ægraphs: Acyclic E-graphs

for Efficient Optimization in a Production Compiler

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In the beginning, there was a compiler backend…

Cranelift

Cranelift

- Open-source general-purpose optimizing compiler backend
  - Written in Rust + a pattern-matching DSL (~200KLoC, ~130KLoC tests)
  - SSA input, four ISAs (x86-64, aarch64, riscv64, s390x)

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  - SSA input, four ISAs (x86-64, aarch64, riscv64, s390x)
- Used in production as part of Wasmtime
- O(3-5) active developers at any time

Cranelift

- **Speed:** JIT focus
- **Simplicity:** “not LLVM”
- **Verifiability:** explicitly design with fuzzing + formal techniques + … in mind
- **Research-friendliness:** we need new ideas to compete with larger peers

1. **Why** *we want a rewrite-based optimizer*
2. **How** *to turn a CFG into an egraph and back again*
3. **Cycles** *why they occur, and what to do about them*
4. **Results** *how well does it work?*
5. **Lessons** *in translating research to production*

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v1 = …
v2 = iadd_imm v1, 16
…
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```

→

```
v1 = …
v2 = iadd_imm v1, 16
…
v10 -> v2
```

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v1 = …
v2 = load.i64 v1+8
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```

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v1 = …
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The Pass-Order Problem

- What do we do with this program?

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v1 = …
v2 = iadd_imm v1, 16
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v11 = load.i64 v10
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The Pass-Order Problem

- What do we do with this program?

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v1 = …
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GVN

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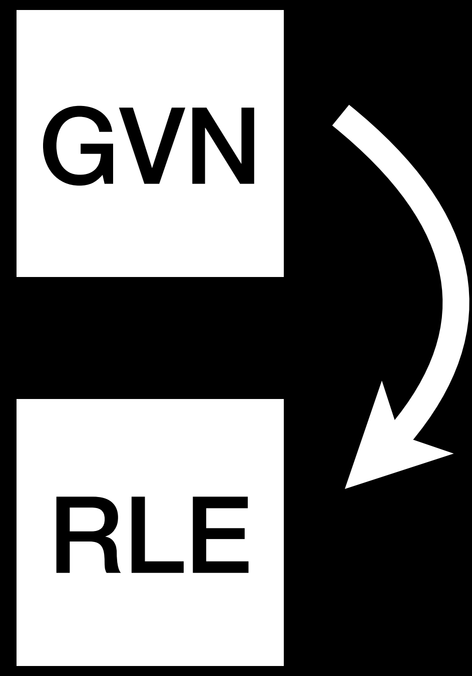

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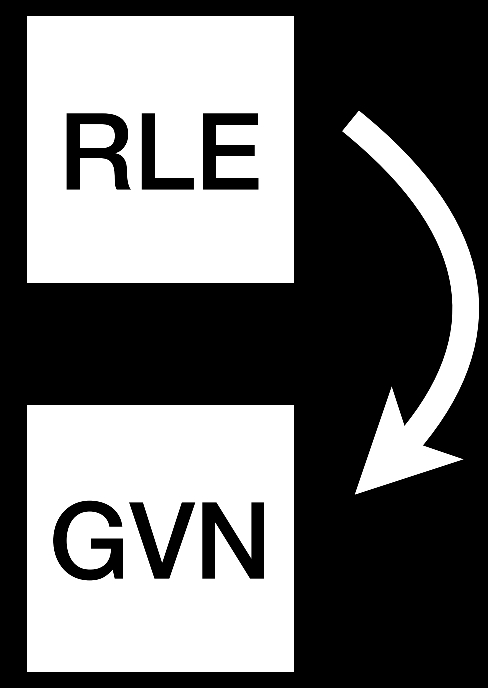

The Pass-Order Problem

- Proposed optimization pipeline:

```
fn optimize(&mut self) {
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  self.rle();
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fn optimize(&mut self) {
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GCC:

```
NEXT_PASS (pass_cselim);
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NEXT_PASS (pass_cse_sincos);
NEXT_PASS (pass_cse_reciprocals);
…
NEXT_PASS (pass_cse);
…
NEXT_PASS (pass_cse_after_global_opts);
…
NEXT_PASS (pass_cse2);
…
NEXT_PASS (pass_postreload_cse);
```

The Pass-Order Problem

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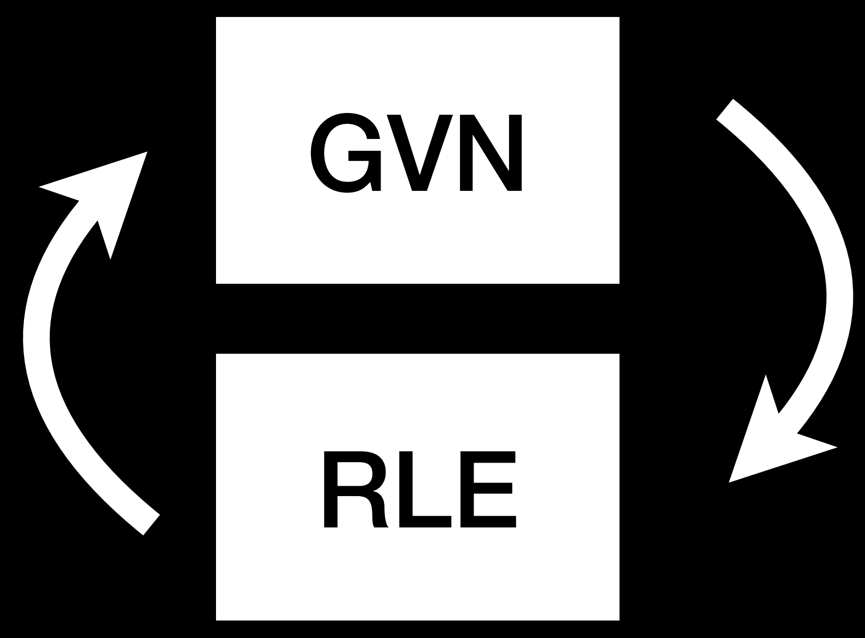
GCC:

540 lines (passes.def)

The Pass-Order Problem

(or: “Fix-point All The Things?”)

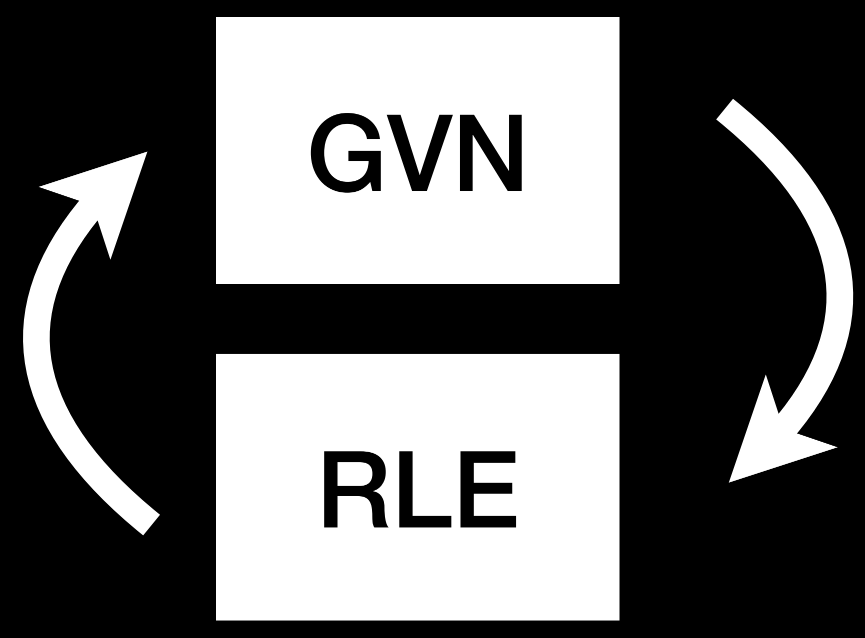
- Goal: find a way to put all (ish) of our optimizations in a single fixpoint loop



… cprop, algebraic rewrites, strength reduction, …

The Pass-Order Problem
(or: “Fix-point All The Things?”)

- Goal: find a way to put all (ish) of our optimizations in a single fixpoint loop
  - Remember: compile-cost focus! (We can’t afford to run a pass N times)
  - We’d prefer not to maintain a brittle heuristic pass order



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Adding some “simple” rewrites

```
match opcode {
    Opcode::IaddImm
    | Opcode::ImulImm
    | Opcode::BorImm
    | Opcode::BandImm
    | Opcode::BxorImm => {
        // Fold binary_op(C2, binary_op(C1, x)) into binary_op(binary_op(C1, C2), x)
        if let ValueDef::Result(arg_inst, _) = pos.func.dfg.value_def(arg) {
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        if let ValueDef::Result(arg_inst, _) = pos.func.dfg.value_def(arg) {
            if let InstructionData::BinaryImm64 {
                opcode: prev_opcode,
                arg: prev_arg,
                imm: prev_imm,
            } = &pos.func.dfg.insts[arg_inst]
            {
                if opcode == *prev_opcode
                    && ty == pos.func.dfg.ctrl_typevar(arg_inst)
                {
                    let lhs: i64 = imm.into();
                    let rhs: i64 = (*prev_imm).into();
```

Adding some “simple” rewrites (!!!)

```
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    if let ValueDef::Result(arg_inst, _) = pos.func.dfg.value_def(arg) {
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        } = &pos.func.dfg.insts[arg_inst]
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            if opcode == *prev_opcode
                && ty == pos.func.dfg.ctrl_typevar(arg_inst)
            {
                let lhs: i64 = imm.into();
                let rhs: i64 = (*prev_imm).into();
                let new_imm = match opcode {
                    Opcode::BorImm => lhs | rhs,
                    Opcode::BandImm => lhs & rhs,
                    Opcode::BxorImm => lhs ^ rhs,
                    Opcode::IaddImm => lhs.wrapping_add(rhs),
                    Opcode::ImulImm => lhs.wrapping_mul(rhs),
                    _ => panic!("can't happen"),
                };
                let new_imm = immediates::Imm64::from(new_imm);
                let new_arg = *prev_arg;
                pos.func
                    .dfg
                    .replace(inst)
                    .BinaryImm64(opcode, ty, new_imm, new_arg);
                imm = new_imm;
                arg = new_arg;
            }
        }
    }
```

Adding some simple rewrites

```
(rule (simplify
       (iadd (fits_in_64 ty)
             (iconst ty (u64_from_imm64 k1))
             (iconst ty (u64_from_imm64 k2))))
      (subsume (iconst ty (imm64_masked ty (u64_add k1 k2)))))
```

(Cranelift's ISLE term-rewriting DSL)

Adding some simple rewrites

