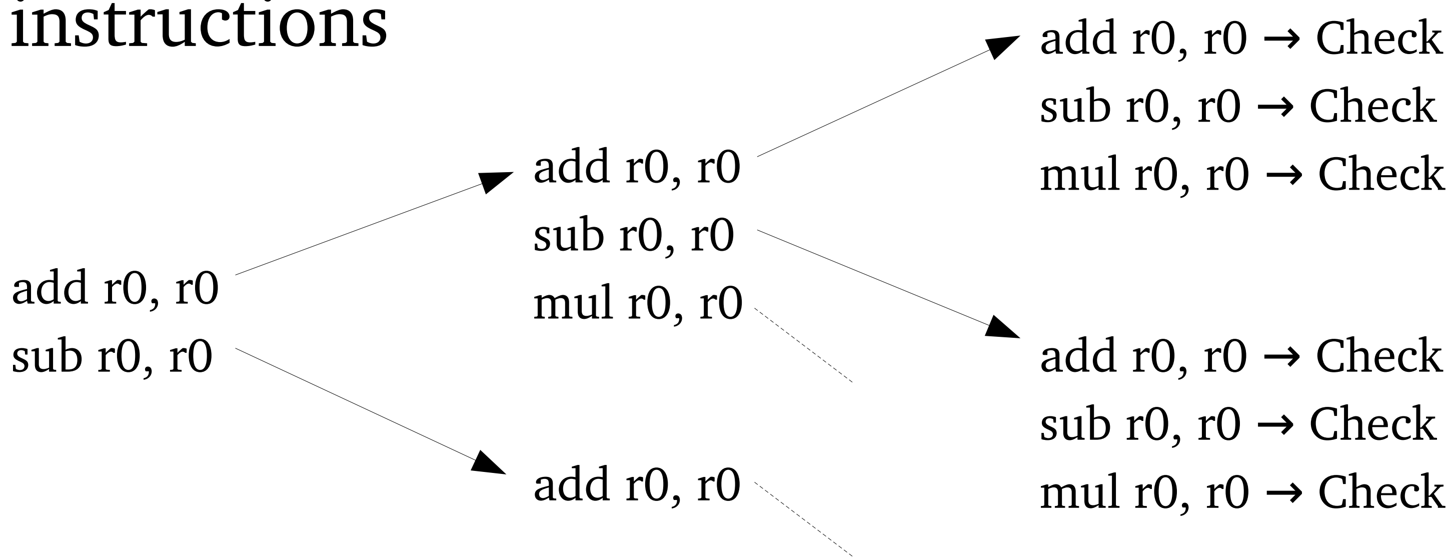

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How does it work?

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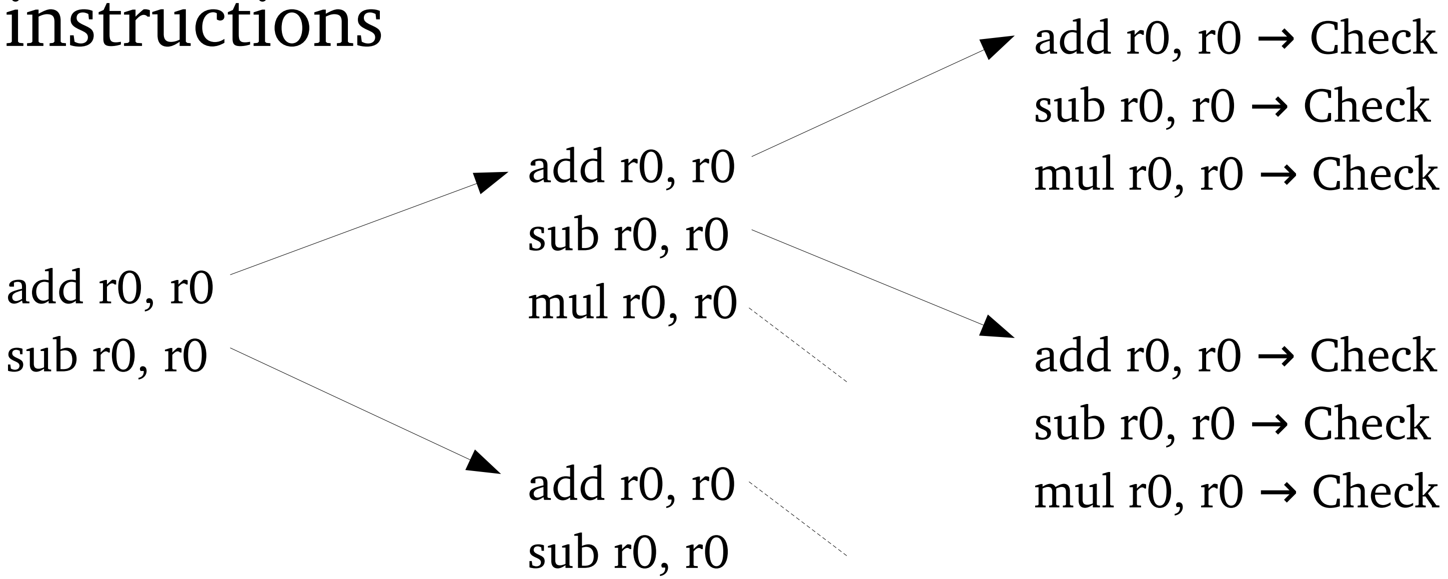

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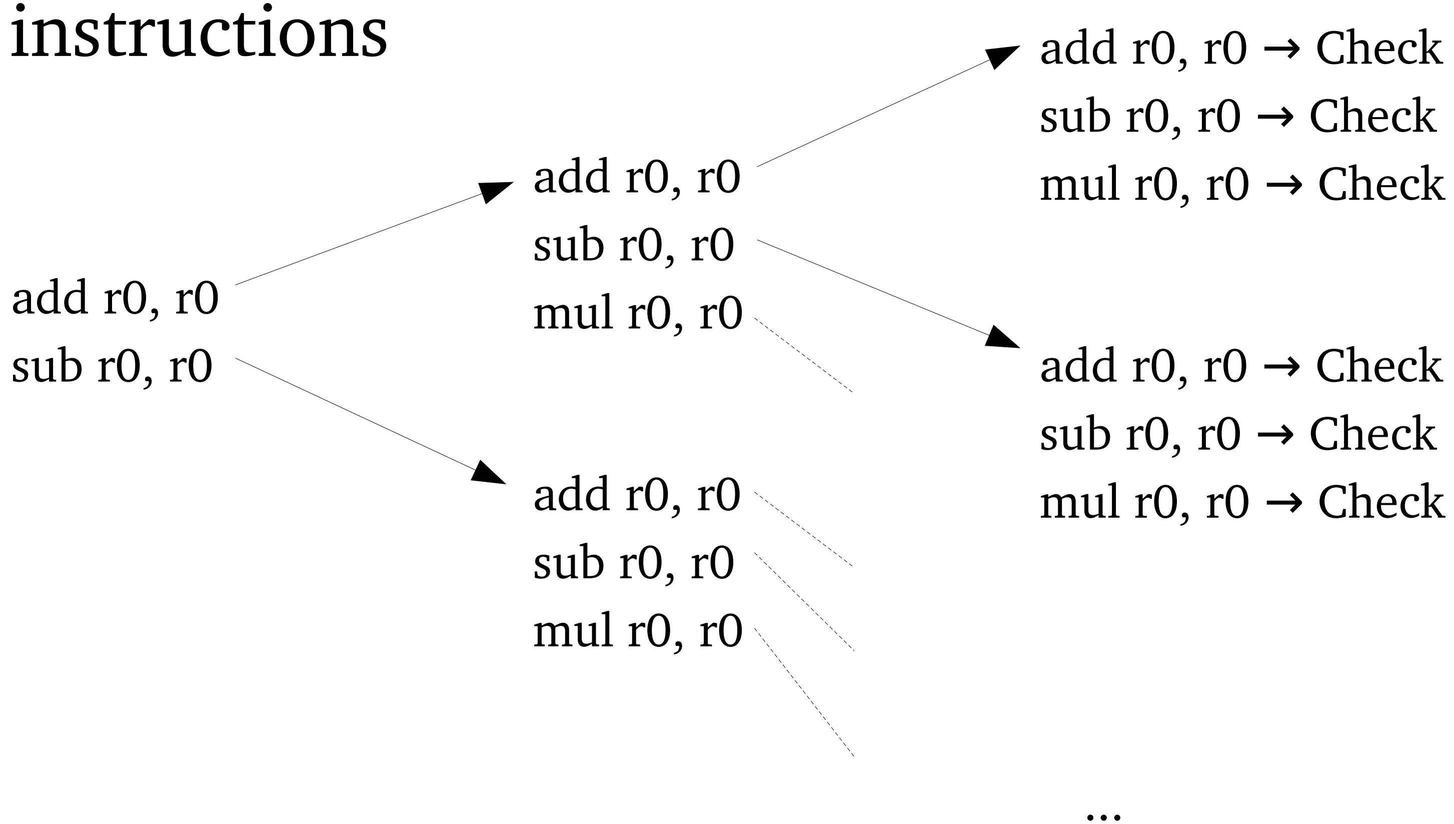