```
;; ineg(ineg(x)) == x.
(rule (simplify (ineg ty (ineg ty x))) (subsume x))
```

👍

Rewrite Systems for Optimization

- Many kinds of optimizations can be expressed as value rewrites
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    - Normalization of input terms to rewriter => GVN
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- Those that can’t are often “rewrite-adjacent”
    - Normalization of input terms to rewriter => GVN
    - Placement of rewritten terms => LICM, code motion in general
- Rewriting is a well-defined framework that works well for verification!
    - “This value is equal to that value”

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Optimization pipeline

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block0(v0, v1):
  v2 = iadd v0, v1
  v3 = isub v0, v2
  if v3,
    block1(v2),
    block2(v3)
```

```
block1(v4):
  v5 = iconst 1
  v6 = isub v4, v5
  br block3(v6)
```

```
block2(v7):
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```
block3(v8):
  return v8
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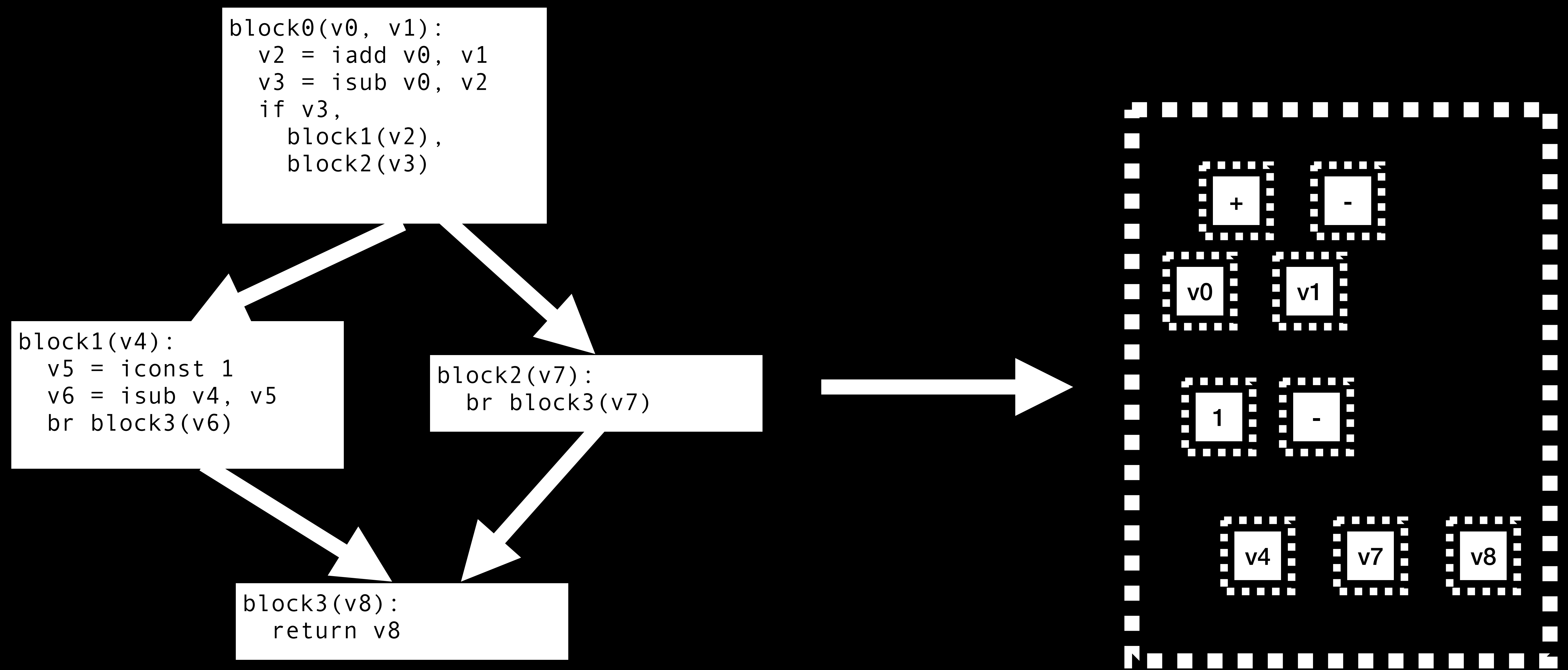
Optimization pipeline



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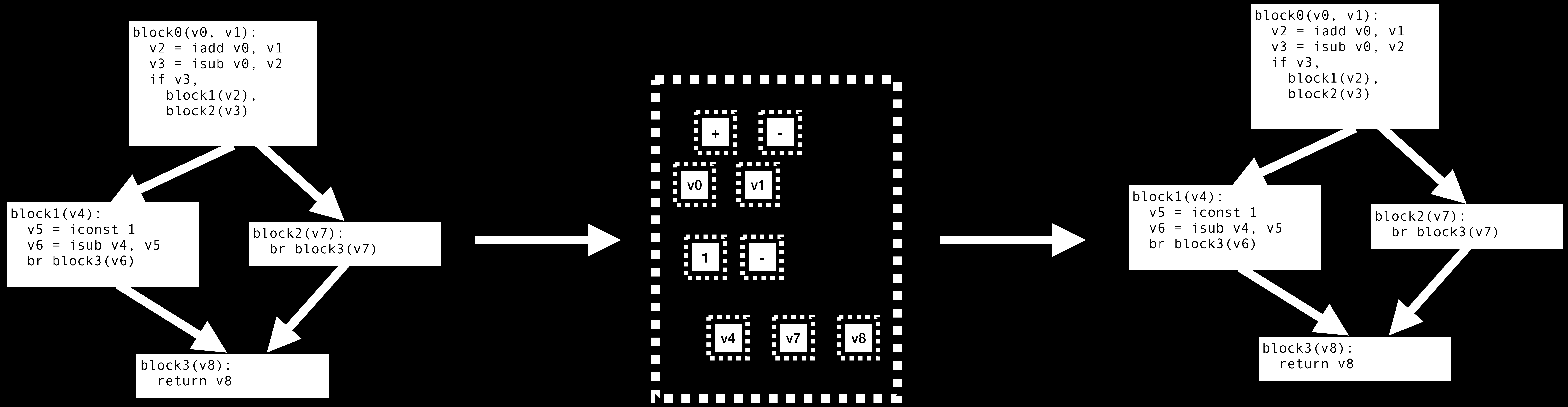

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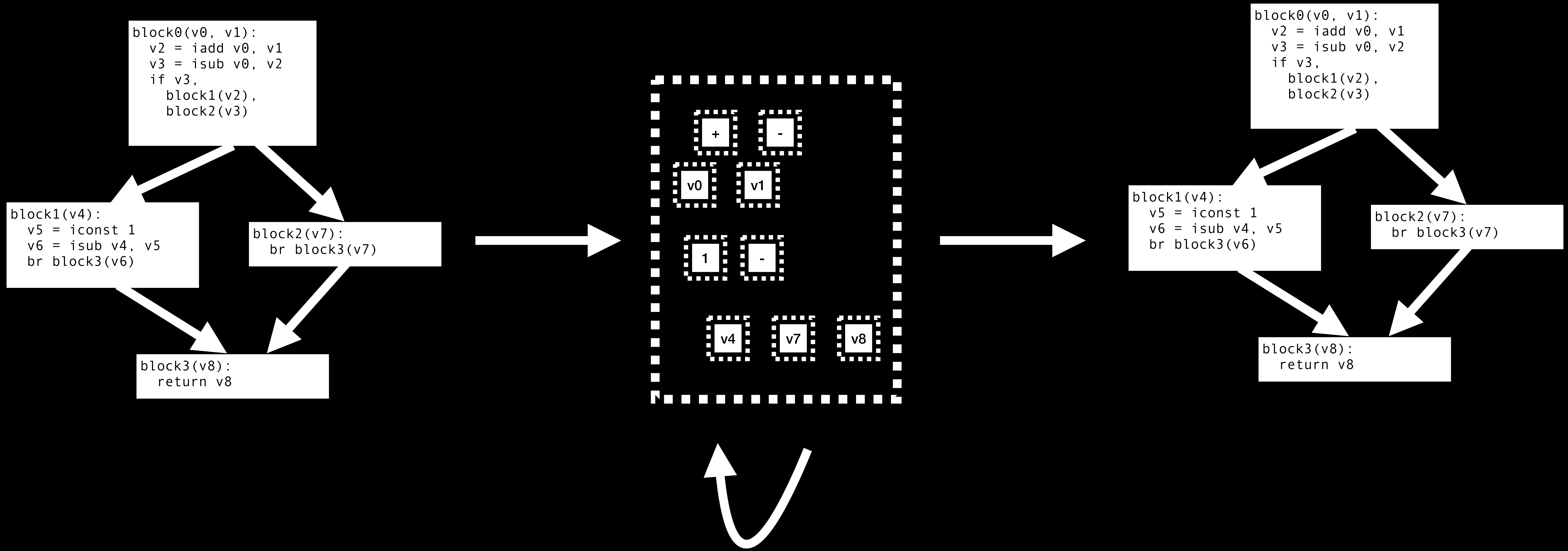
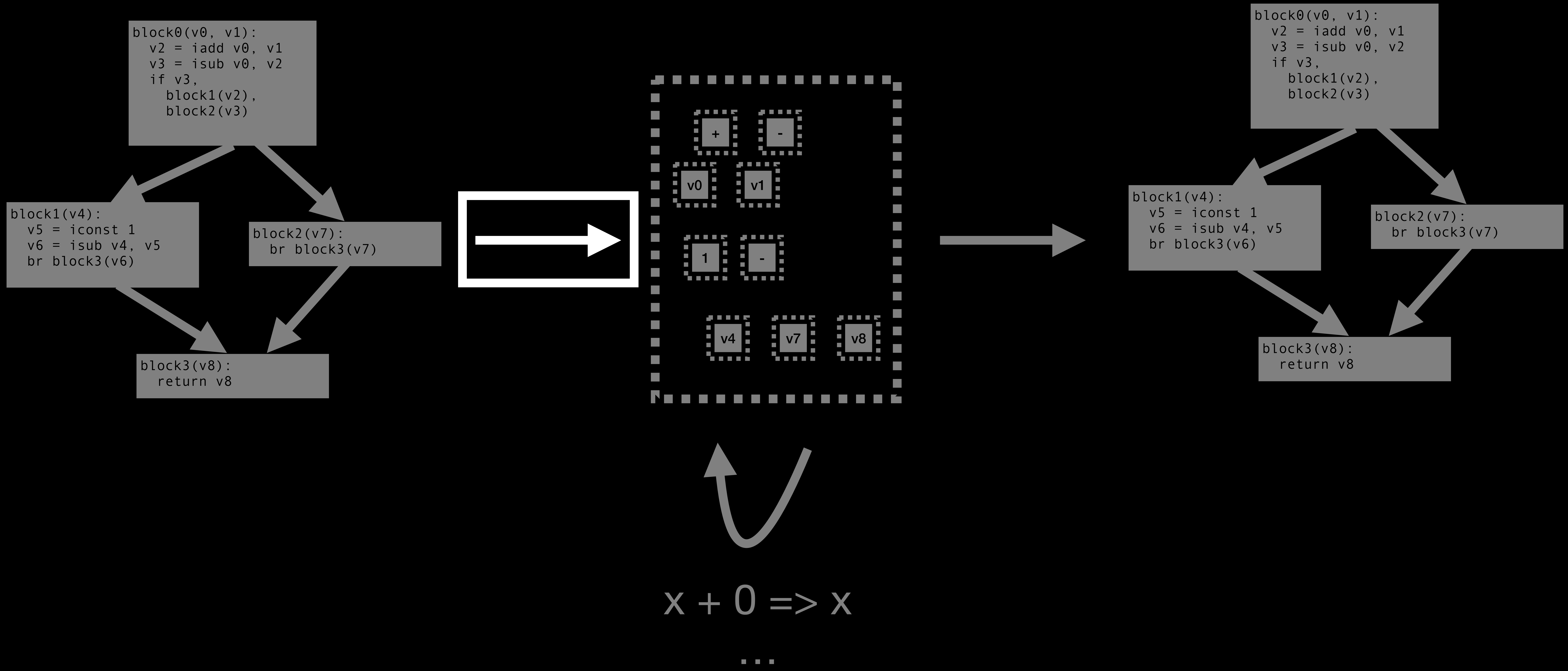


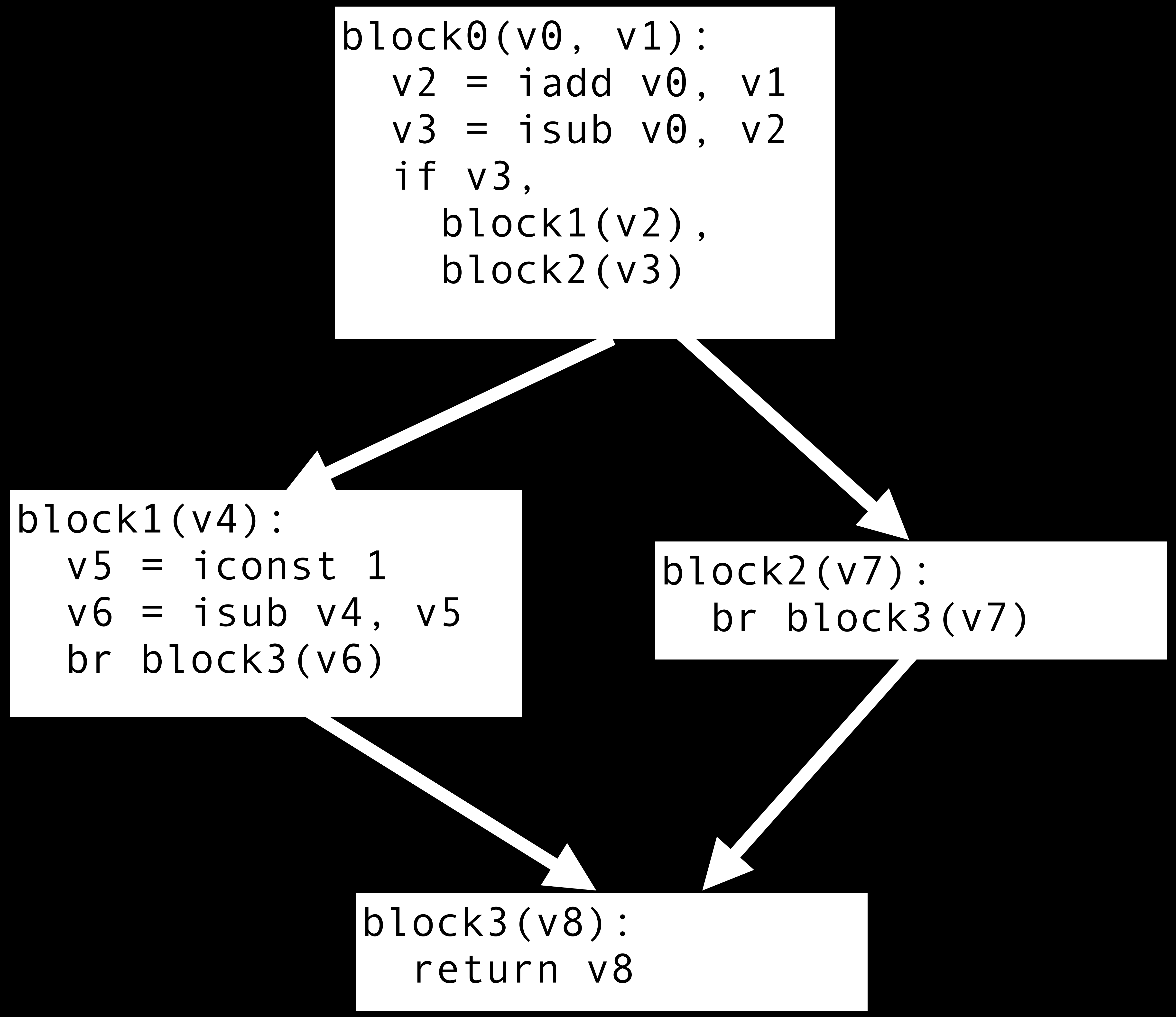
x + 0 => x

…

Optimization pipeline



E-graph + CFG == ???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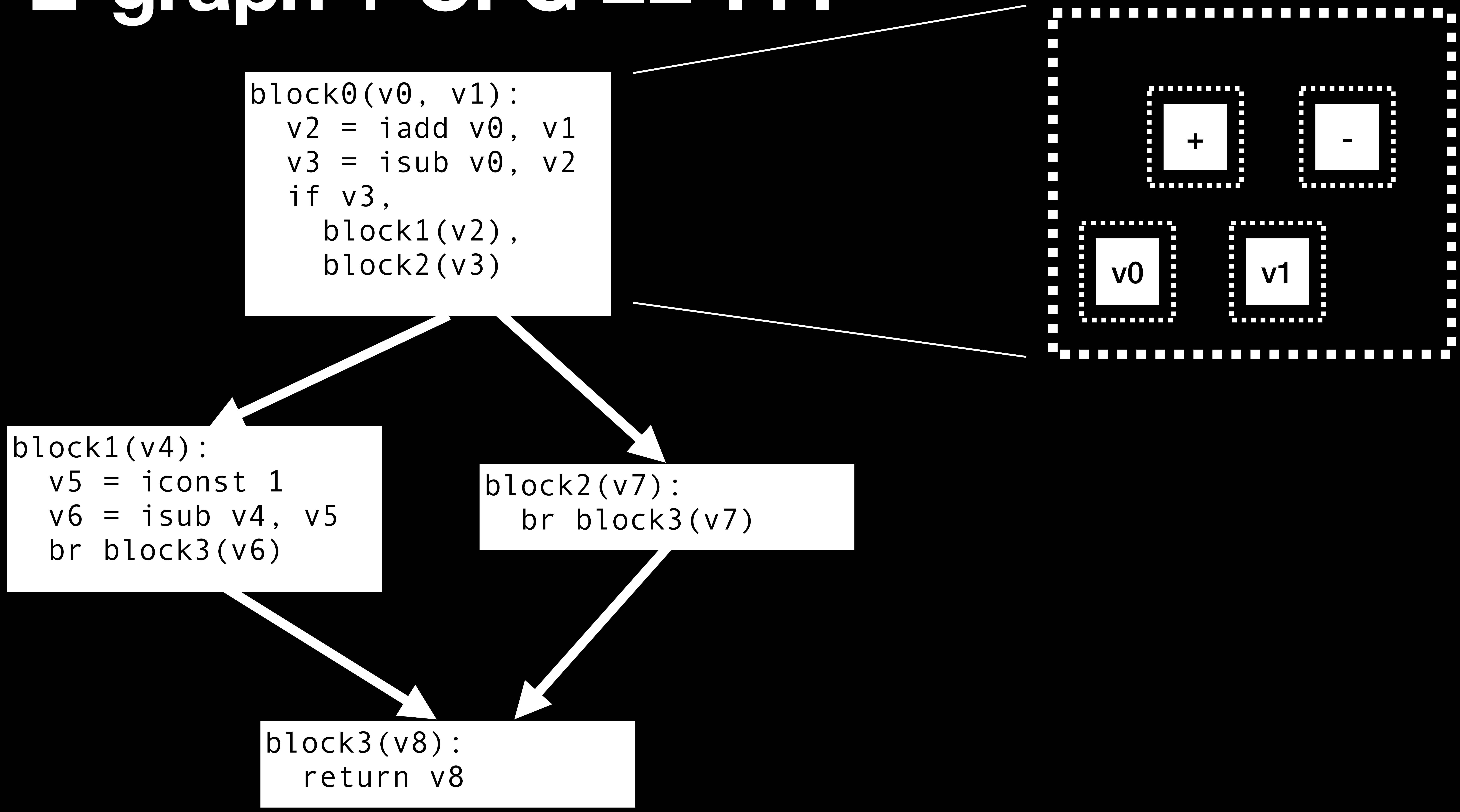
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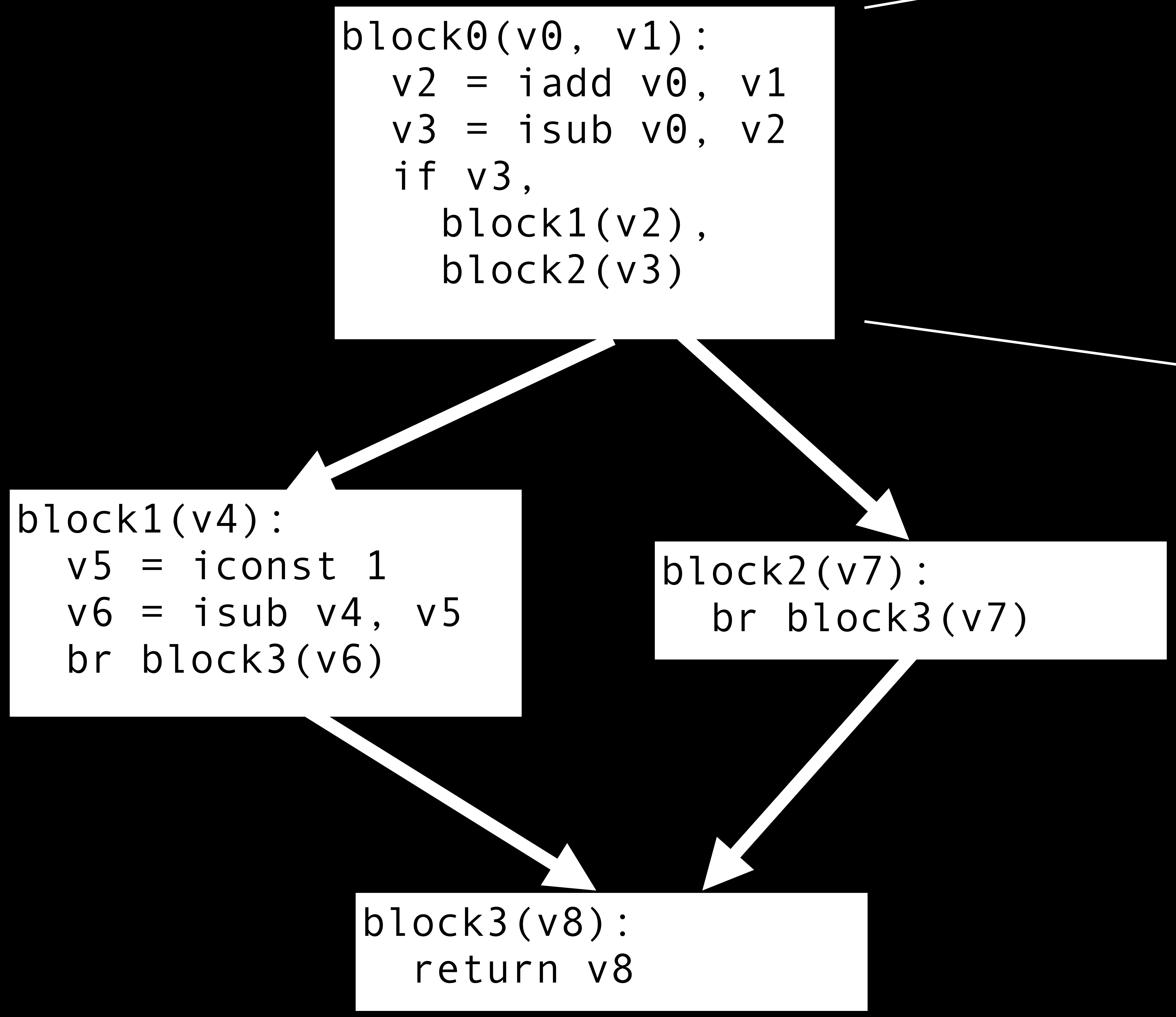

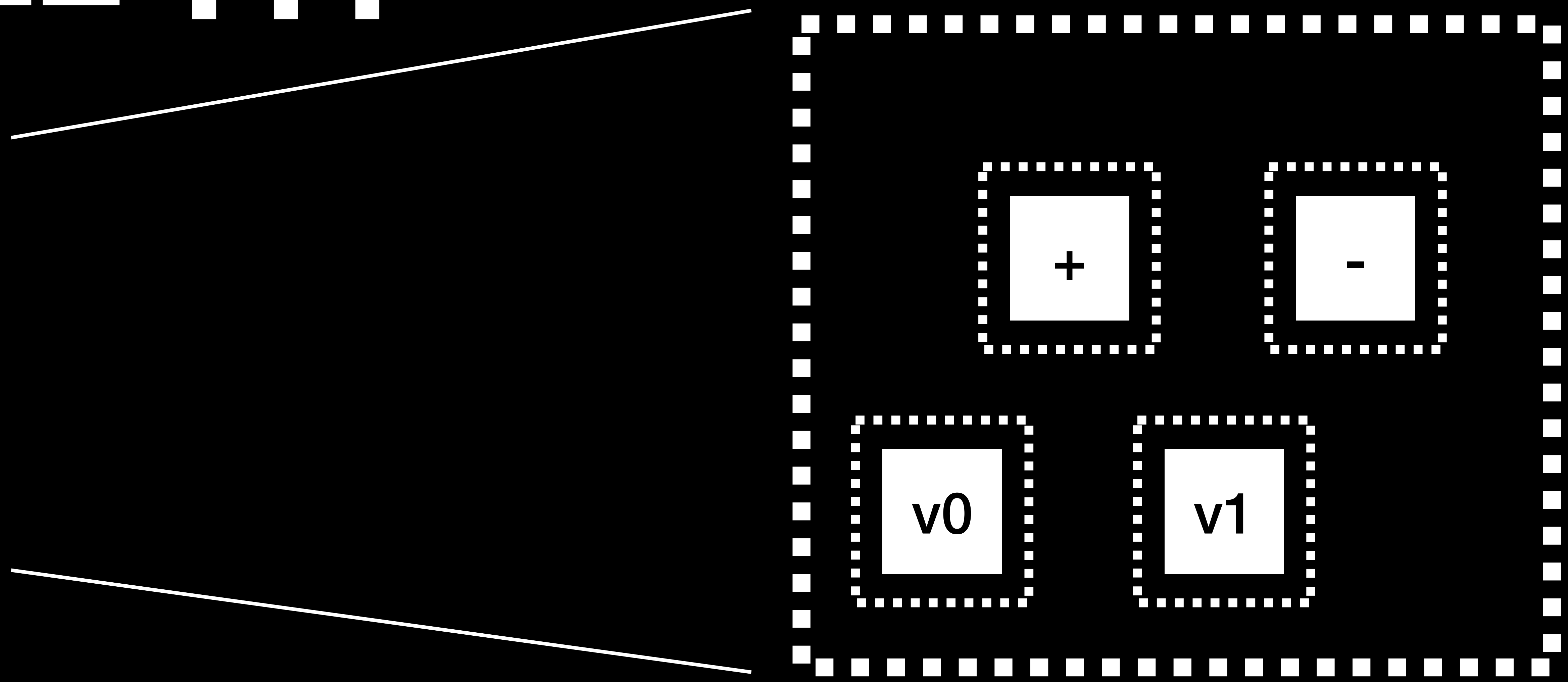

egraph per basic block:

\+ simple
- limited rewrite scope
- limited sharing/amortization
- rules out control optimizations

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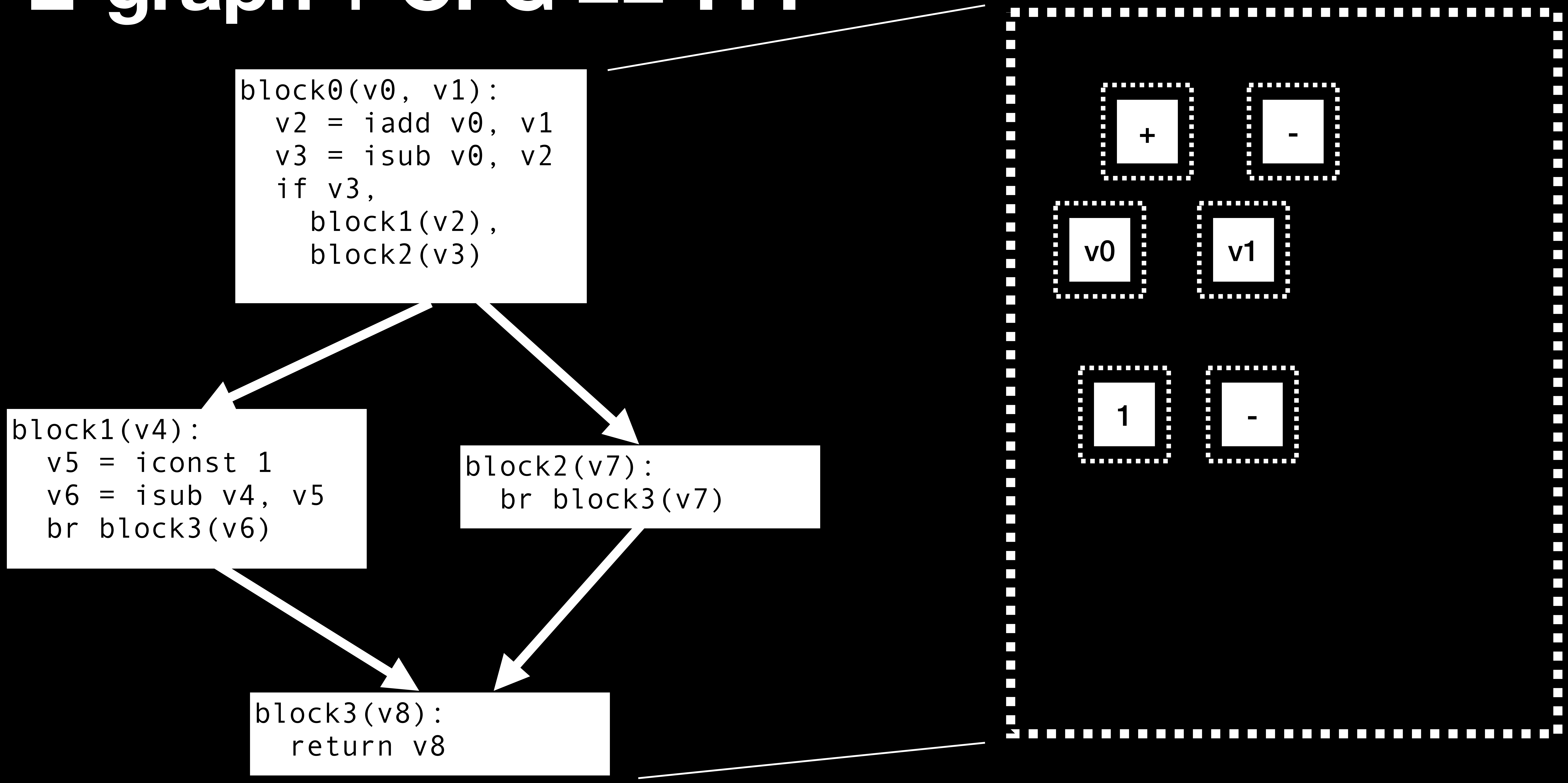
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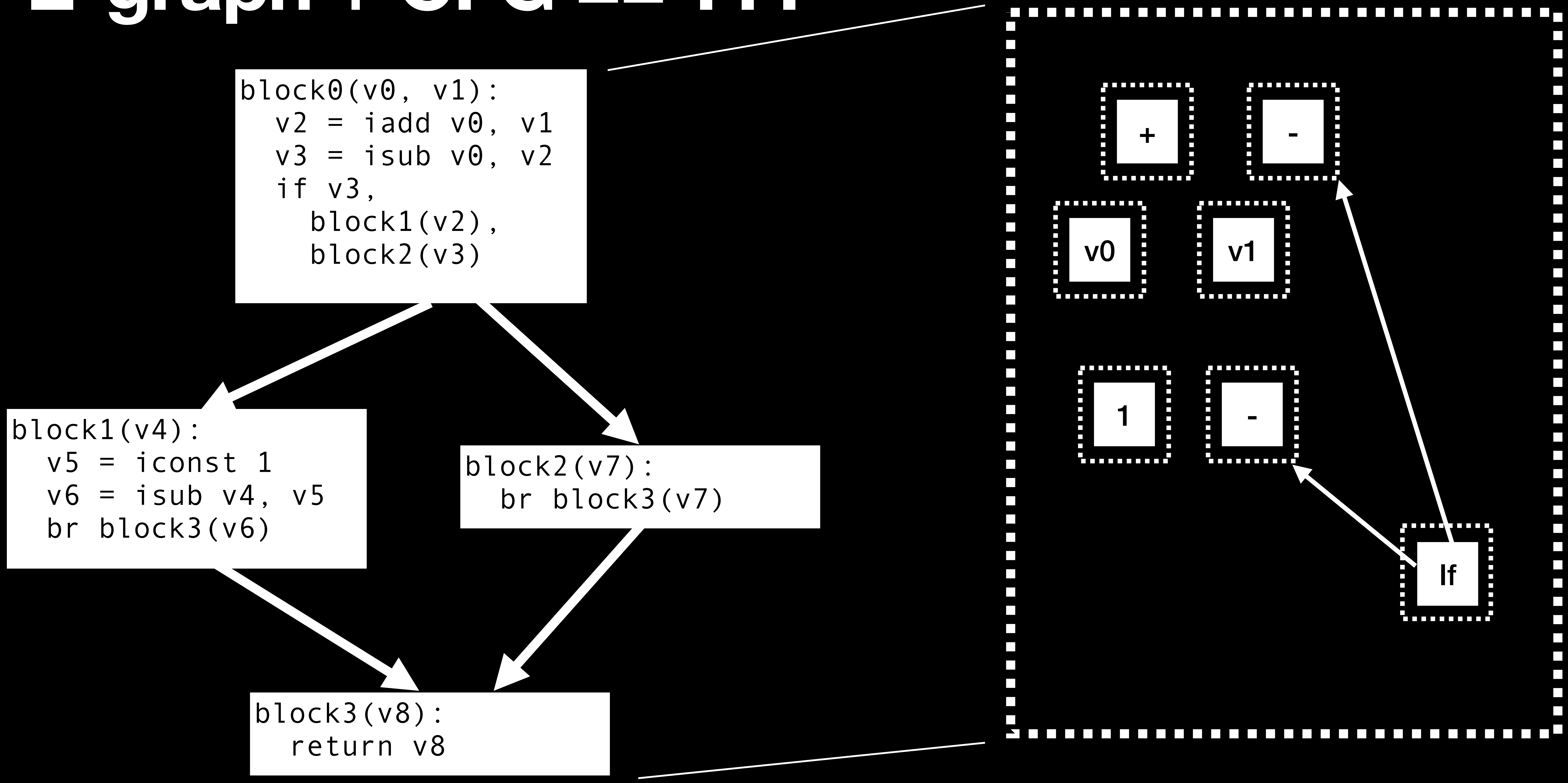
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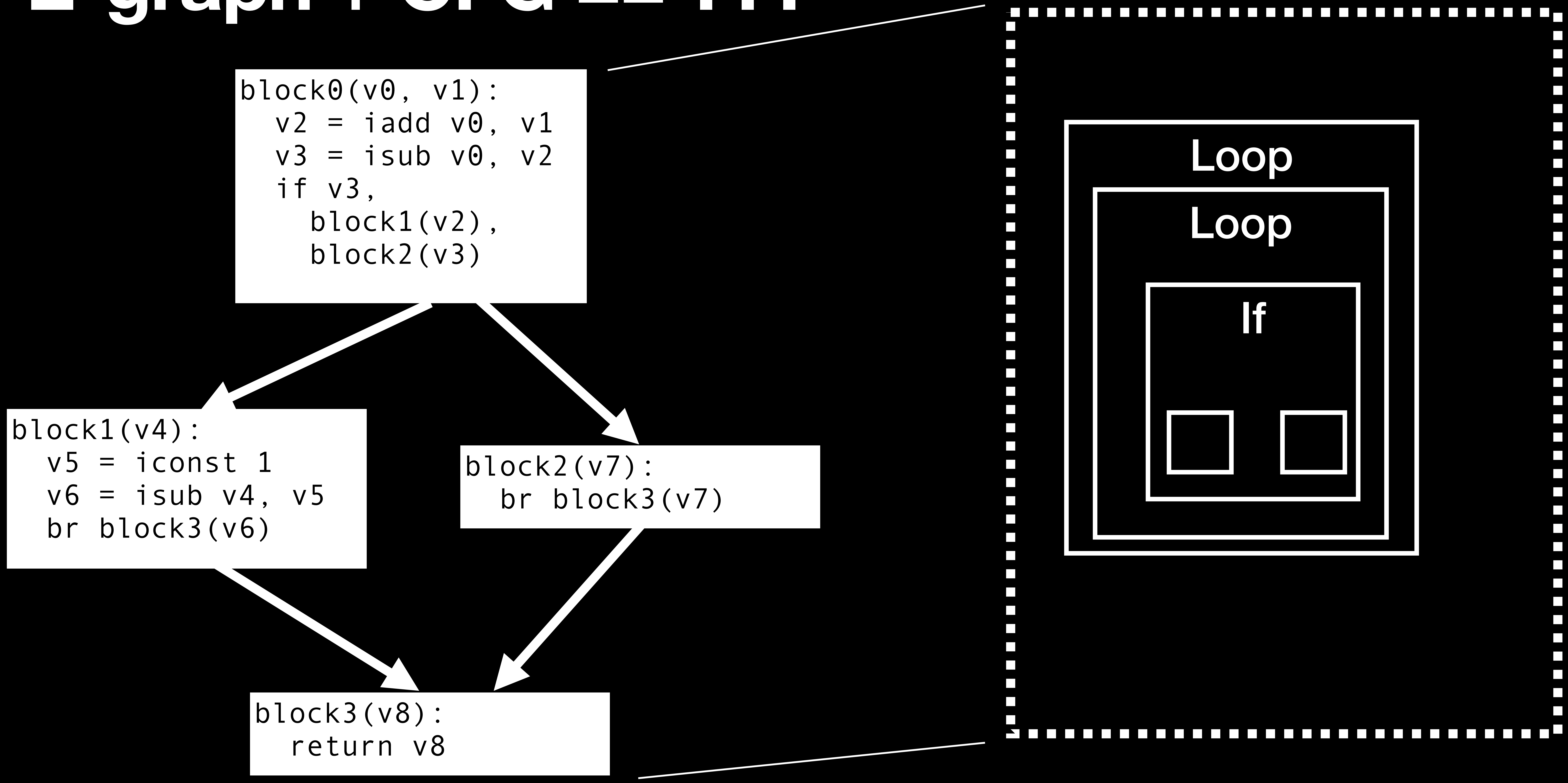
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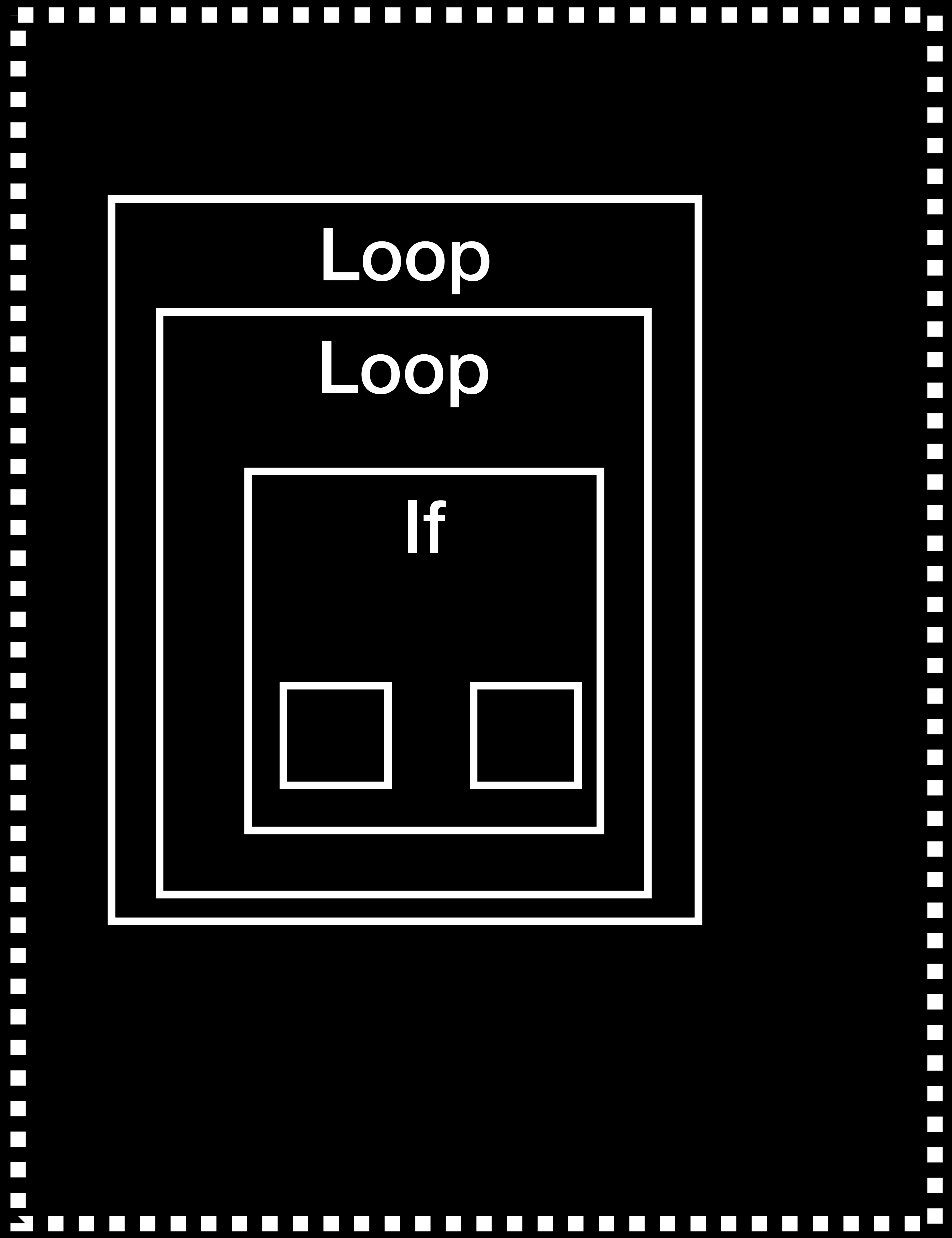
E-graph + CFG == ???

Region-nodes in egraph:

+ powerful optimizations!
+ strongly normalizing
+ more compact IR
+ cheaper analysis?

- very different from CFG
  (conversion overheads)
- side-effects are tricky
- issues with irreducible
  control flow



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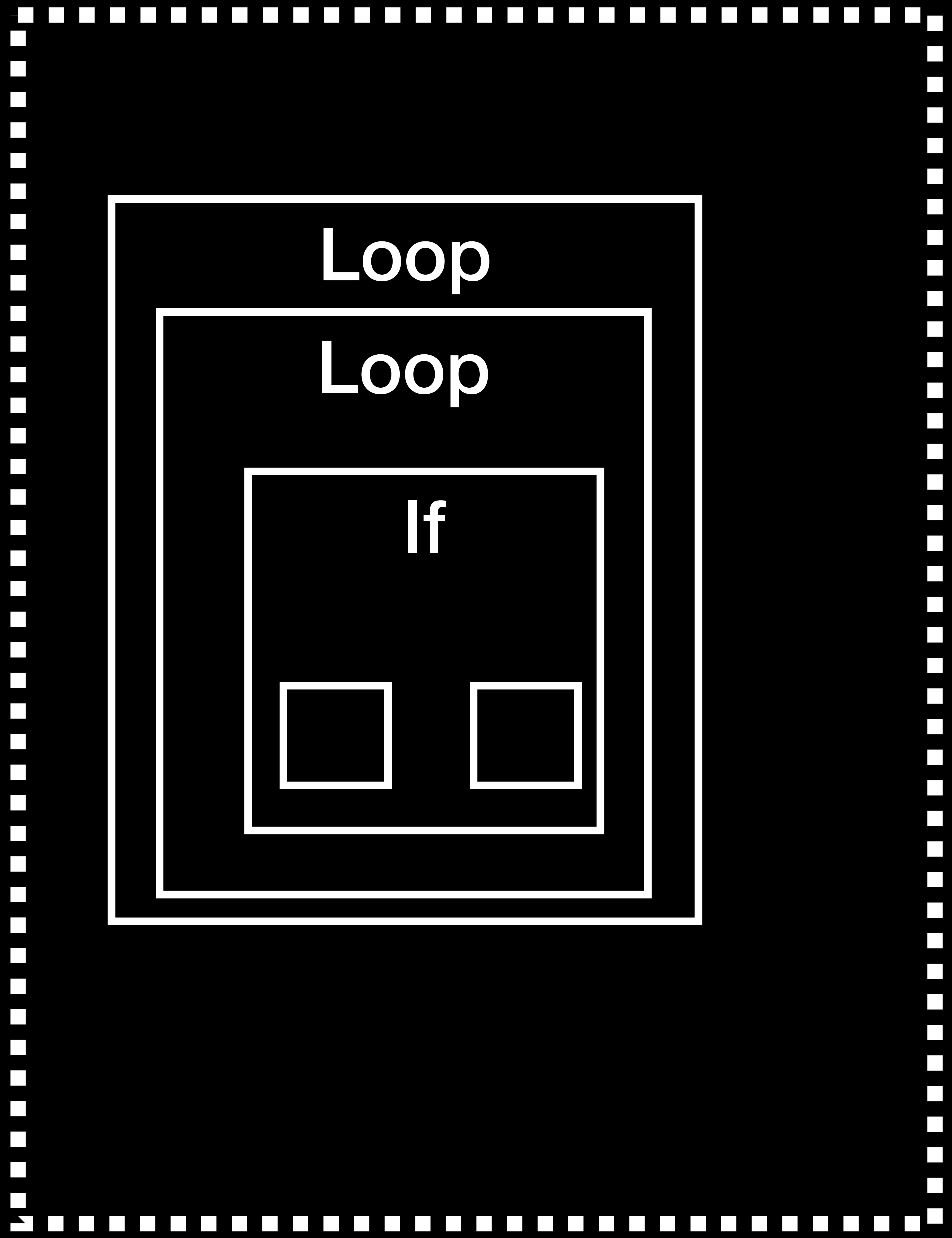

Jamey Sharp's prototype: https://github.com/jameysharp/optir

E-graph + CFG == ???

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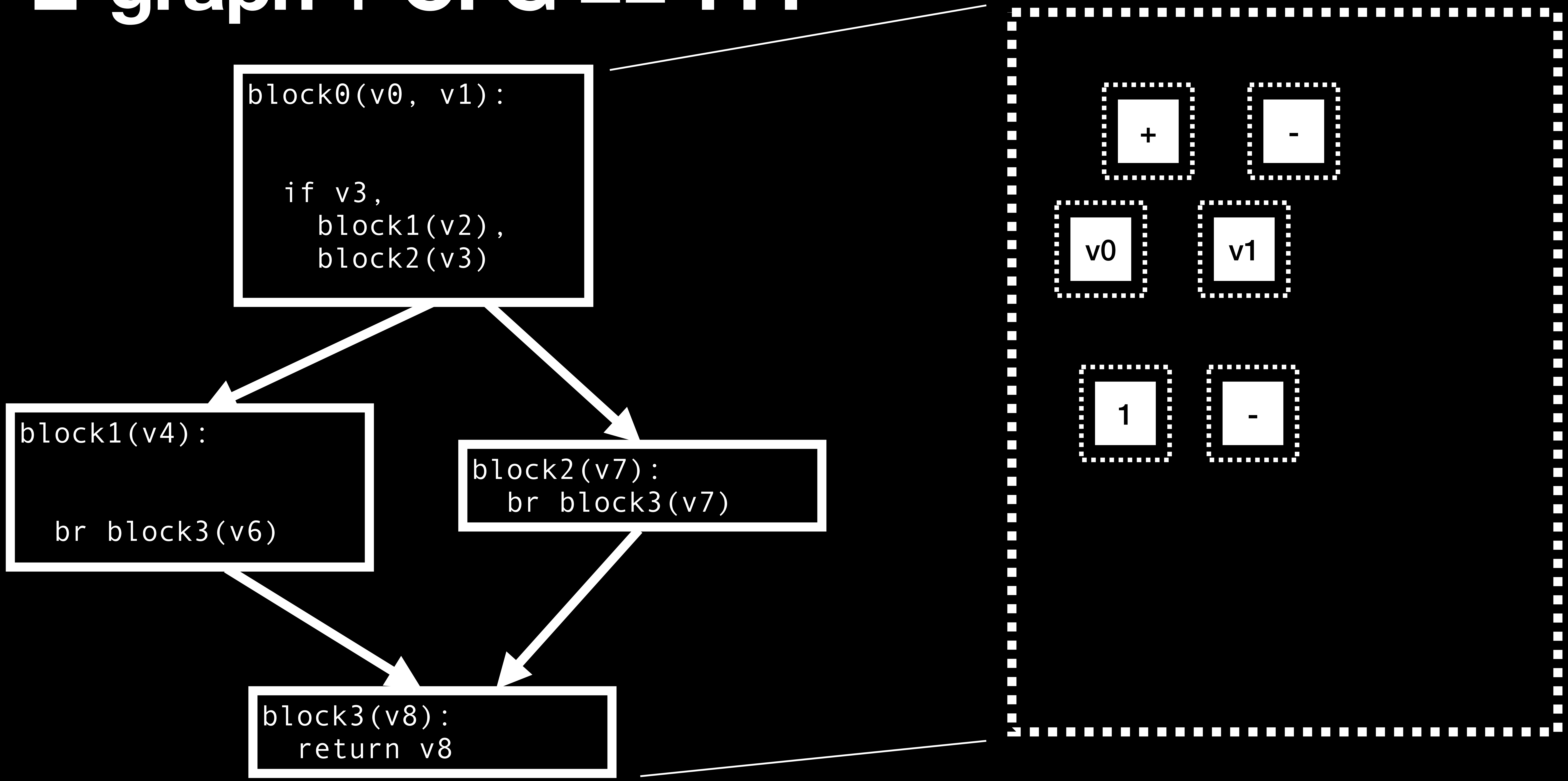
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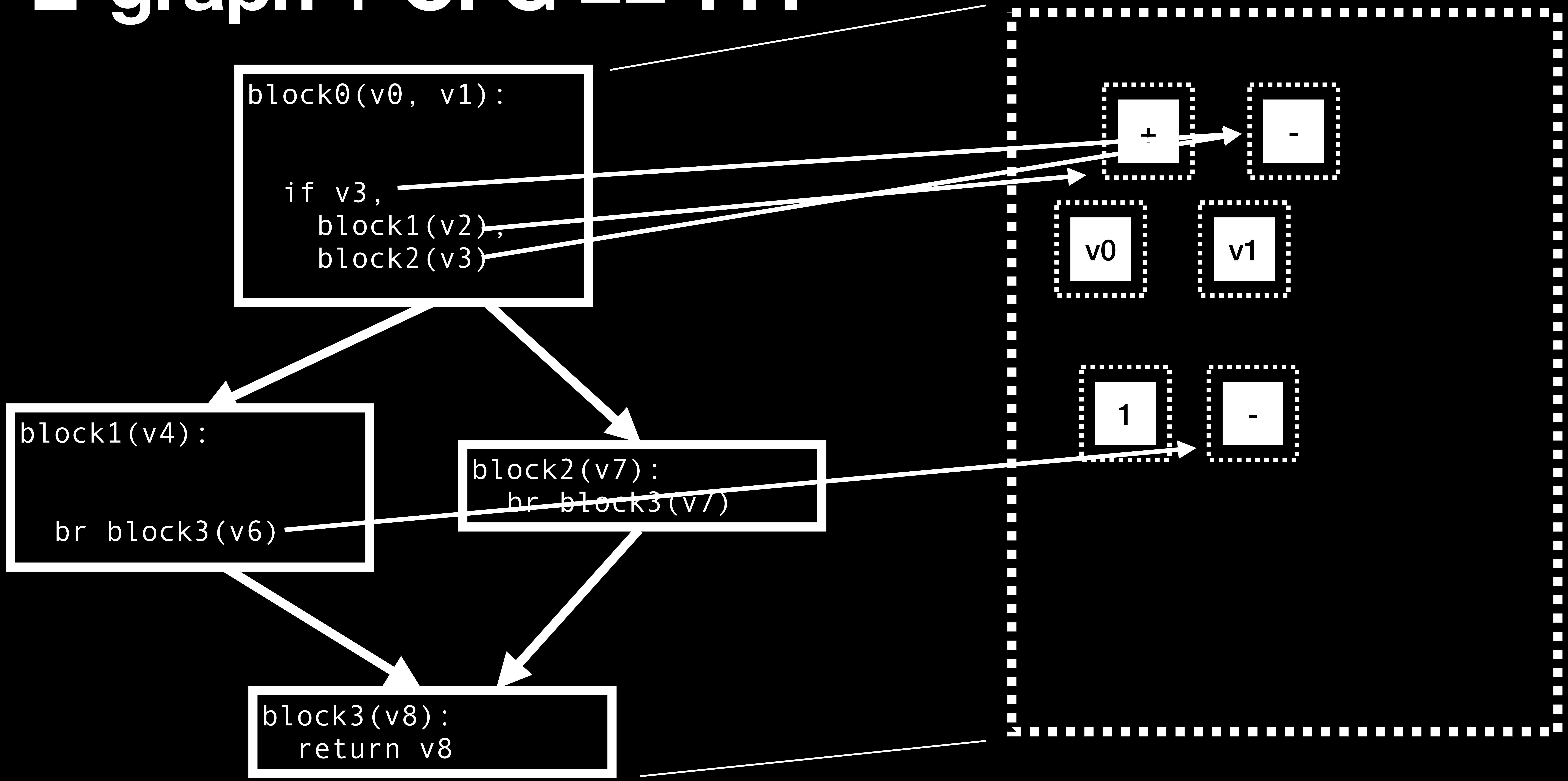

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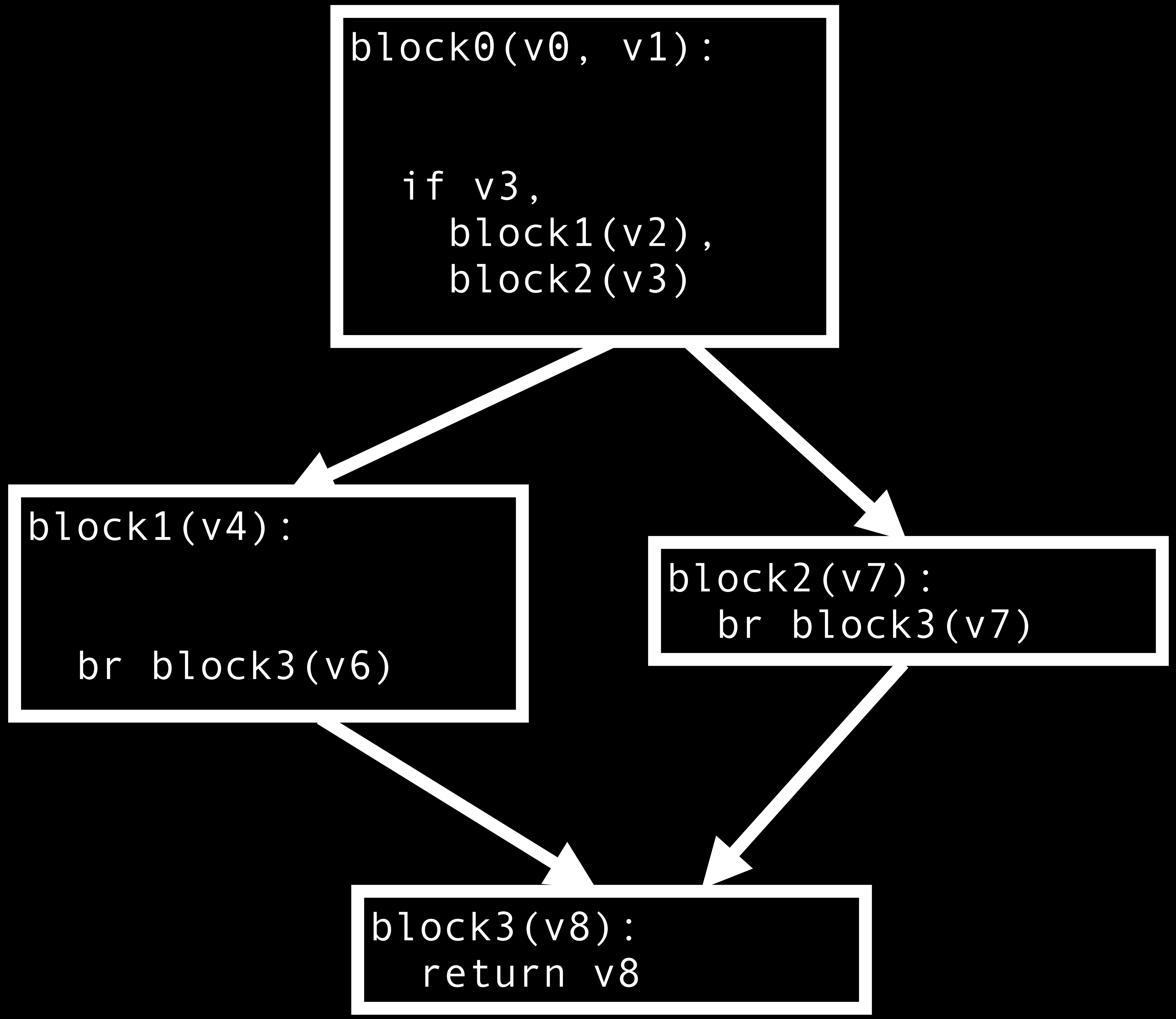


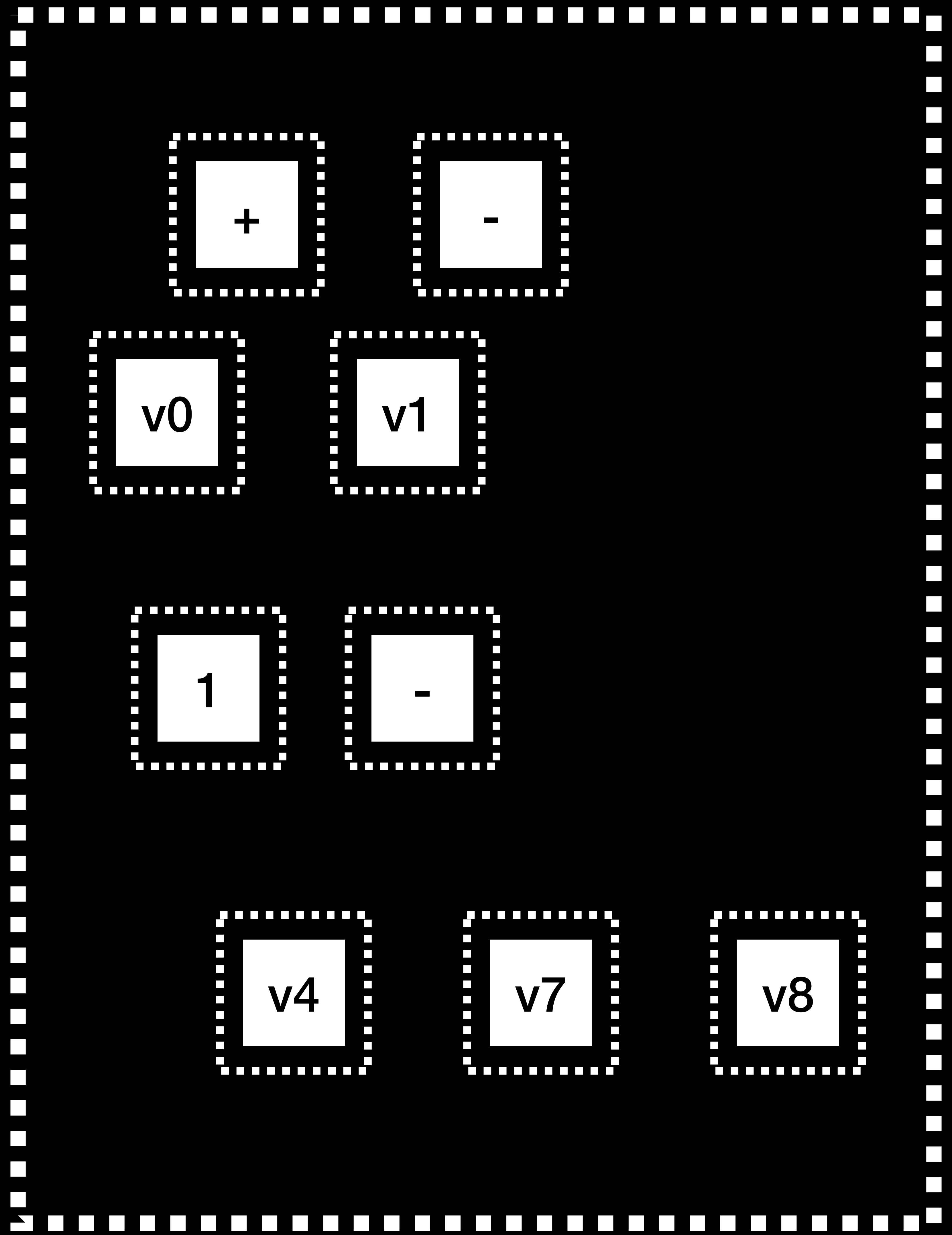
CFG skeleton contains:

- all blocks, with blockparams
- side-effecting operators
- block terminators (branches)

E-graph + CFG == ???

egraph contains:

- blockparam values, as terminals
- all pure operators, *without* associated location



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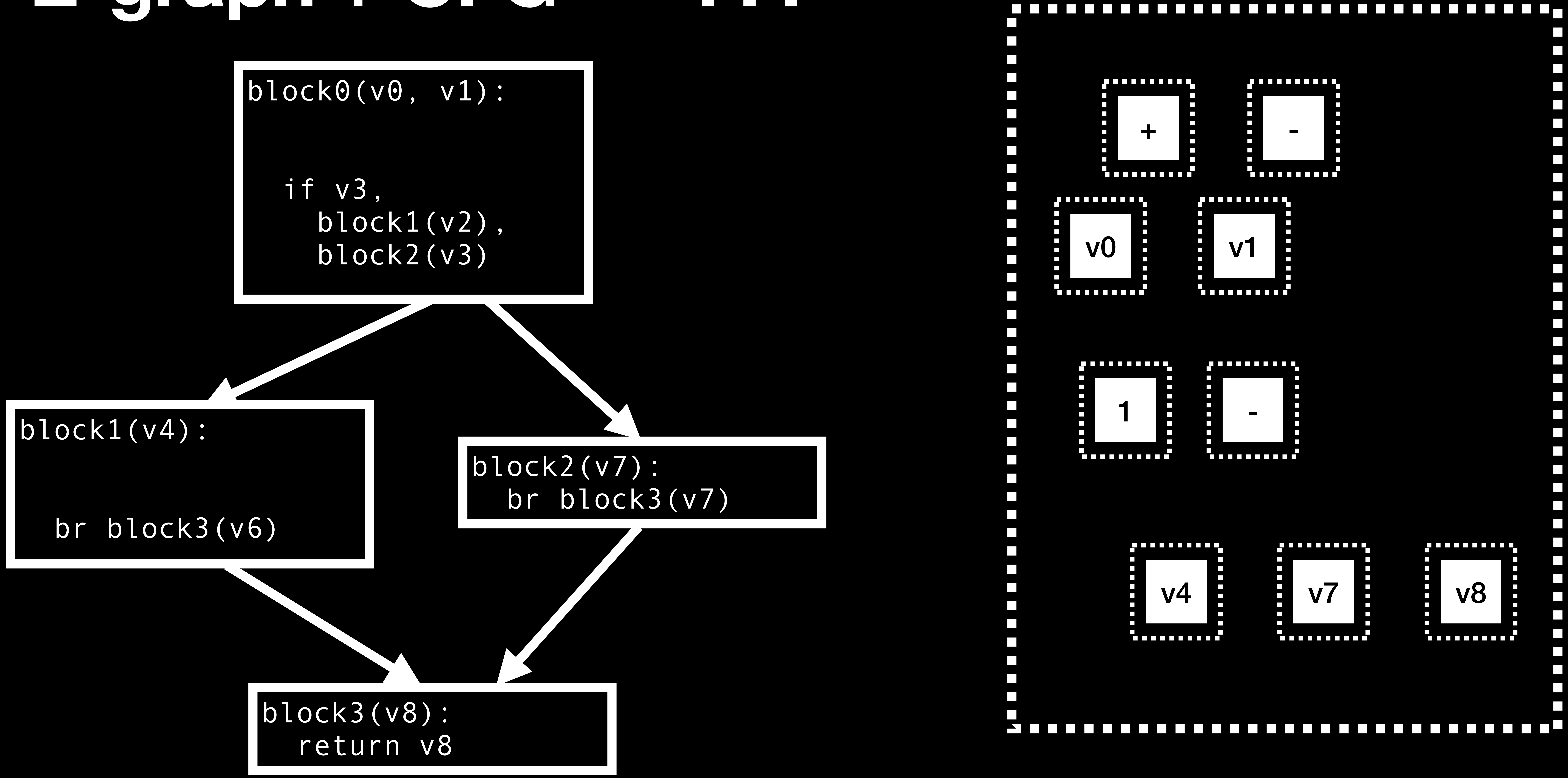
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egraph with CFG skeleton:

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+ optimizations across function scope (mostly)

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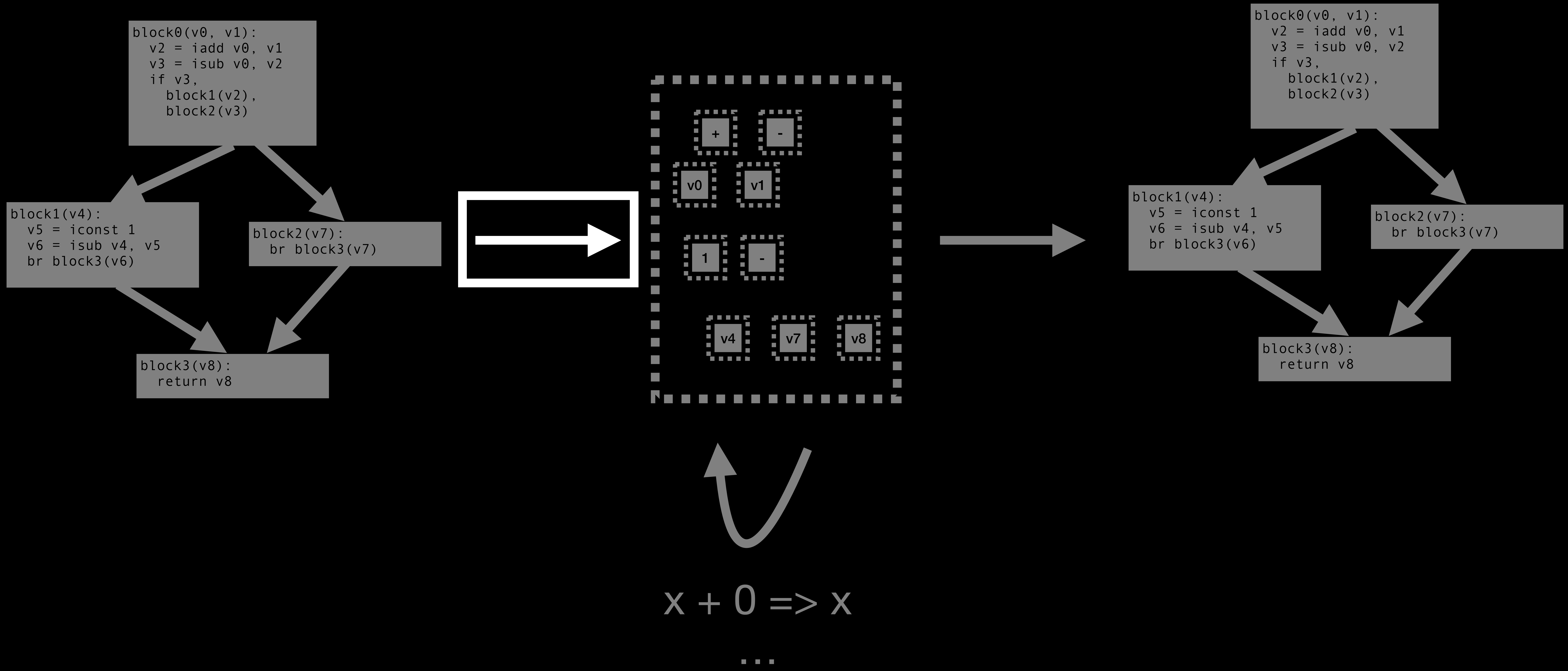
→ good enough for now! (incremental approach)

Optimization pipeline



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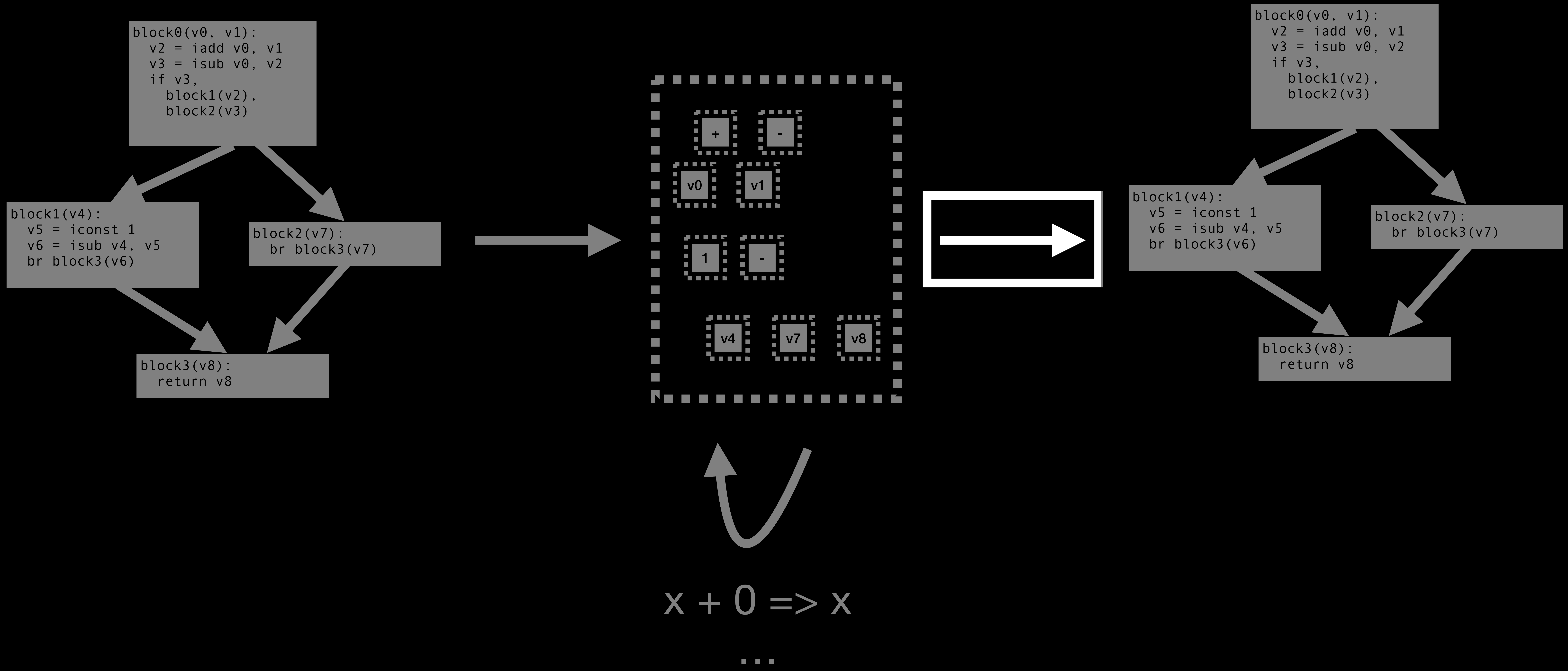
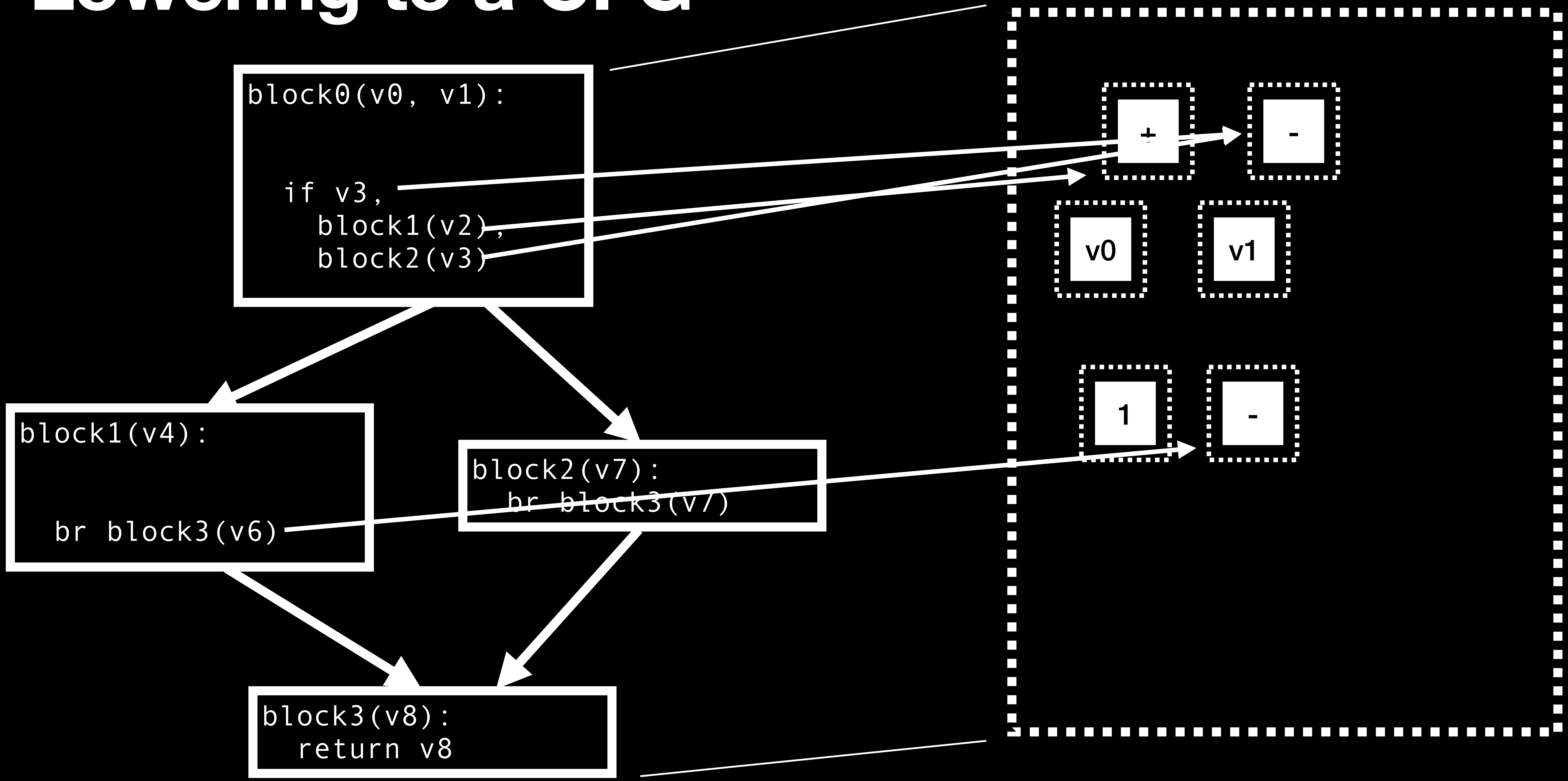


Lowering to a CFG



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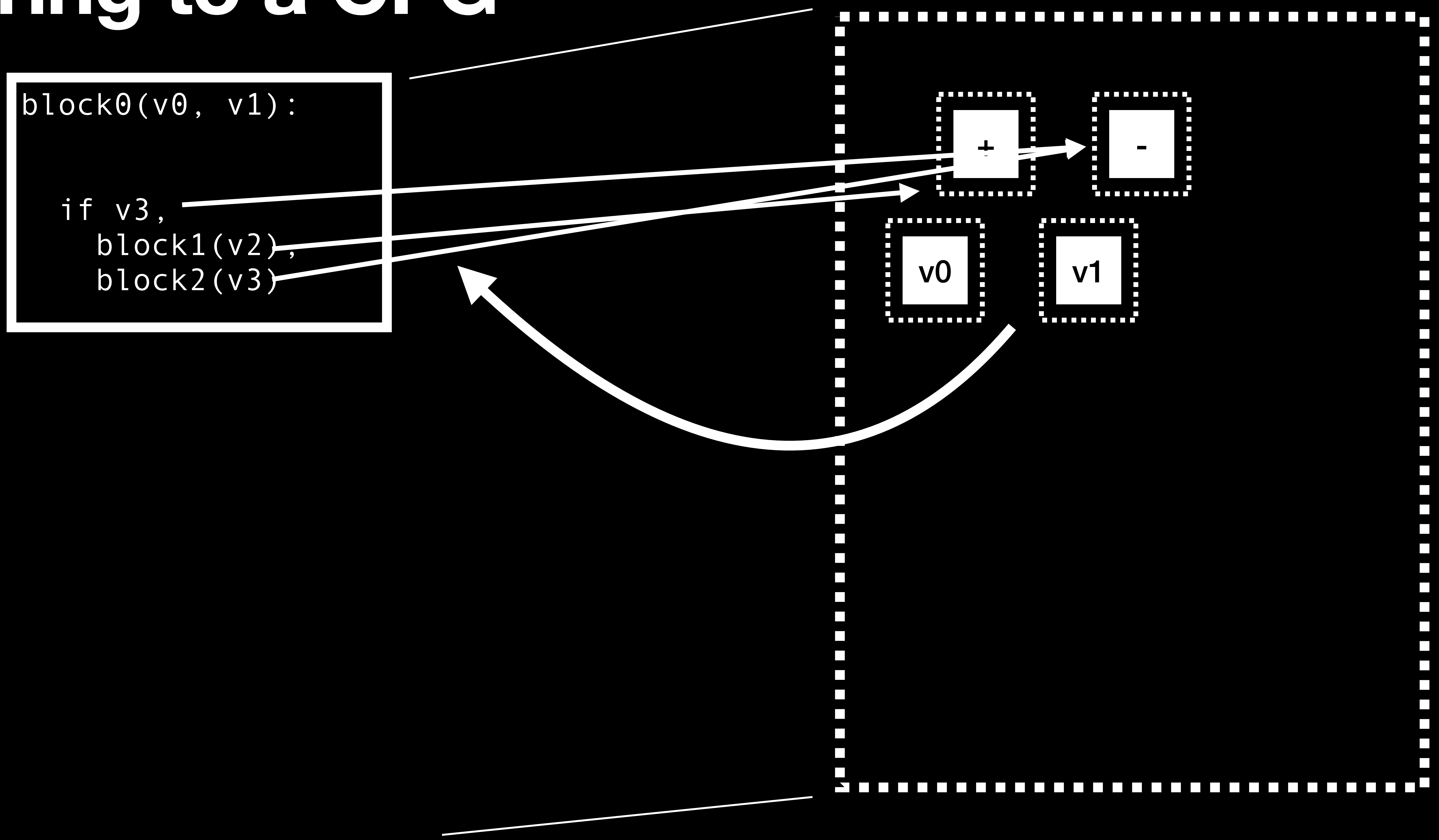

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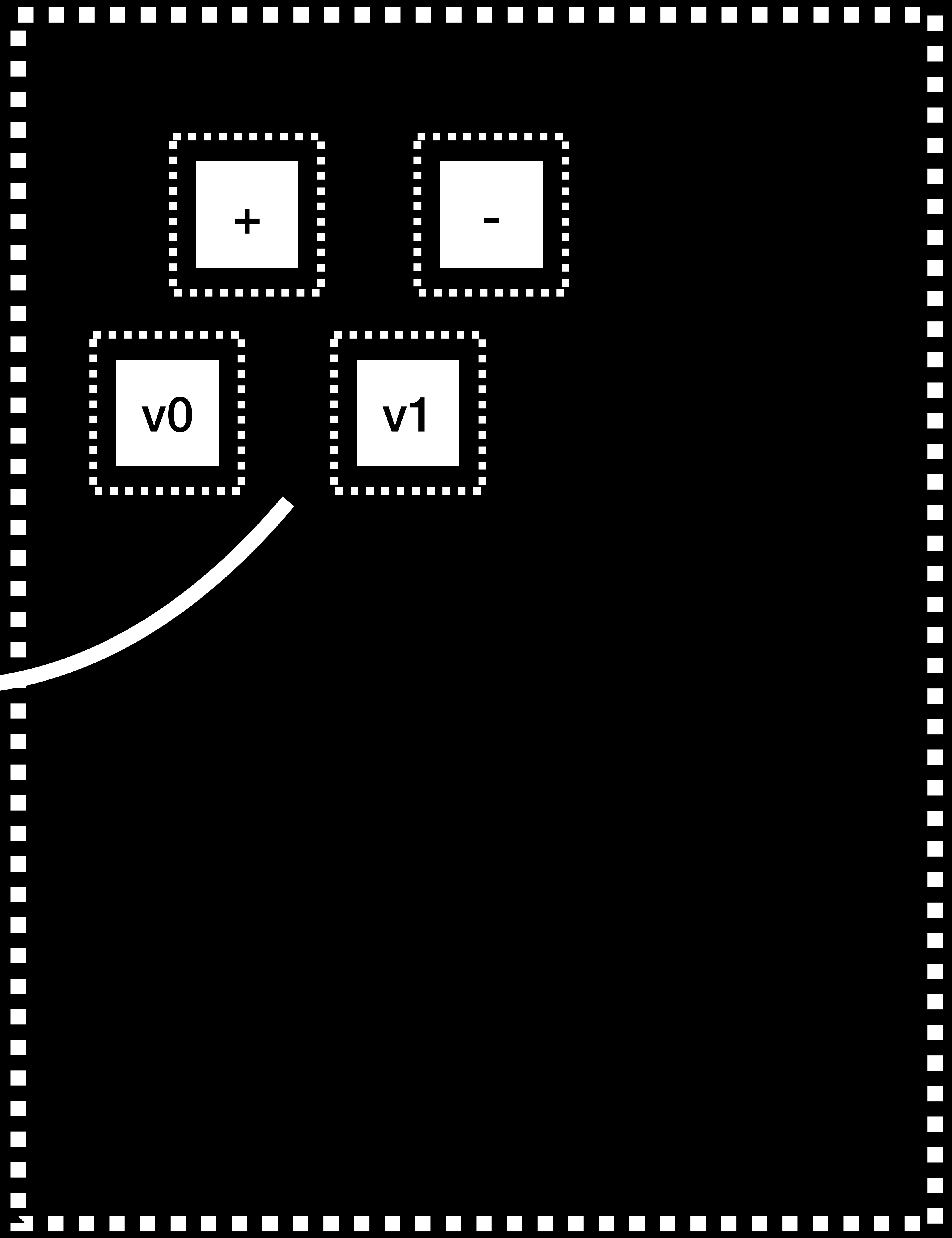
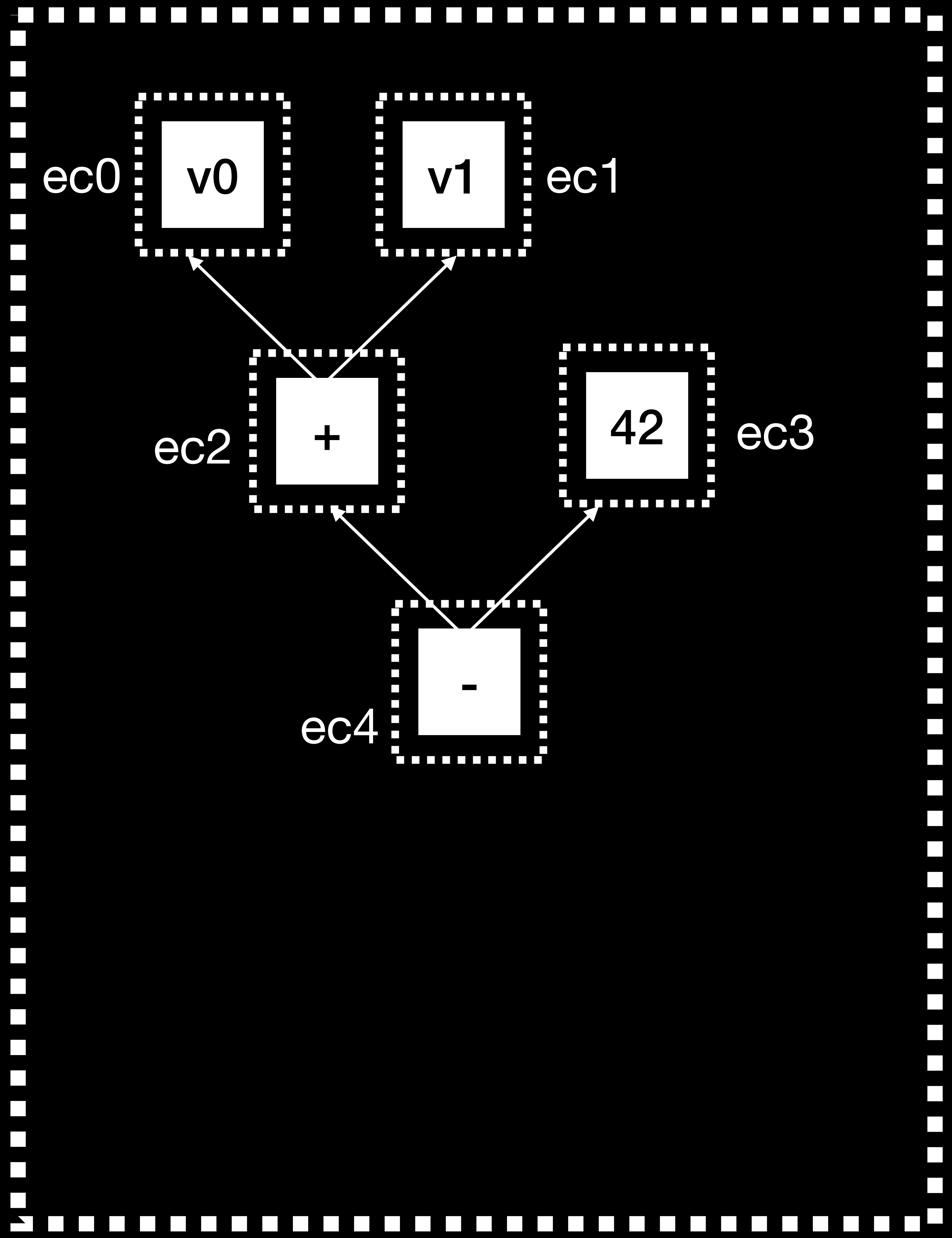


Elaboration

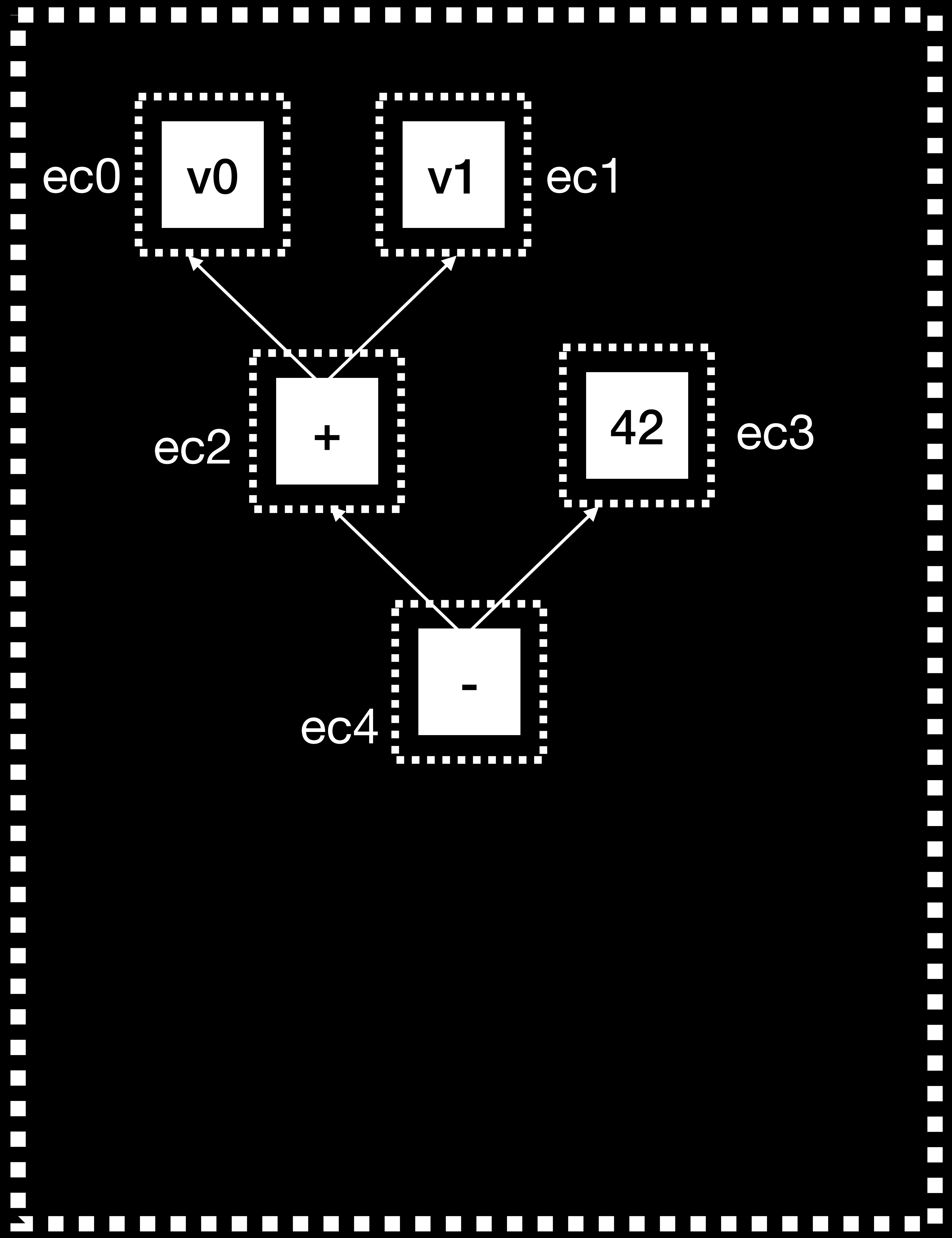
```
block0(v0, v1):
  store ec0, ec4
  return ec2
```



Elaboration