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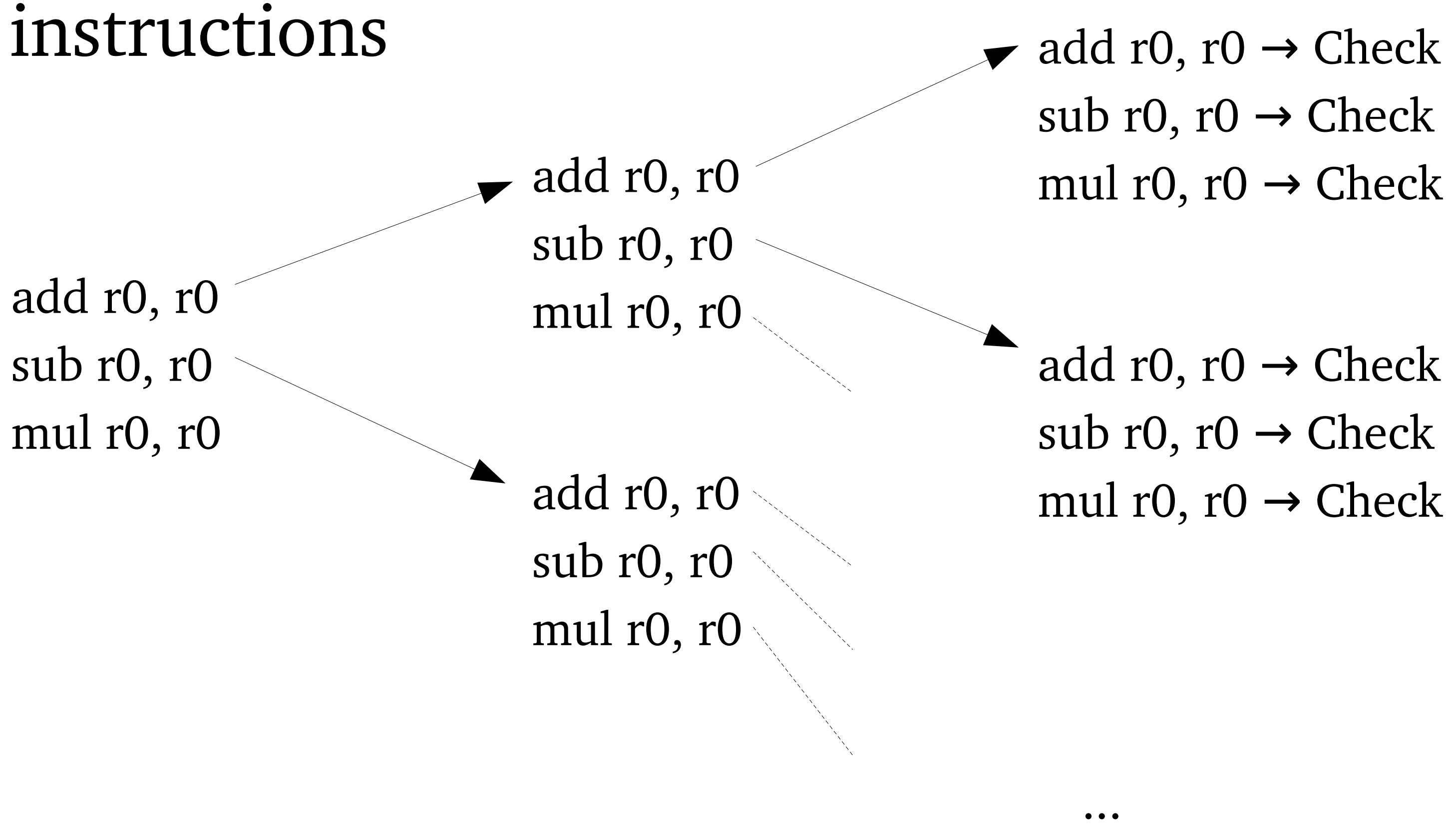

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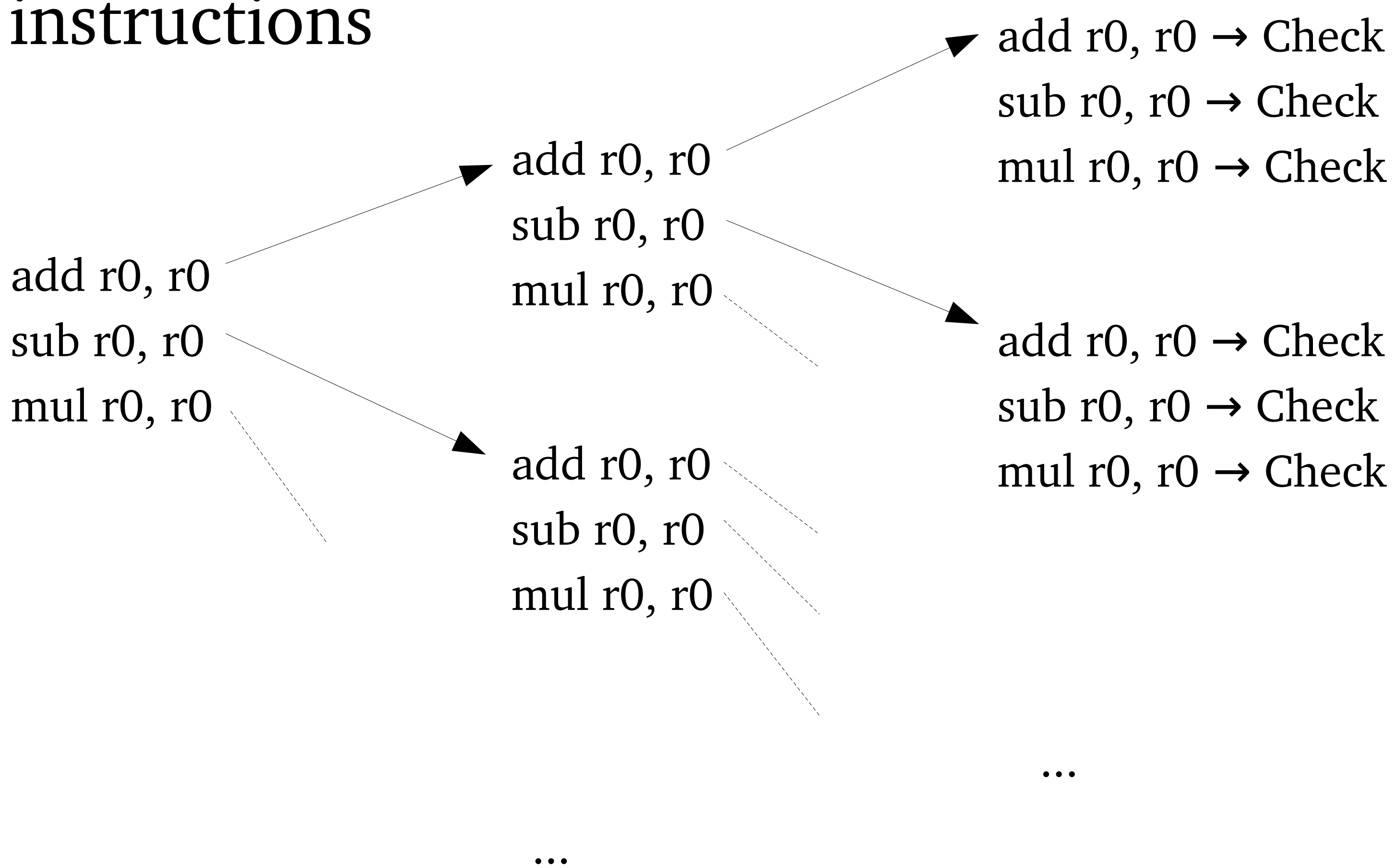