```
block0(v0, v1):
  store ec0, ec4
  return ec2
```

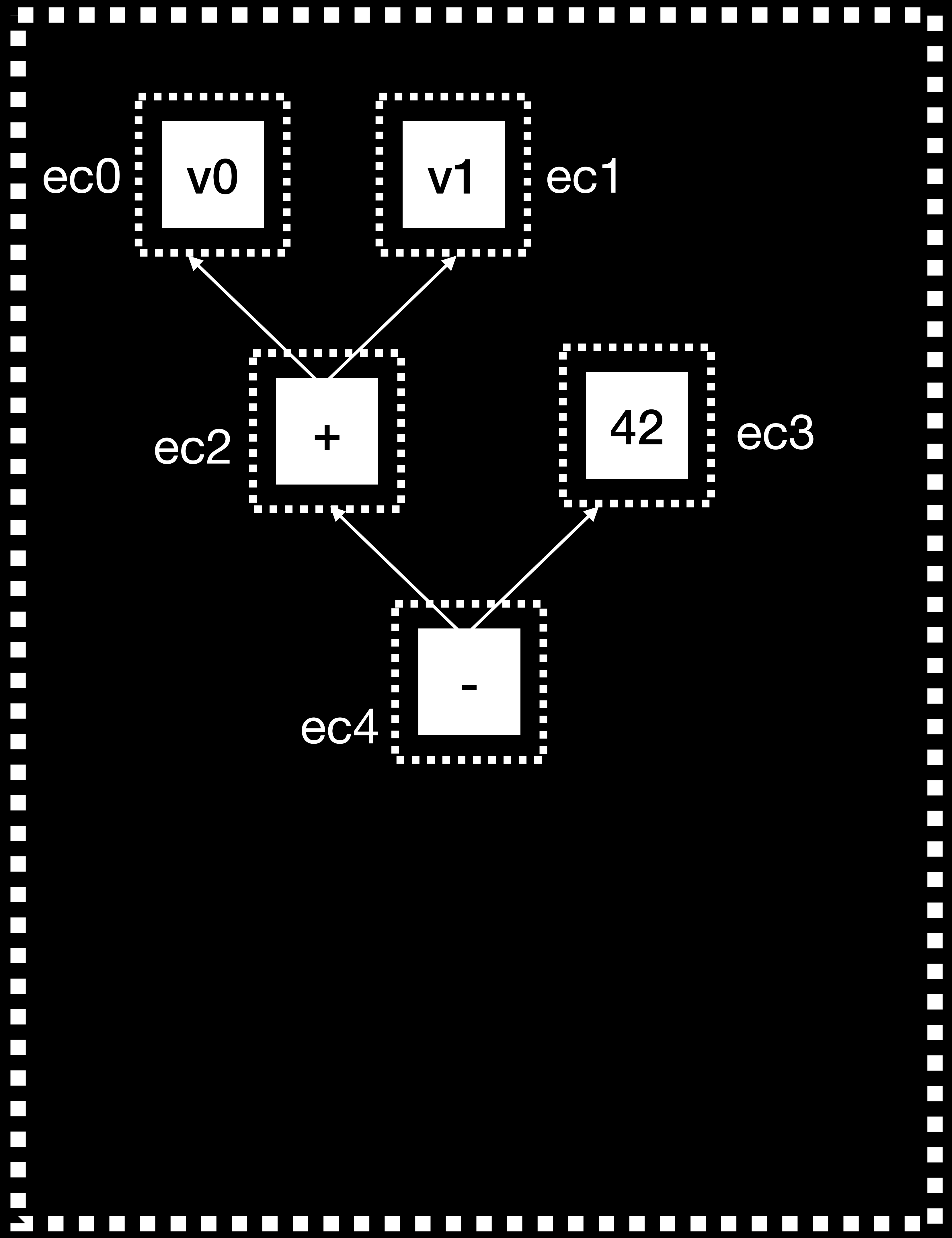
eclass	elaborated
ec0	v0
ec1	v1



Elaboration