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How to add a new goal

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How to add a new goal

Goal is GSO's term for a target function to superoptimize

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Goal is GSO's term for a target function to superoptimize

File: `goal.def`

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File: `goal.def`

Examples:

```
DEF_GOAL (SHIFTL_1, 1, "sll1", { r = v0 << 1; })
DEF_GOAL (SHIFTL_2, 1, "sll2", { r = v0 << 2; })
```

How to add a new goal

Goal is GSO's term for a target function to superoptimize

File: `goal.def`

Examples:

```
DEF_GOAL (SHIFTL_1, 1, "sll1", { r = v0 << 1; })
DEF_GOAL (SHIFTL_2, 1, "sll2", { r = v0 << 2; })
DEF_GOAL (SIGNUM,   1, "signum",
  {
    if(v0 < 0)
      r = -1;
    else if(v0 > 0)
      r = 1;
    else
      r = 0;
  })
```

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How to add a new goal

How to add a new goal

```
DEF_GOAL (EQ_MINUS, 3, "eq-",  { r = v2 - (v0 == v1); })
```

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DEF_GOAL (EQ_MINUS, 3, "eq-",  { r = v2 - (v0 == v1); })
```

Format:

DEF_GOAL (*unique id*, *#args*, "*name*", { *C code*; })

r	result
v0	argument 1
v1	argument 2
...	

How to add a new goal

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```

Format:

DEF_GOAL (*unique id*, *#args*, "*name*", { *C code*; })

r	result
v0	argument 1
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...	

Using the new goal:

$ make all

$ ./superopt-avr -f*name*

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How to add a new architecture

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Define the implementation in `superopt.h`

- Name, types (bitwidth)

How to add a new architecture

Define the implementation in `superopt.h`

- Name, types (bitwidth)
- “Unusual” instructions

```
#ifndef PERFORM_AND
#define PERFORM_AND(d, co, r1, r2, ci) \
  ((d) = (r1) & (r2), (co) = (ci))
#endif
```

How to add a new architecture

Define the implementation in `superopt.h`

- Name, types (bitwidth)
- "Unusual" instructions

```
#ifndef PERFORM_AND
#define PERFORM_AND(d, co, r1, r2, ci) \
  ((d) = (r1) & (r2), (co) = (ci))
#endif
```

- Also add mnemonic into `insn.def`

```
DEF_INSN (AND,'b',"and")
```

Identifier

Type (binary, unary, etc)

Name

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How to add a new architecture

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To enable output in native assembler

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To enable output in native assembler

Extend `output_assembly`

- Register names
- Disassembly code

How to add a new architecture

To enable output in native assembler

Extend `output_assembly`

- Register names
- Disassembly code

```
case ADD_CO:
  printf("add       %s,%s",NAME(s1),NAME(s2)); break;
case ADD_CIO:
  printf("adc       %s,%s",NAME(s1),NAME(s2)); break;
```

How to add a new architecture

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`SYNTH(...)` in `synth.def`

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- Where the magic happens

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- Where the magic happens
- Loops over all the registers and all the instructions

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- Use the macros for performing the instruction

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- Then recurses (next level of iterative deepening)

How to add a new architecture

`SYNTH(...)` in `synth.def`

- Where the magic happens
- Loops over all the registers and all the instructions
- Use the macros for performing the instruction
- Then recurses (next level of iterative deepening)
- Add architecture entries for standard & custom instructions

How to add a new architecture

`SYNTH(...)` in `synth.def`

- Where the magic happens
- Loops over all the registers and all the instructions
- Use the macros for performing the instruction
- Then recurses (next level of iterative deepening)
- Add architecture entries for standard & custom instructions