```
block0(v0, v1):
  v2 = isub ec2, ec3
  store ec0, ec4
  return ec2
```

eclass	elaborated
ec0	v0
ec1	v1
ec4	v2

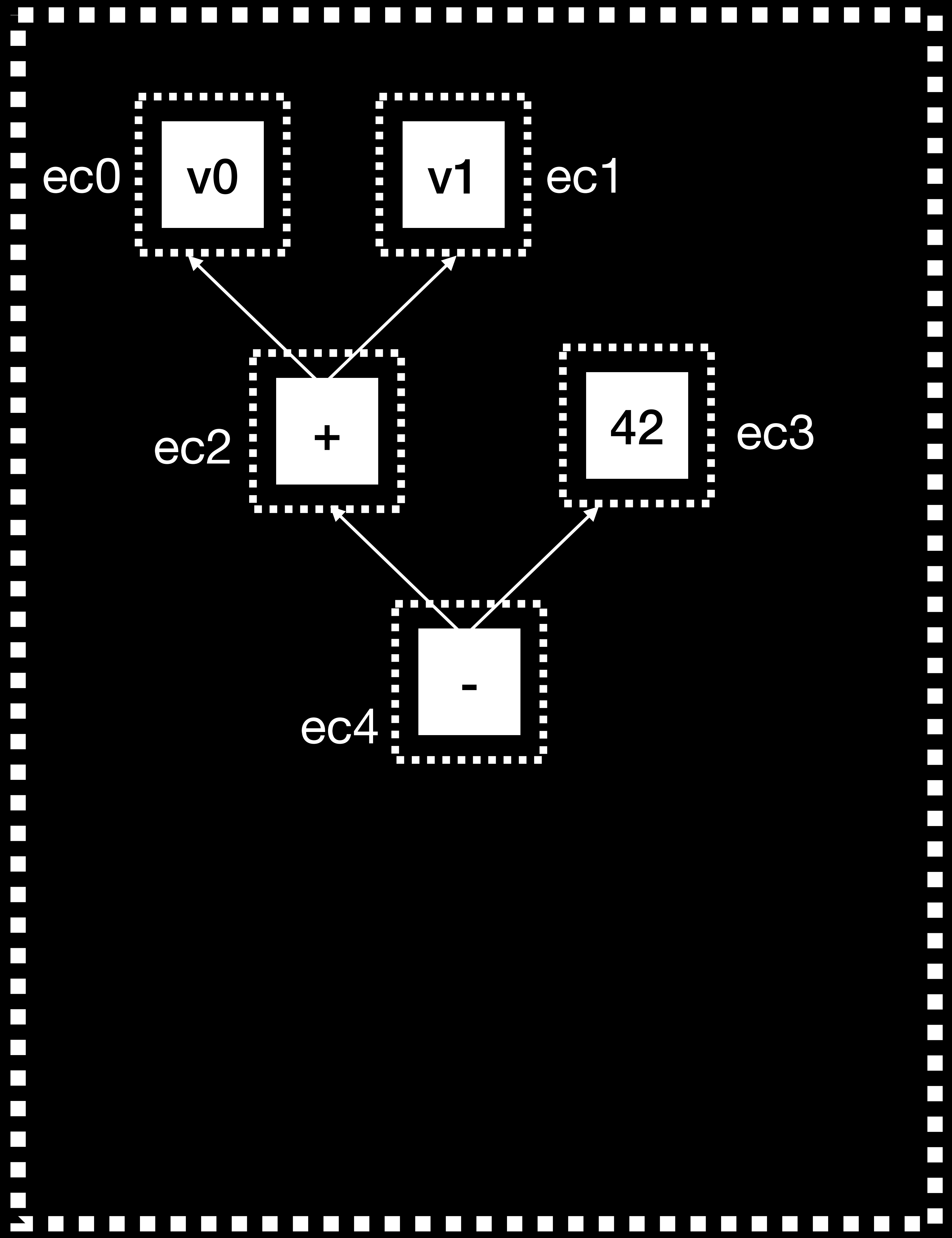


** Note: assume extraction (node selection) is done already!*

Elaboration

```
block0(v0, v1):
  v3 = iadd ec0, ec1
  v2 = isub ec2, ec3
  store ec0, ec4
  return ec2
```

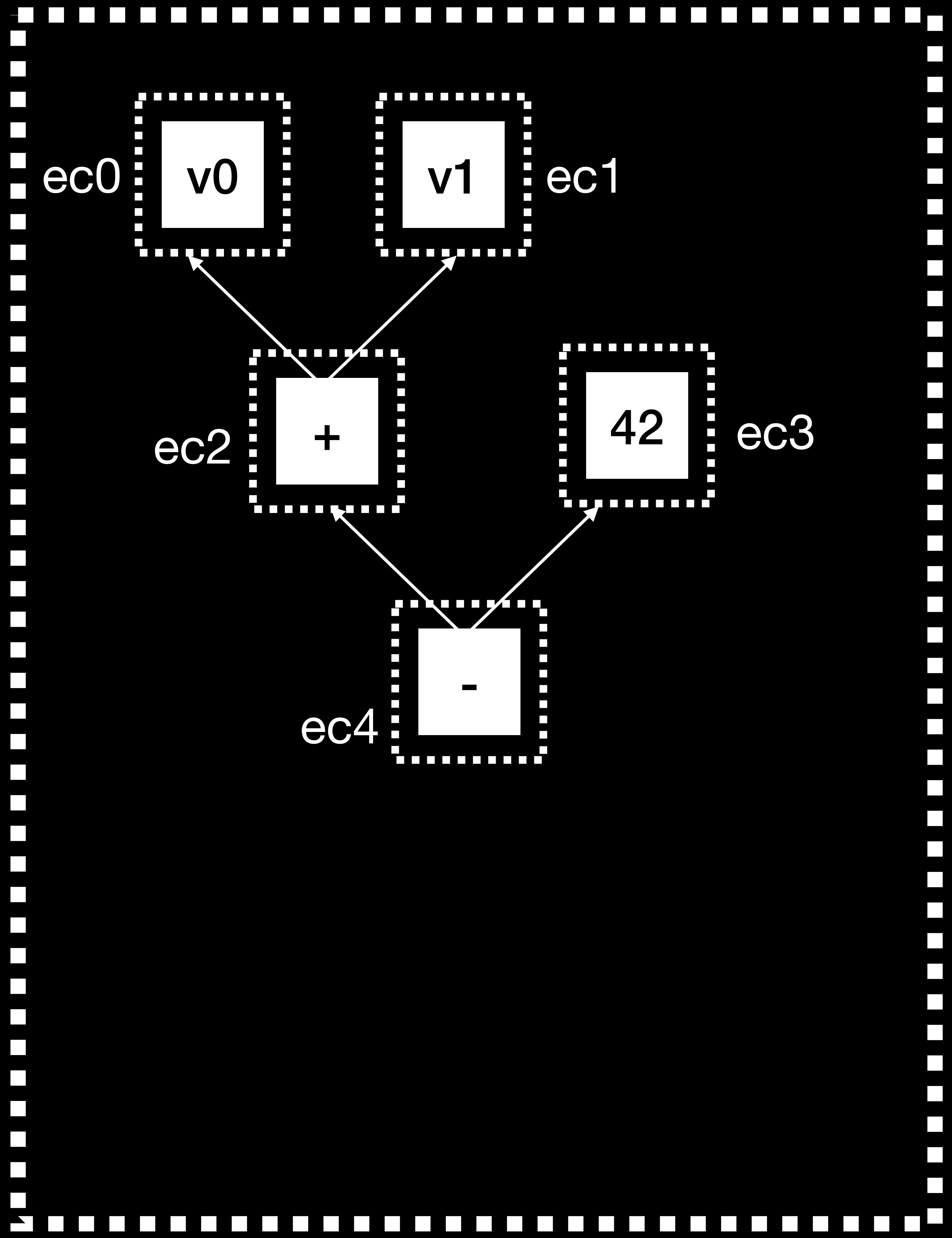
eclass	elaborated
ec0	v0
ec1	v1
ec2	v3
ec4	v2



Elaboration

```
block0(v0, v1):
  v3 = iadd v0, v1
  v2 = isub ec2, ec3
  store ec0, ec4
  return ec2
```

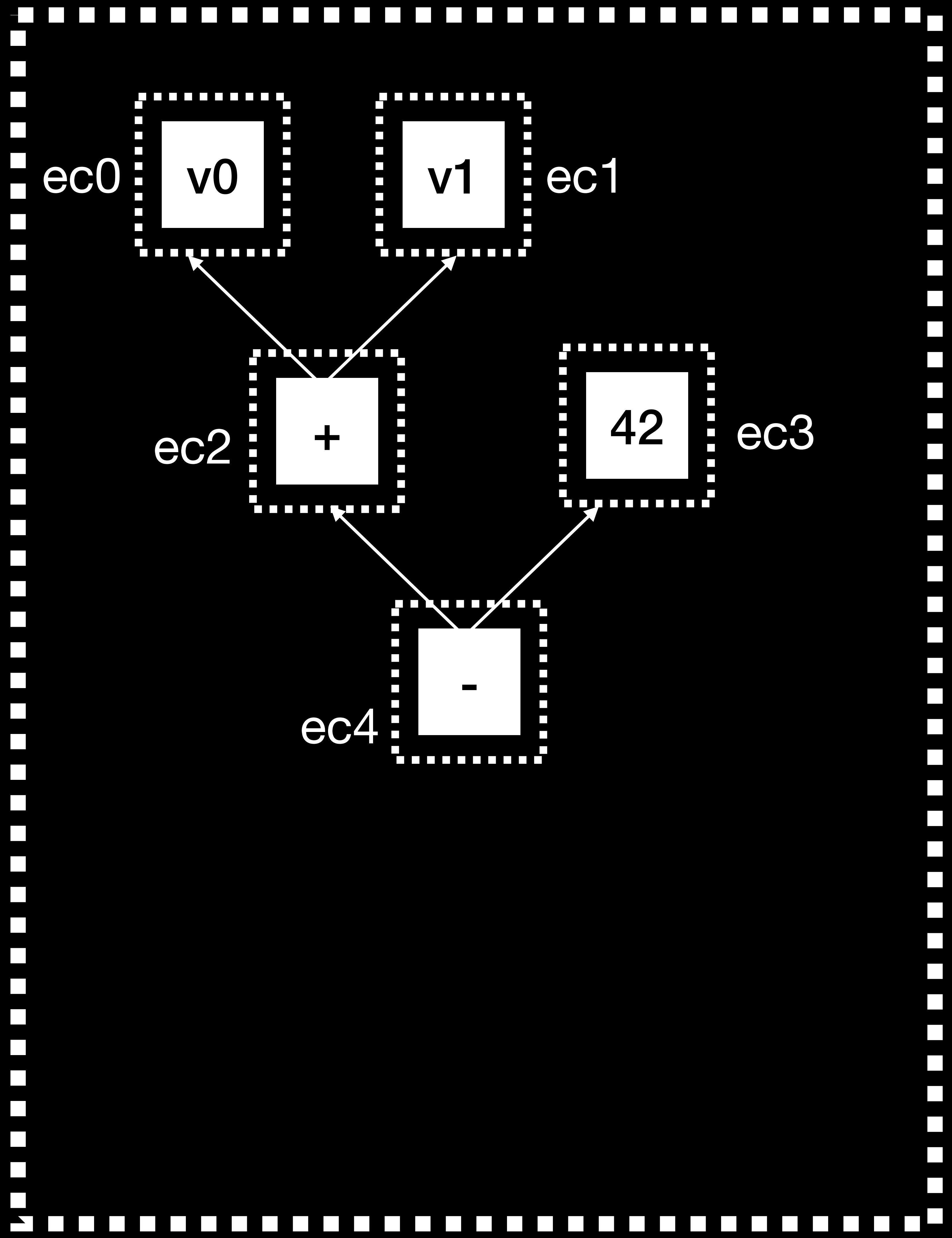
eclass	elaborated
ec0	v0
ec1	v1
ec2	v3
ec4	v2



Elaboration