```
#if SPARC || M88000
    /* sparc:          addx
       m88000:         addu.ci */
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Identifier
(insn.def)

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Registers
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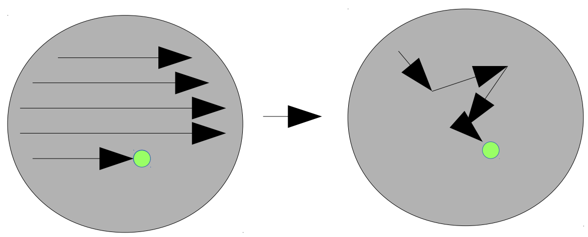
Identifier (`insn.def`)

Registers used

Speed hints. (we didn't just set the carry)

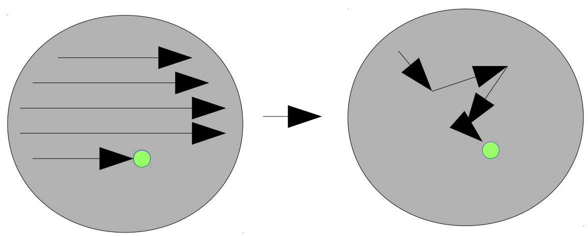
Our plans to extend GSO

Our plans to extend GSO

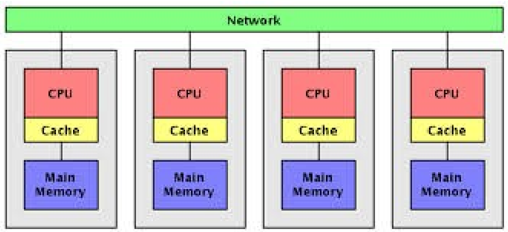


Machine learning

Our plans to extend GSO

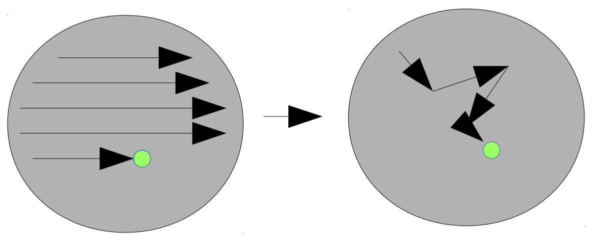


Machine learning

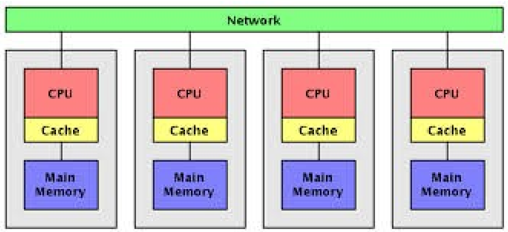


Parallelism

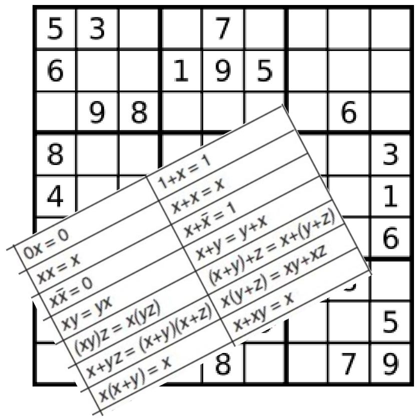
Our plans to extend GSO



Machine learning

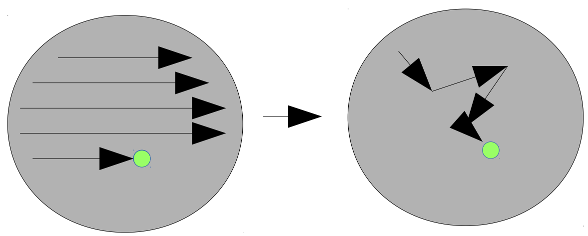


Parallelism



Instruction sequence verification

Our plans to extend GSO



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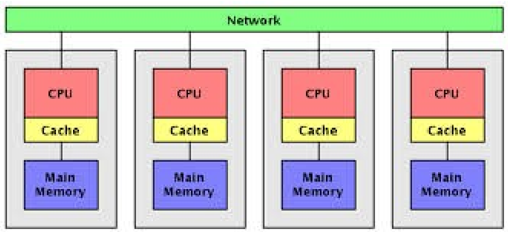

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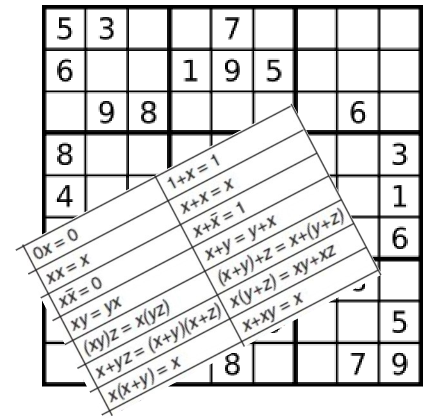
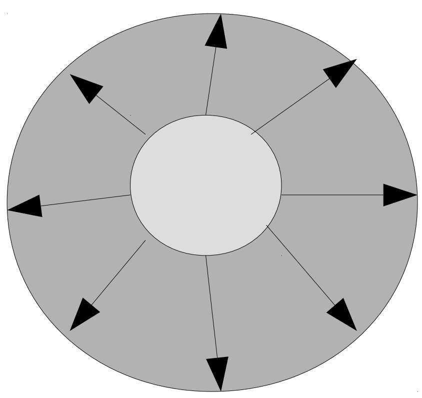
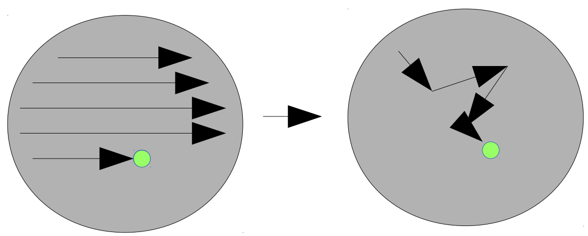


Instruction sequence verification

More instruction types



Our plans to extend GSO



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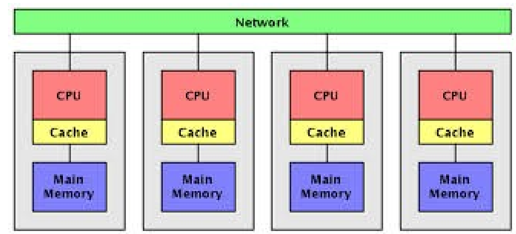

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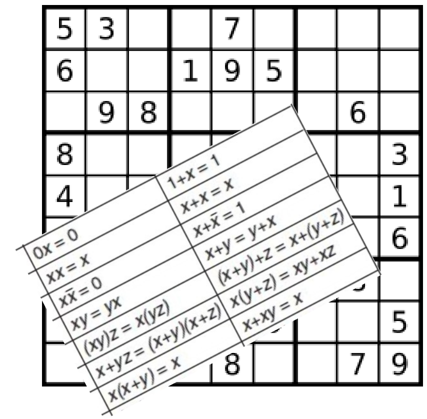
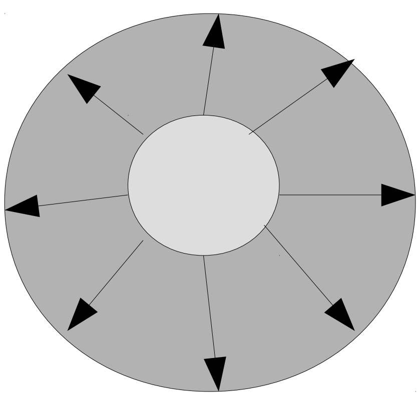


Instruction sequence verification

More instruction types

Memory access



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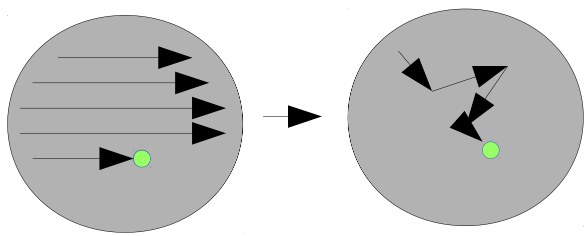