```
block0(v0, v1):
  v3 = iadd v0, v1
  v2 = isub ec2, ec3
  store ec0, ec4
  return ec2
```

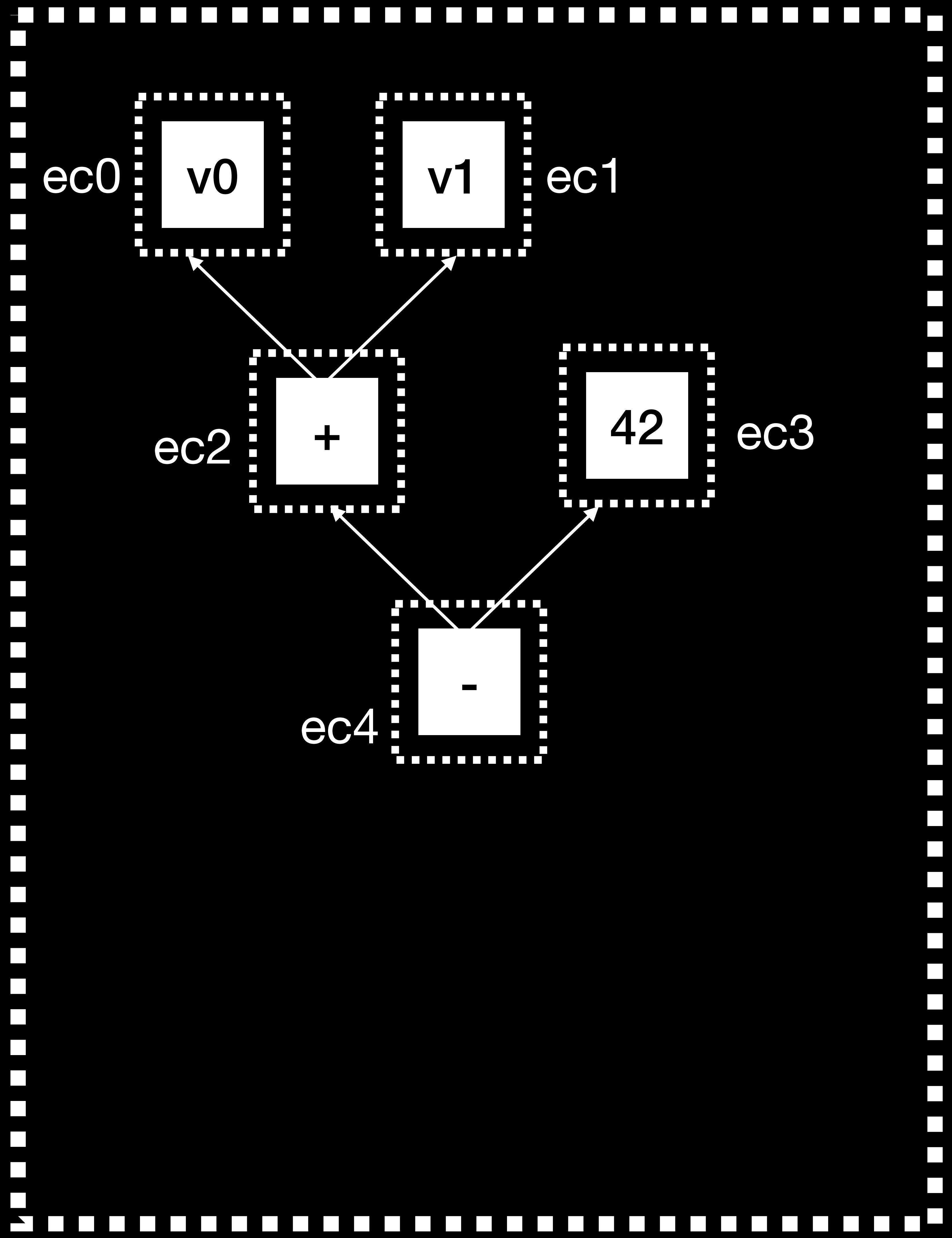
eclass	elaborated
ec0	v0
ec1	v1
ec2	v3
ec4	v2



Elaboration

```
block0(v0, v1):
  v3 = iadd v0, v1
  v4 = iconst 42
  v2 = isub ec2, ec3
  store ec0, ec4
  return ec2
```

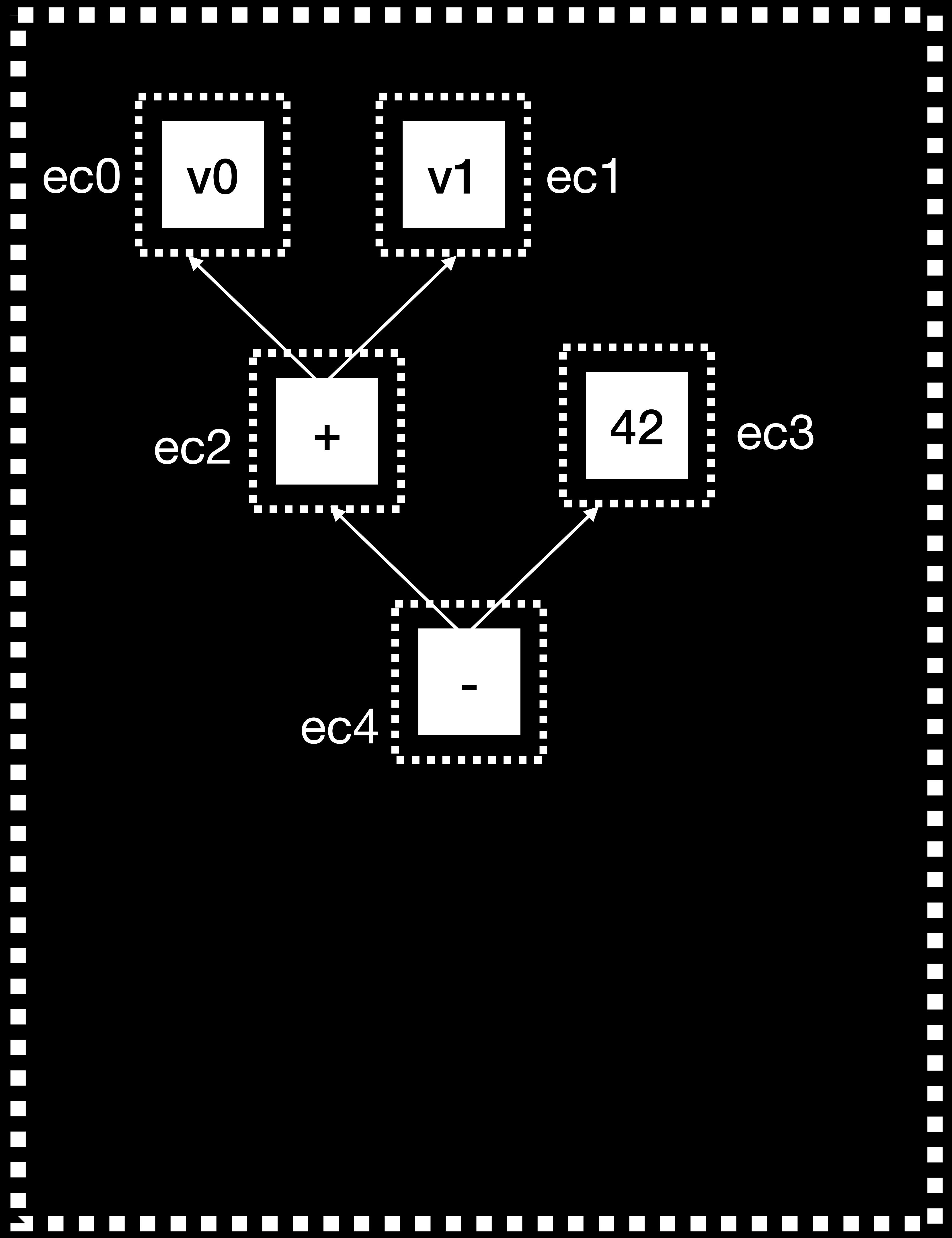
eclass	elaborated
ec0	v0
ec1	v1
ec2	v3
ec3	v4
ec4	v2



Elaboration

```
block0(v0, v1):
  v3 = iadd v0, v1
  v4 = iconst 42
  v2 = isub v3, v4
  store ec0, ec4
  return ec2
```

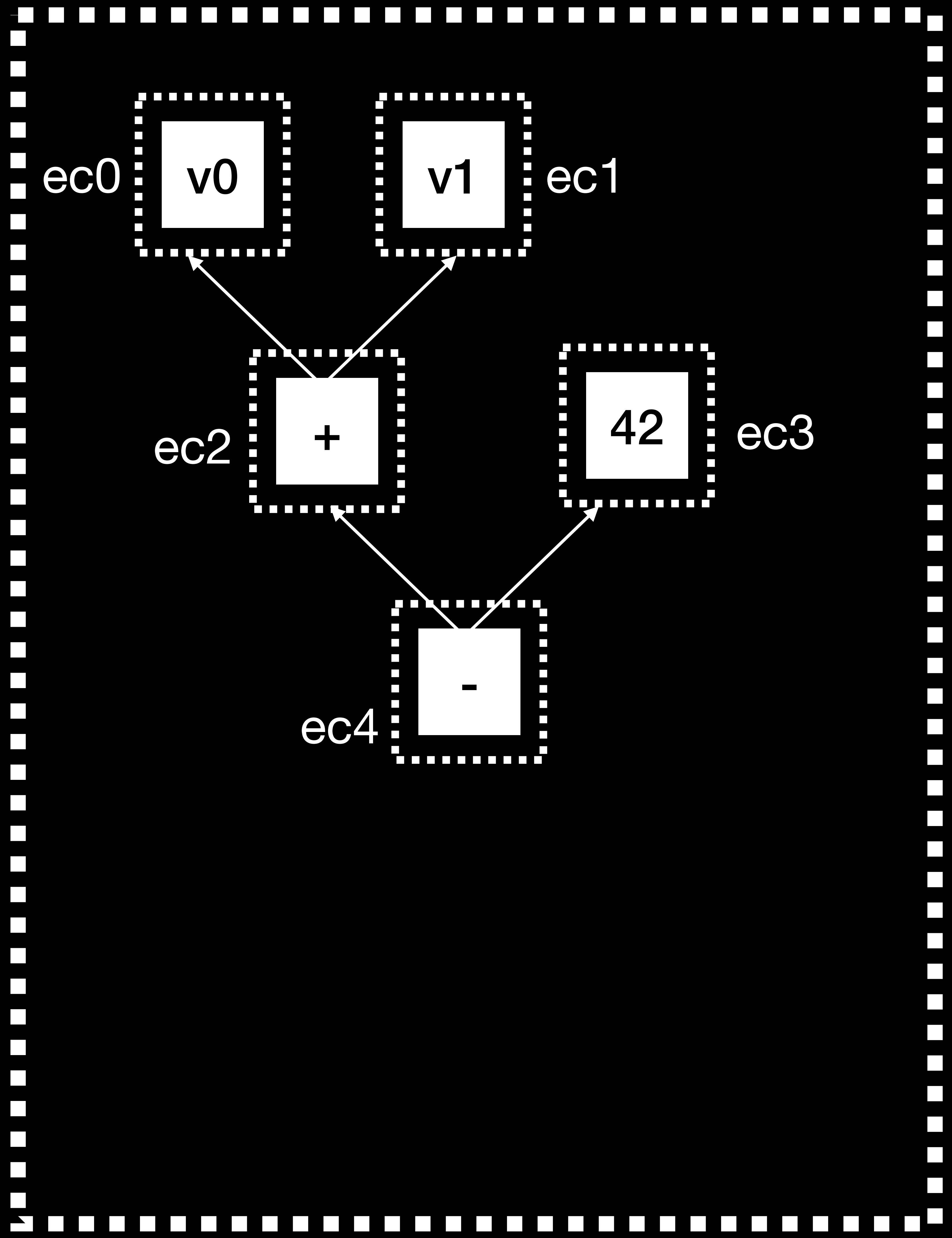
eclass	elaborated
ec0	v0
ec1	v1
ec2	v3
ec3	v4
ec4	v2



Elaboration

```
block0(v0, v1):
  v3 = iadd v0, v1
  v4 = iconst 42
  v2 = isub v3, v4
  store v0, v2
  return ec2
```

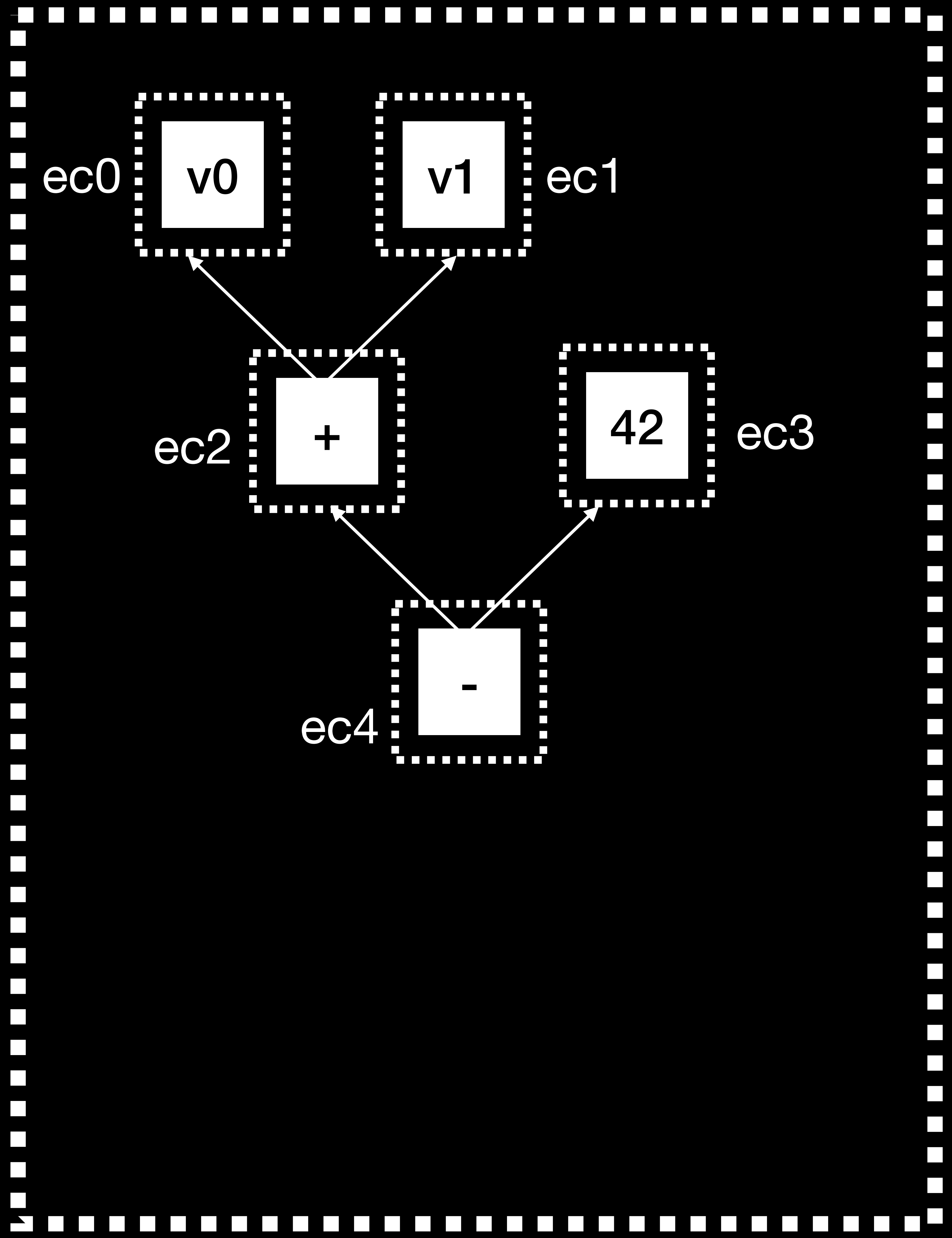
eclass	elaborated
ec0	v0
ec1	v1
ec2	v3
ec3	v4
ec4	v2



Elaboration