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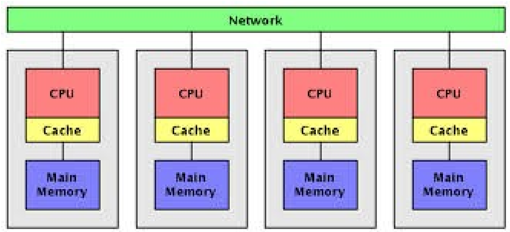

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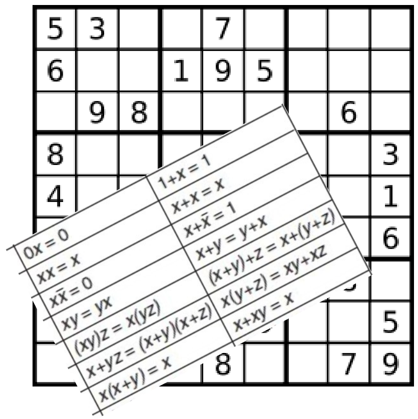

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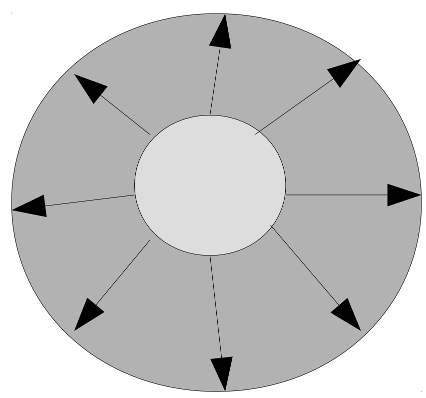

Floating point

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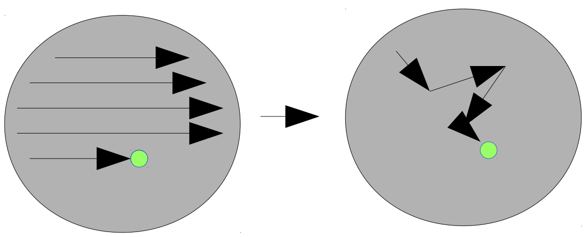
Our plans to extend GSO



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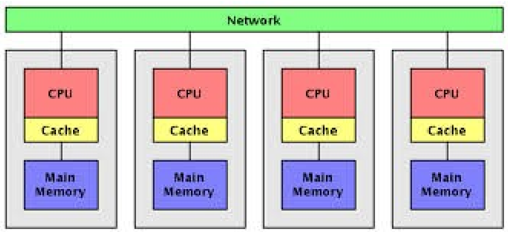

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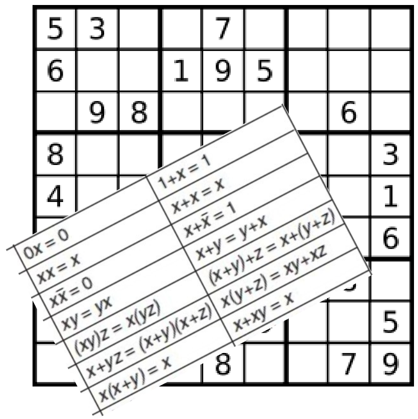

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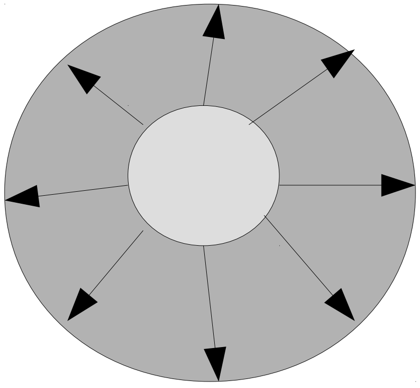

Floating point

Multiple outputs

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Thank You

Thank You

Superoptimization works

Thank You

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New techniques are making it better

Thank You

Superoptimization works

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Lots of *free* software and tools

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Superoptimization works

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Innovate UK
Technology Strategy Board

Thank You

Superoptimization works

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Try it yourself

github.com/embecosm/gnu-superopt