```
block0(v0, v1):
  v3 = iadd v0, v1
  v4 = iconst 42
  v2 = isub v3, v4
  store v0, v2
  return ec2
```

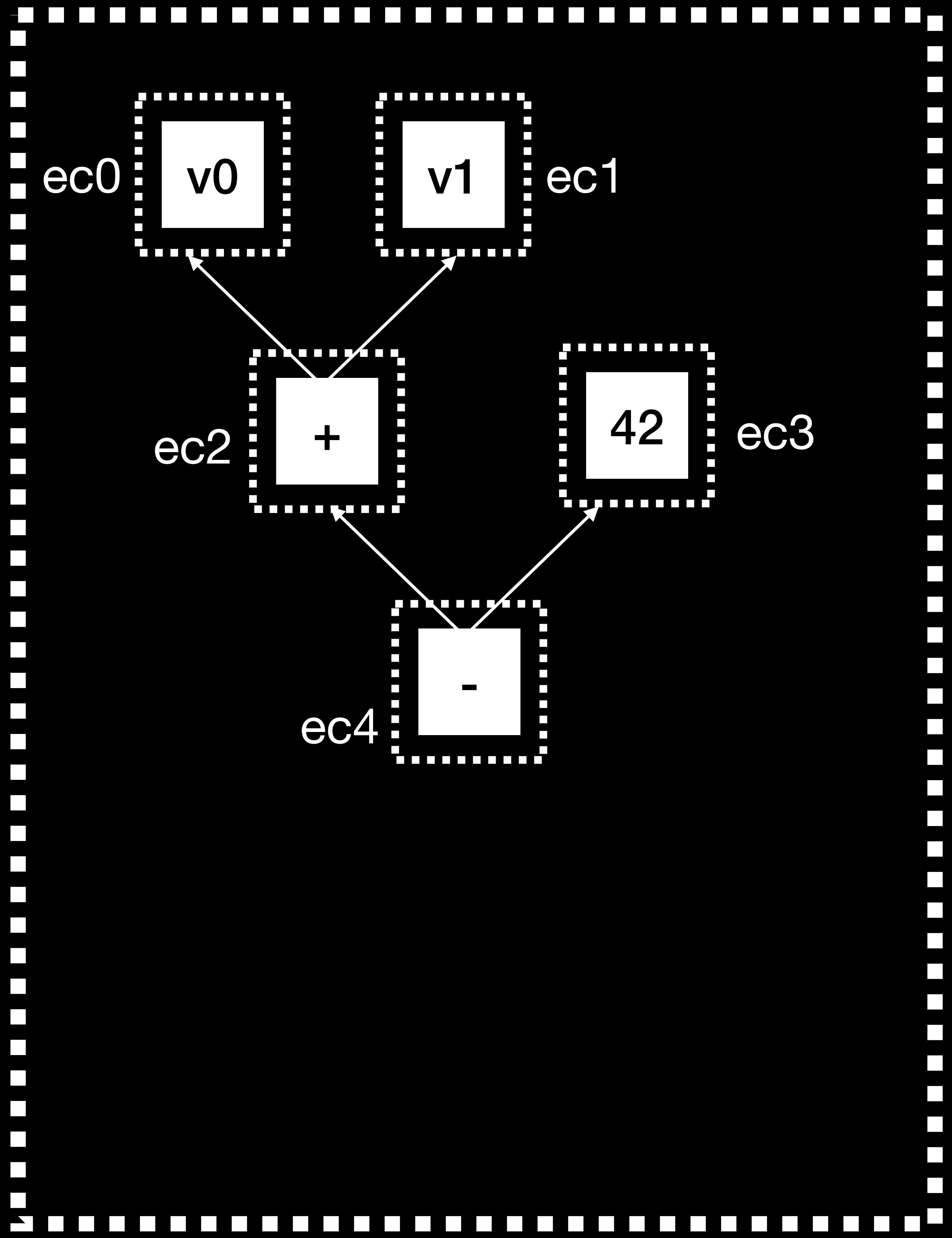
eclass	elaborated
ec0	v0
ec1	v1
ec2	v3
ec3	v4
ec4	v2



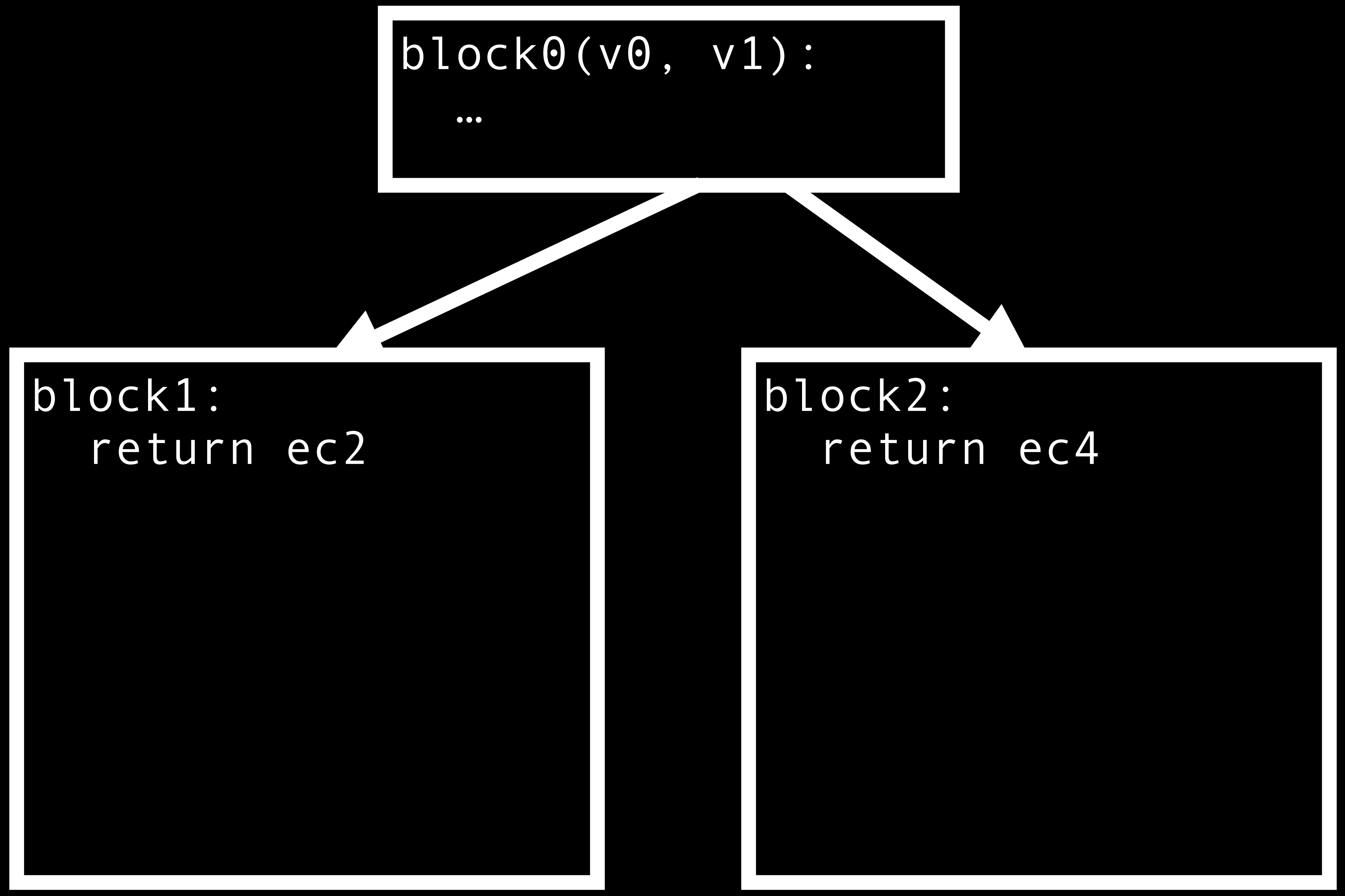
Elaboration

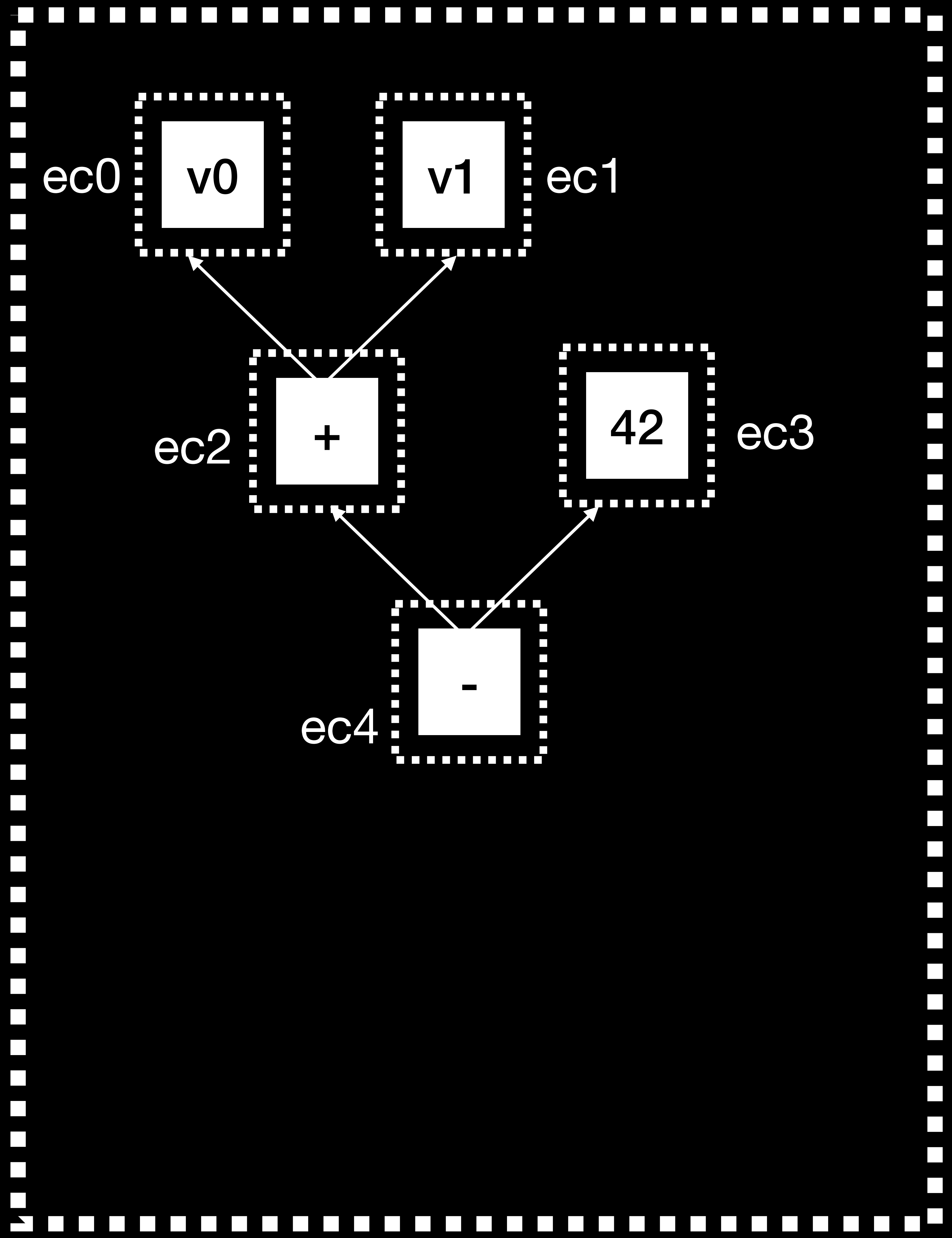
```
block0(v0, v1):
  v3 = iadd v0, v1
  v4 = iconst 42
  v2 = isub v3, v4
  store v0, v2
  return v3
```

eclass	elaborated
ec0	v0
ec1	v1
ec2	v3
ec3	v4
ec4	v2

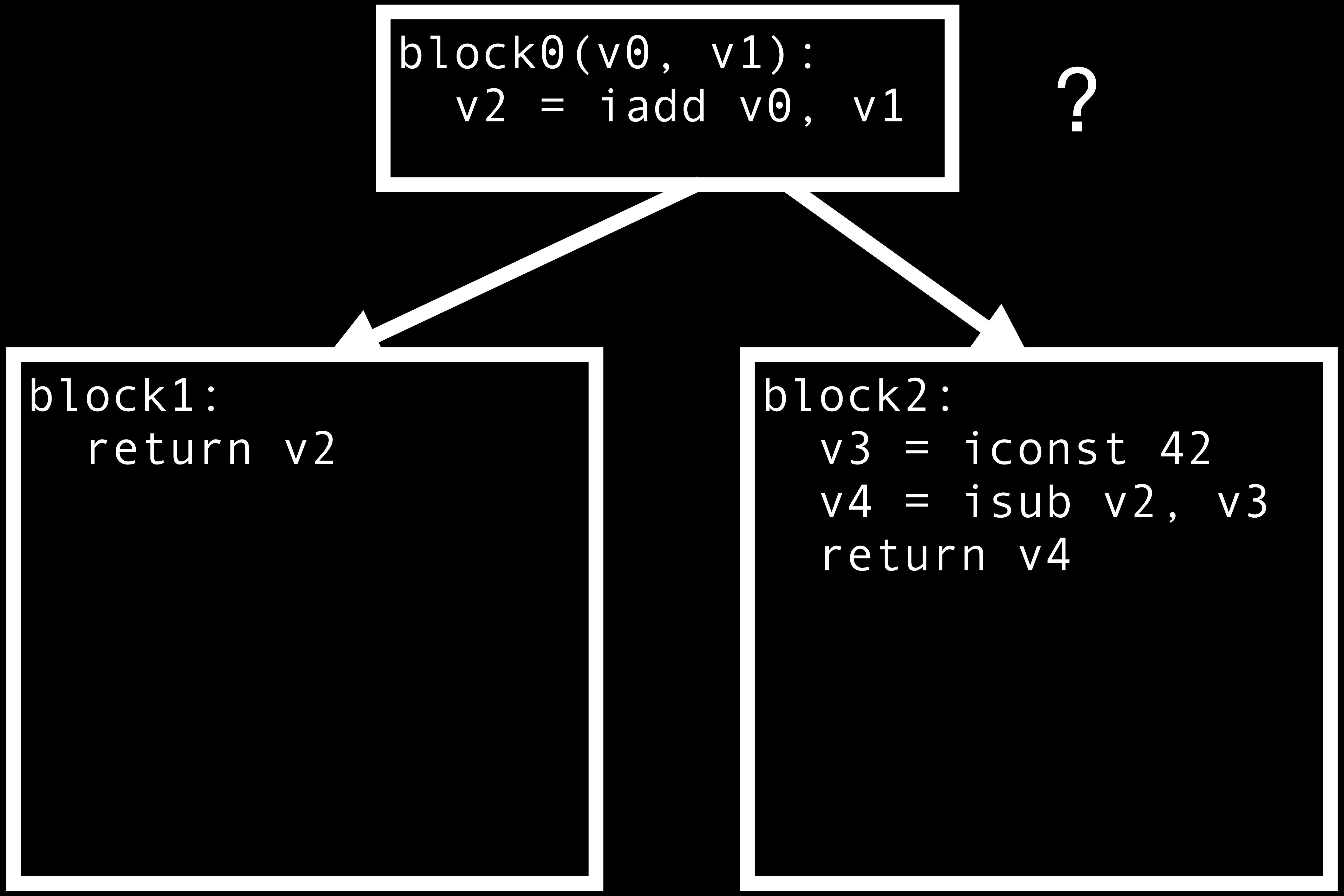


Elaboration… twice?

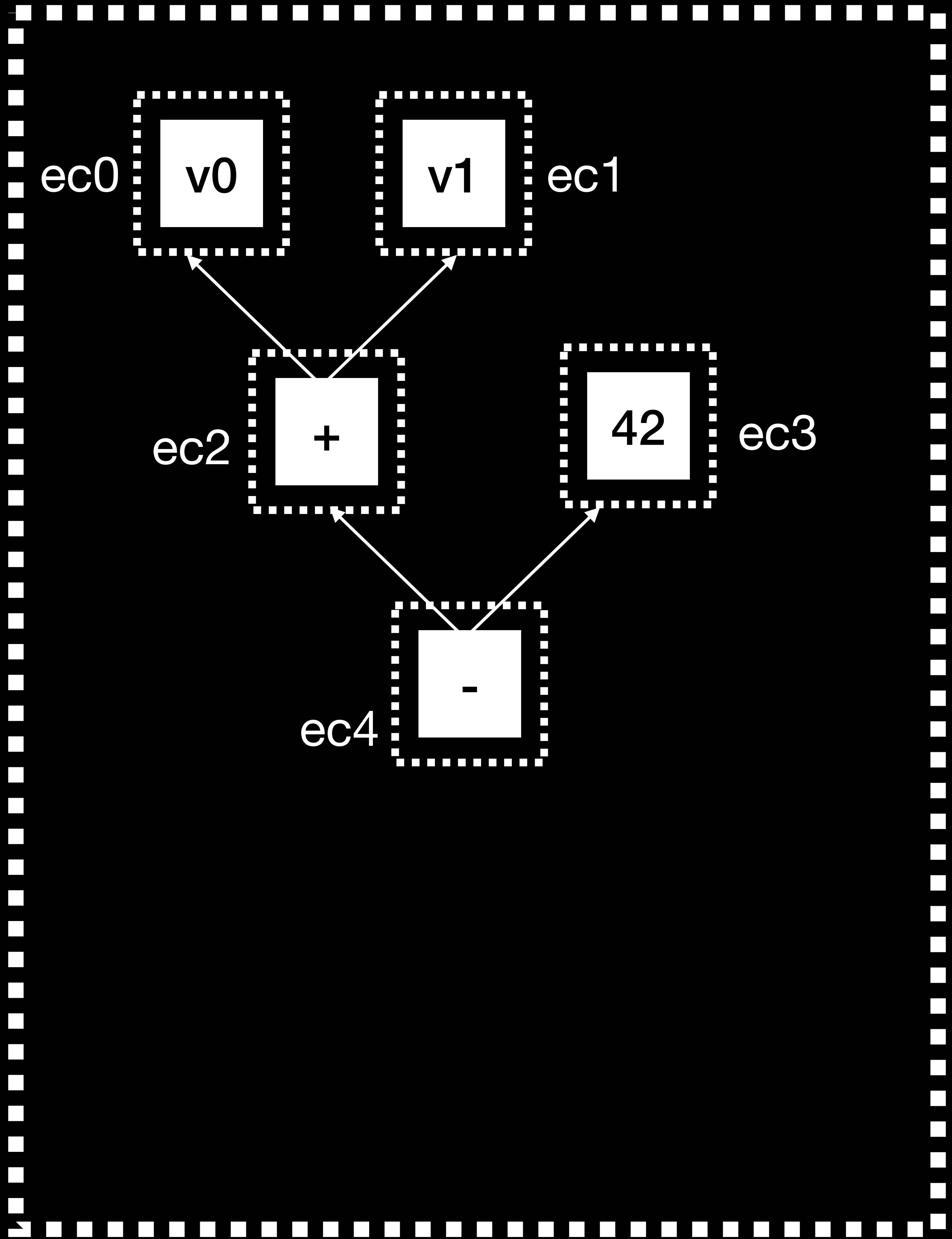




Elaboration… twice?



?



Elaboration… twice?

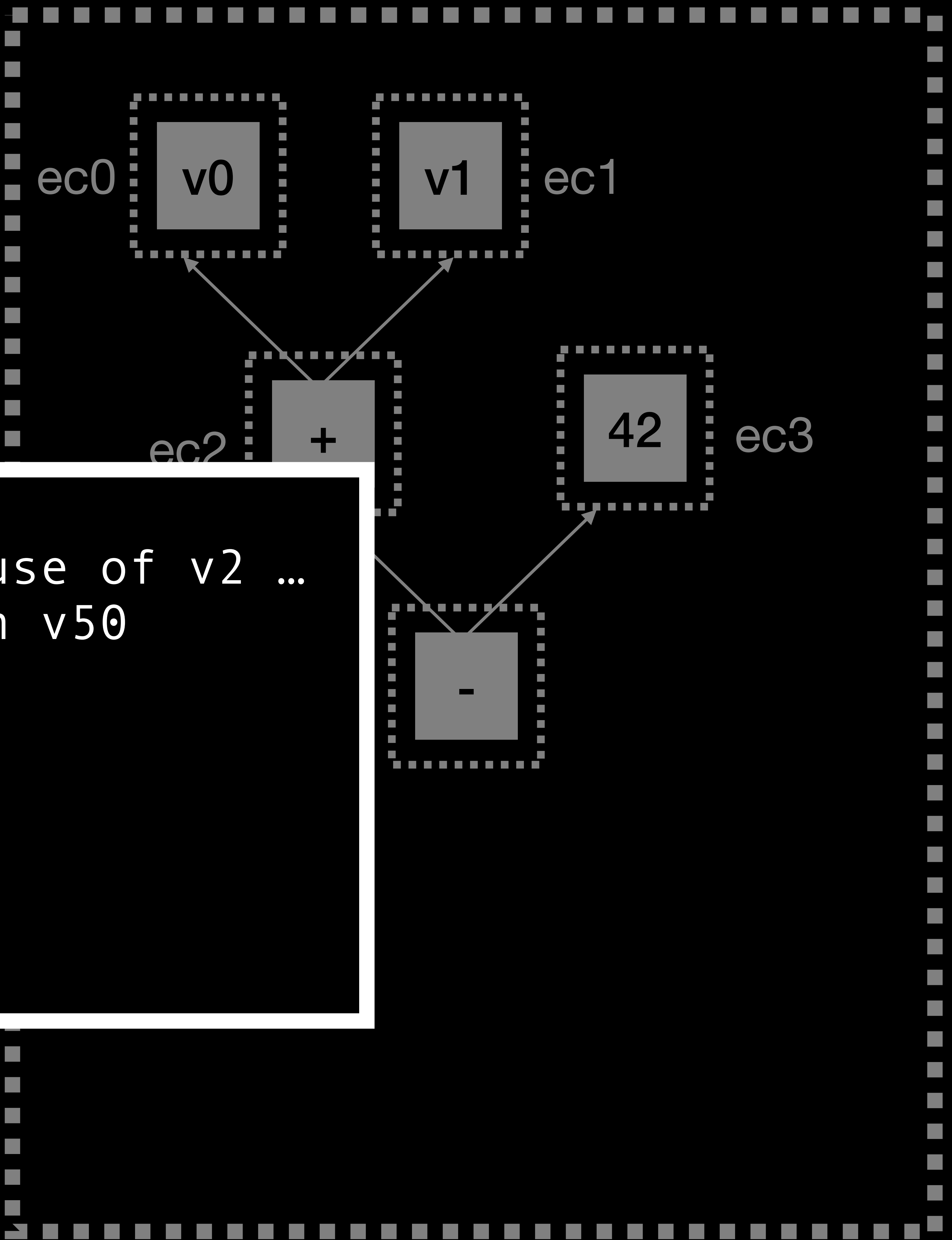
```
block0(v0, v1):
  v2 = iadd v0, v1
```

partial redundancy!

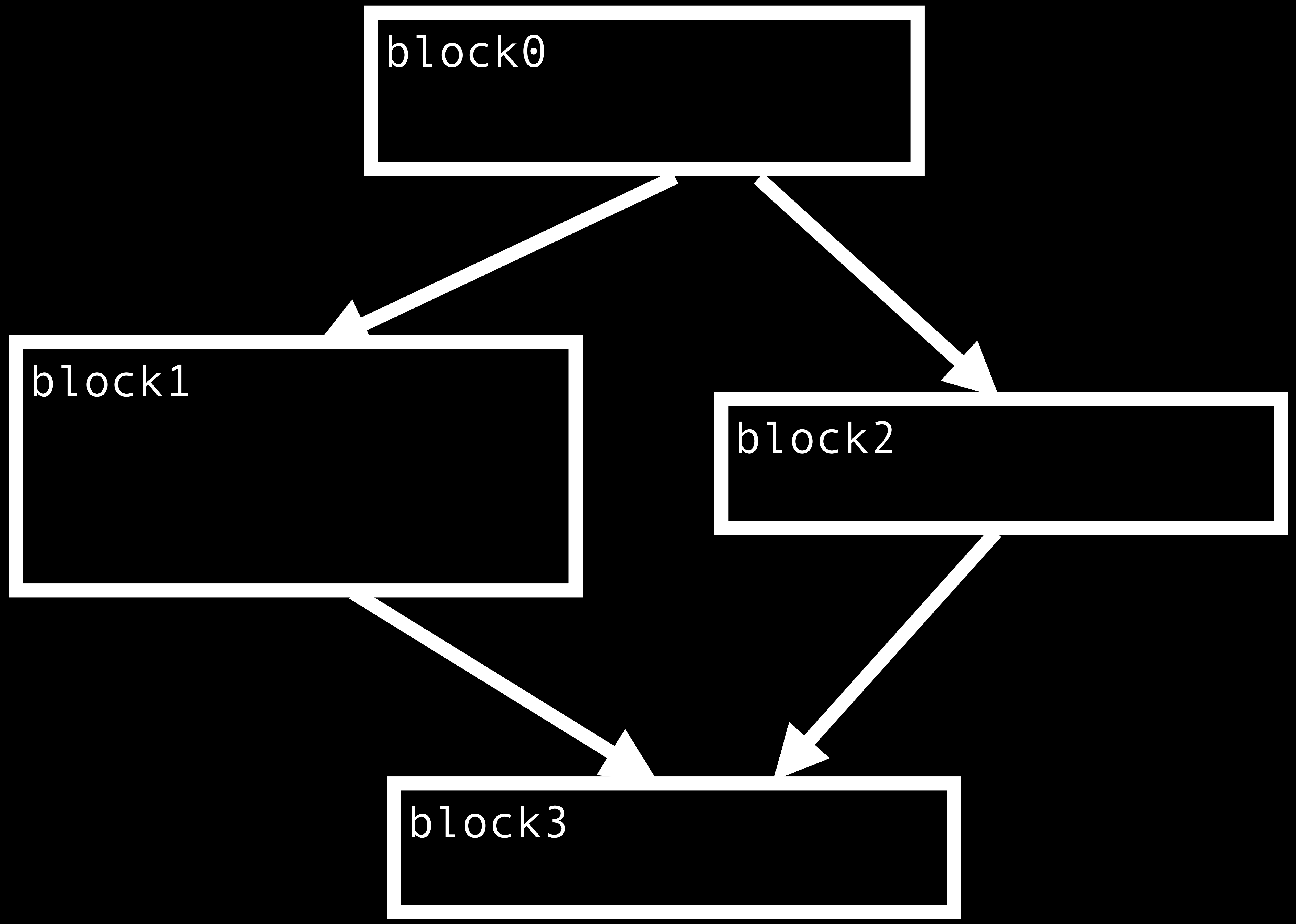
```
block1:
  return v2
```

```
block2:
  v3 = iconst 42
  v4 = isub v2, v3
  return v4
```

```
block2:
  … no use of v2 …
  return v50
```

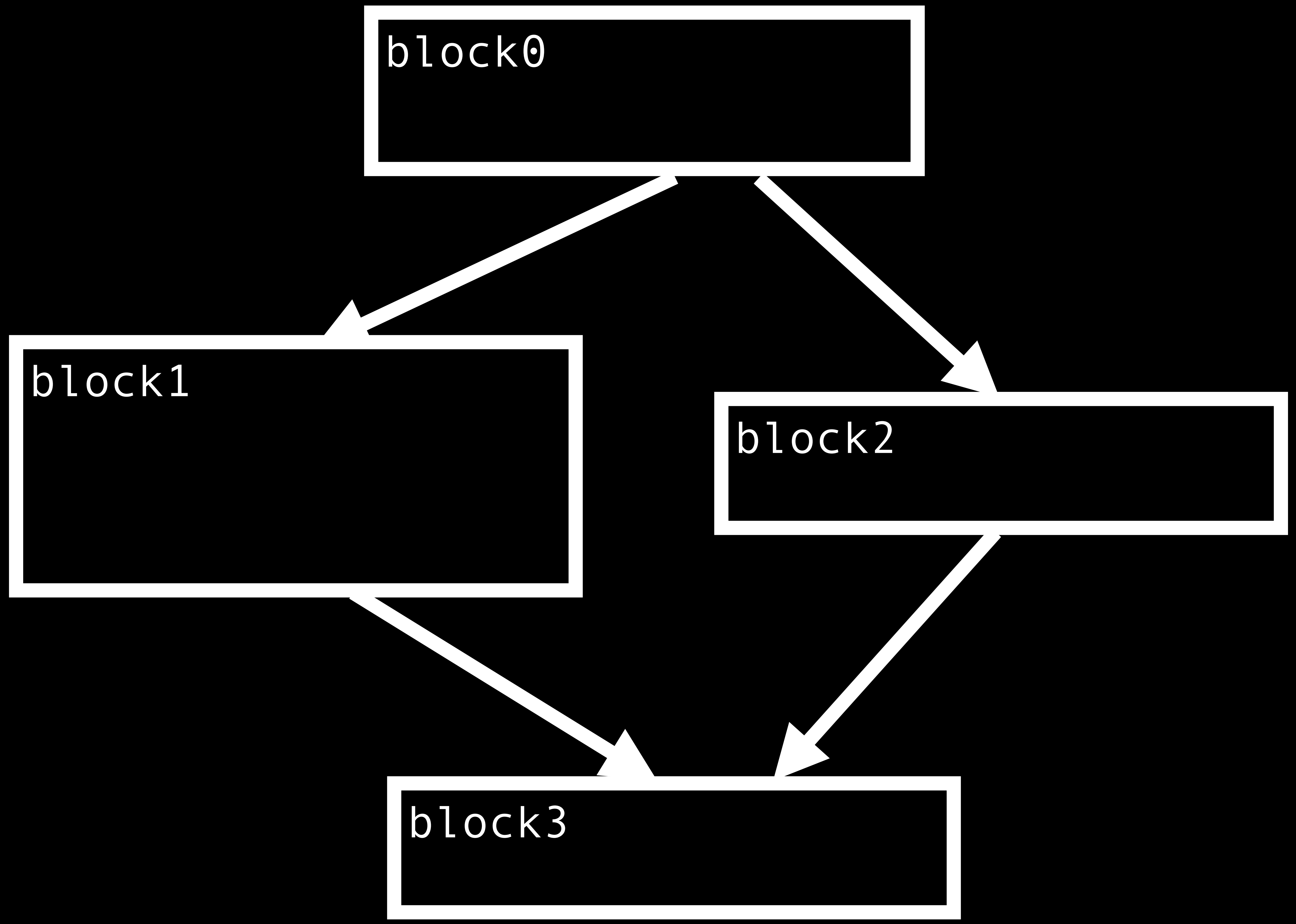


SSA

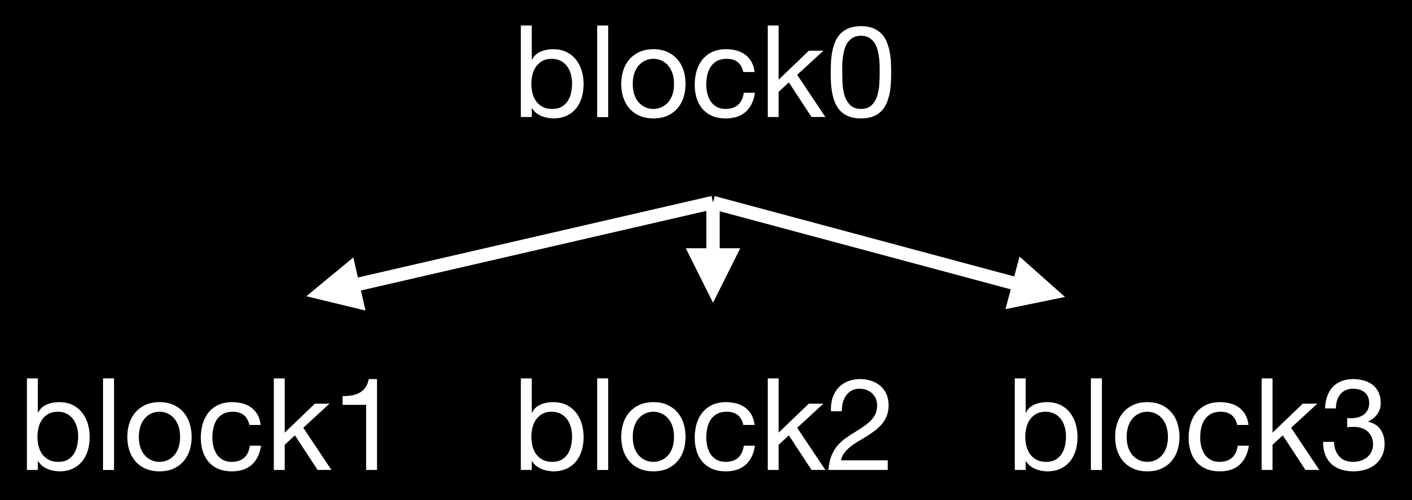


CFG

SSA

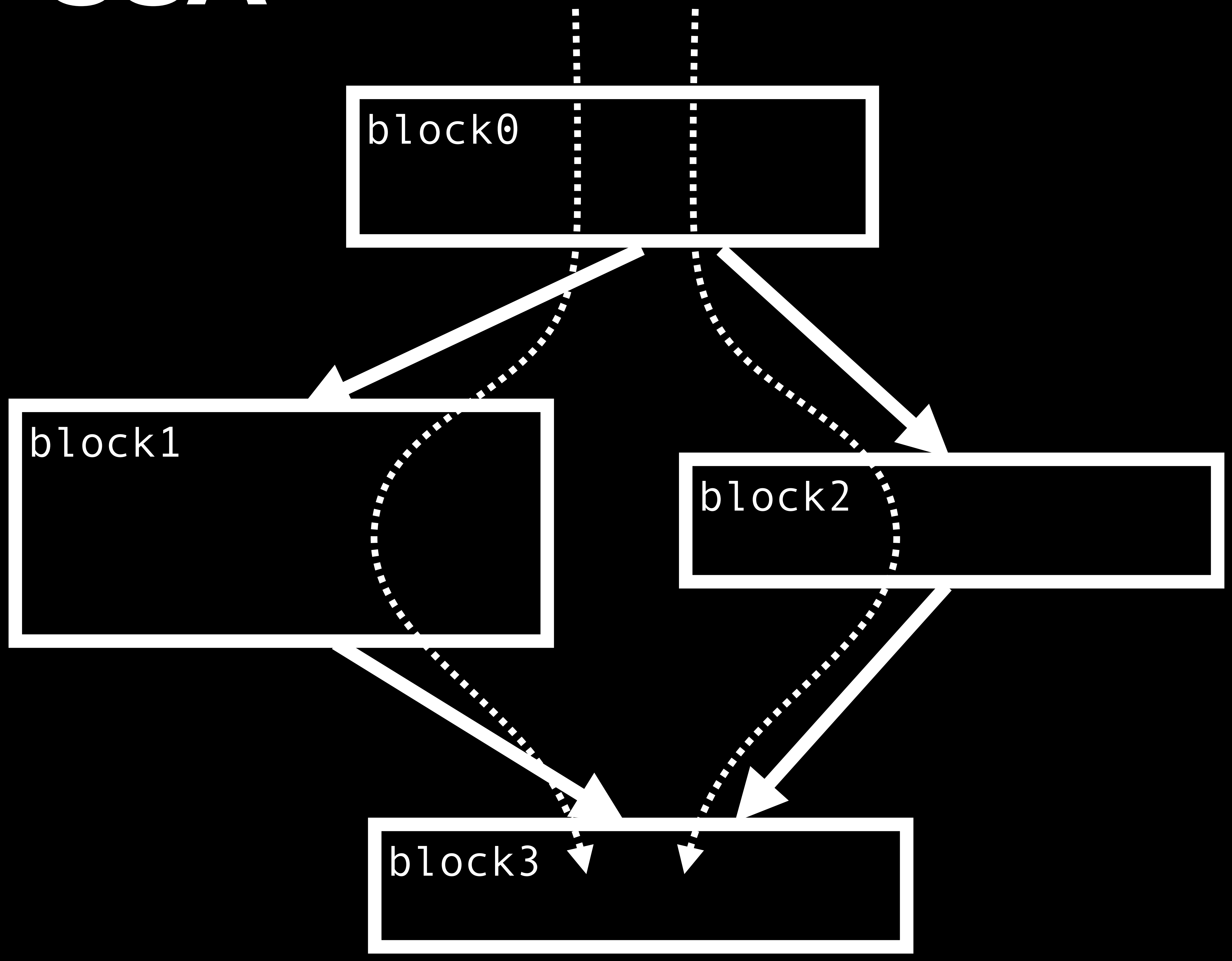


CFG

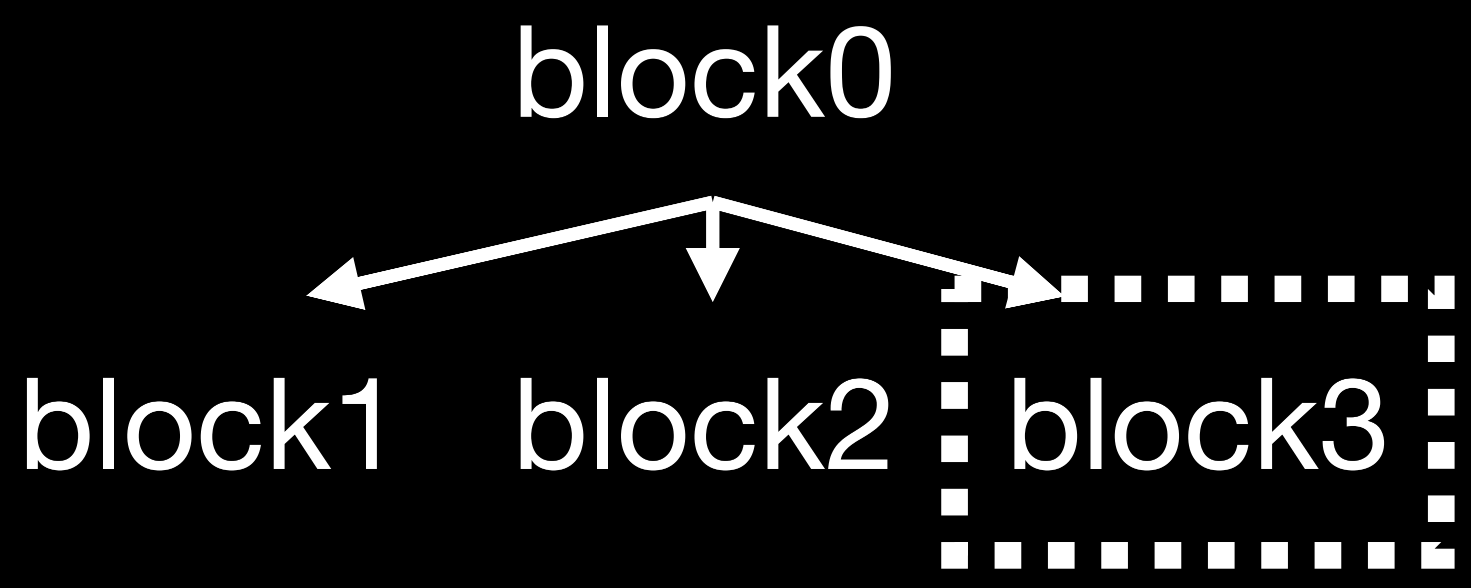


Dominator Tree

SSA



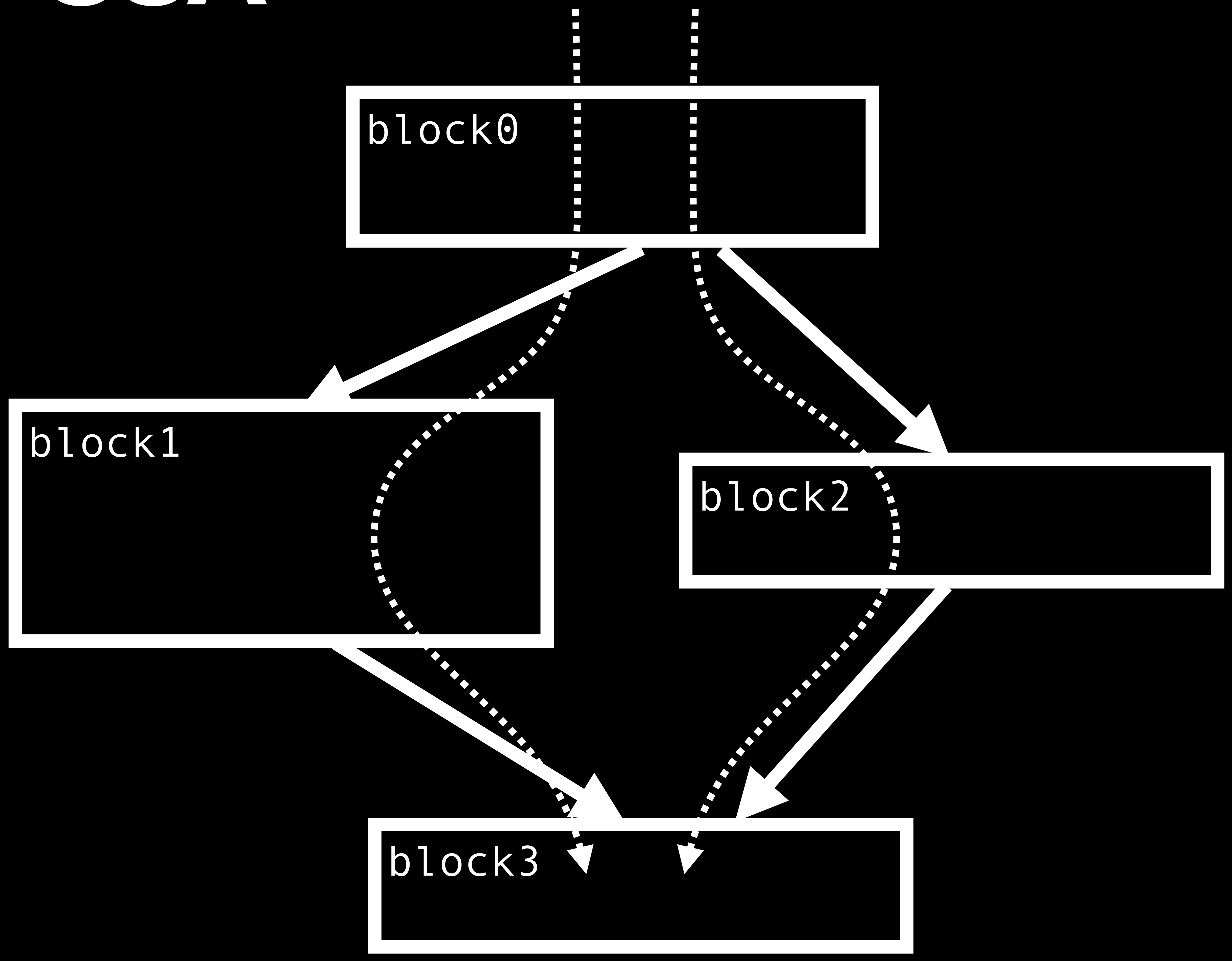
CFG



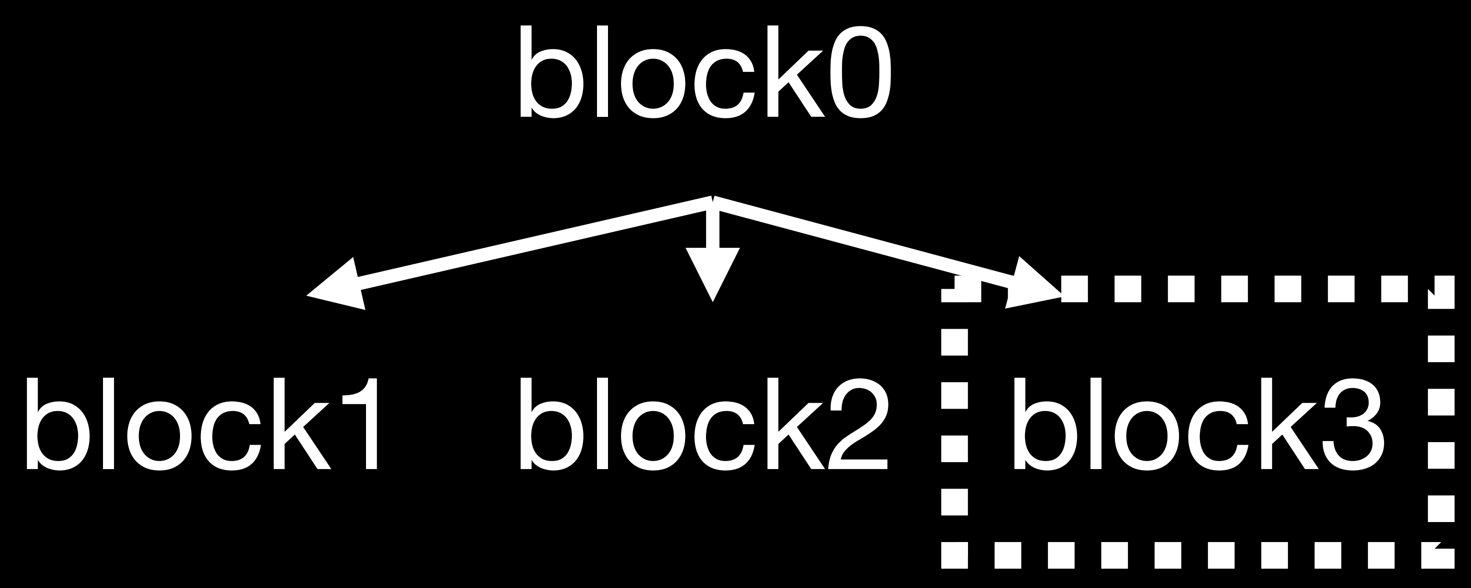
A dominates B if
all paths to B first pass through A.

Dominator Tree

SSA



CFG

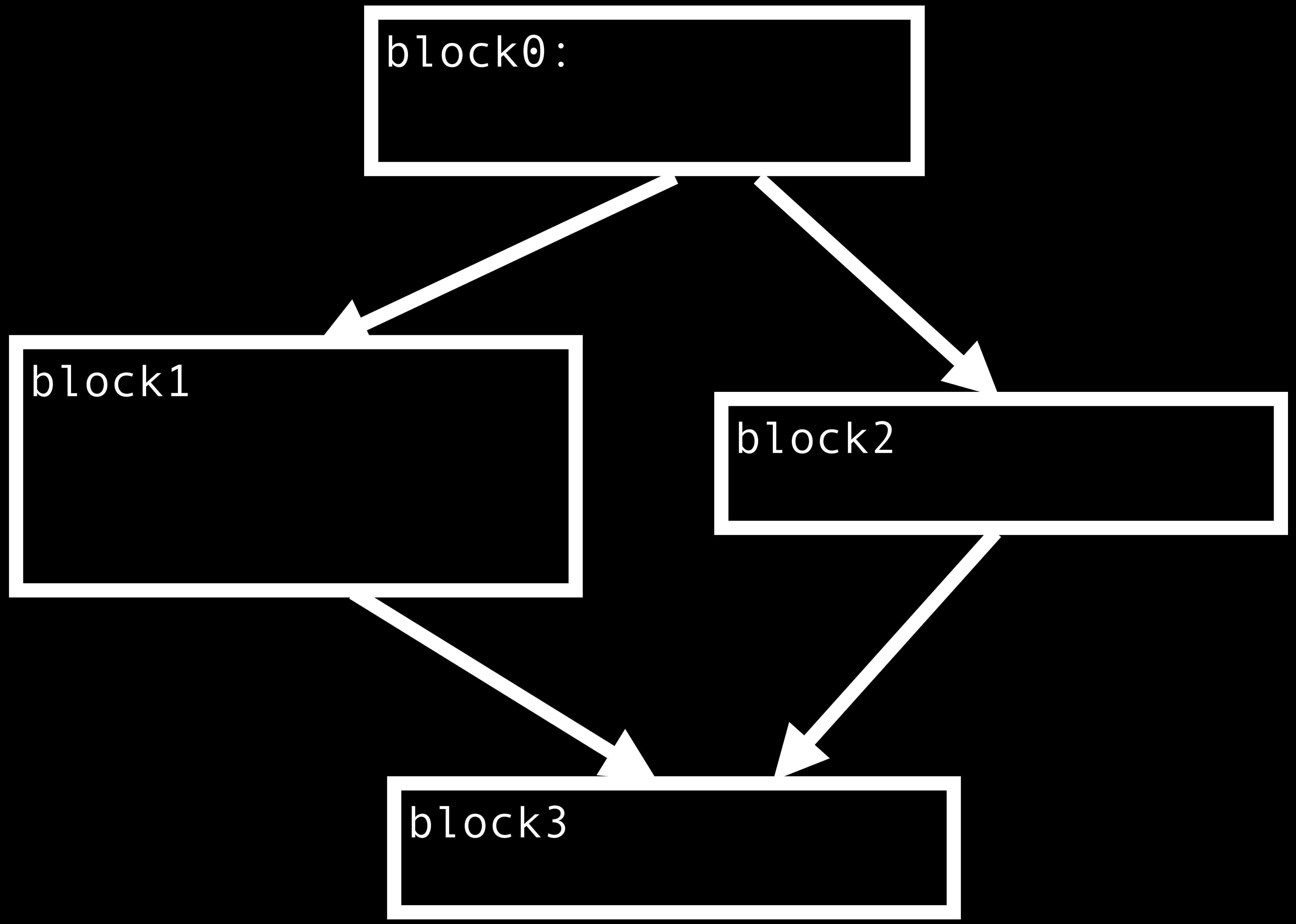


A dominates B if
all paths to B first pass through A.

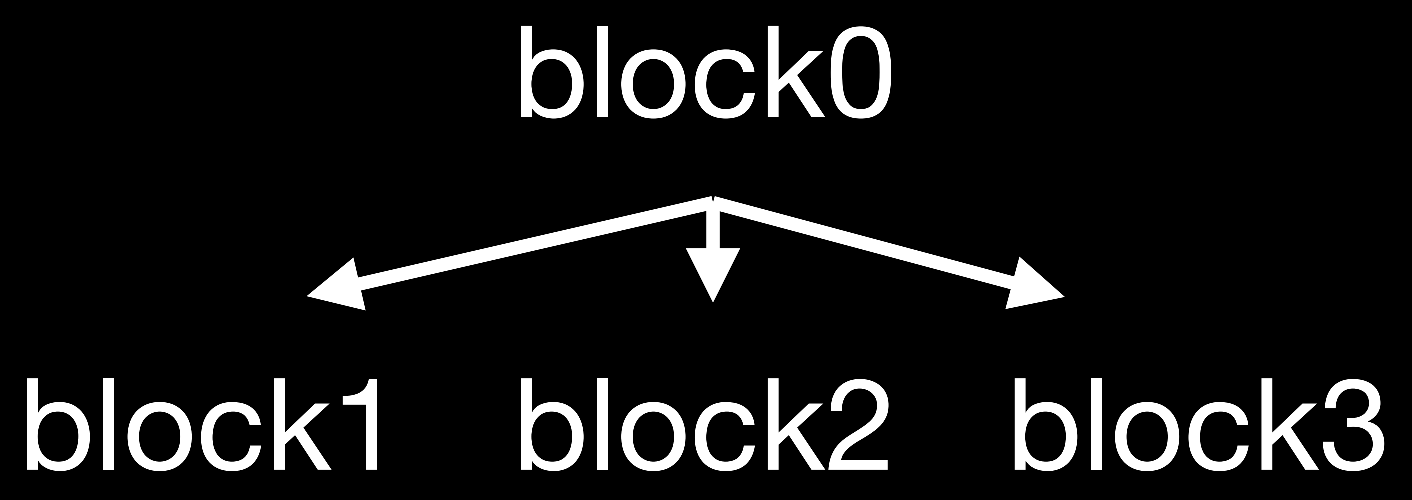
Dominance forms a *tree*.
Many compiler algorithms work
by traversing the domtree.

Dominator Tree

SSA

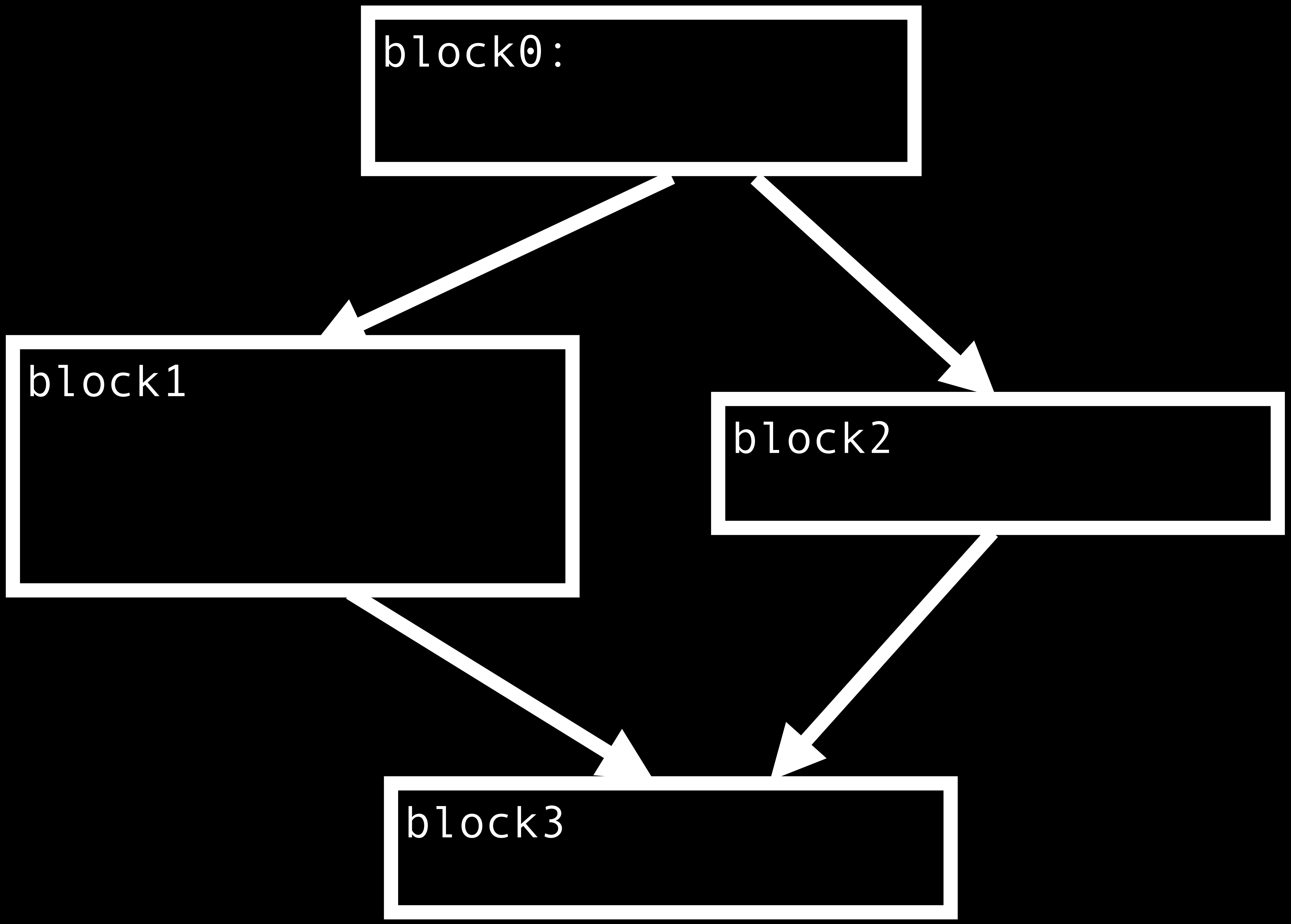


CFG

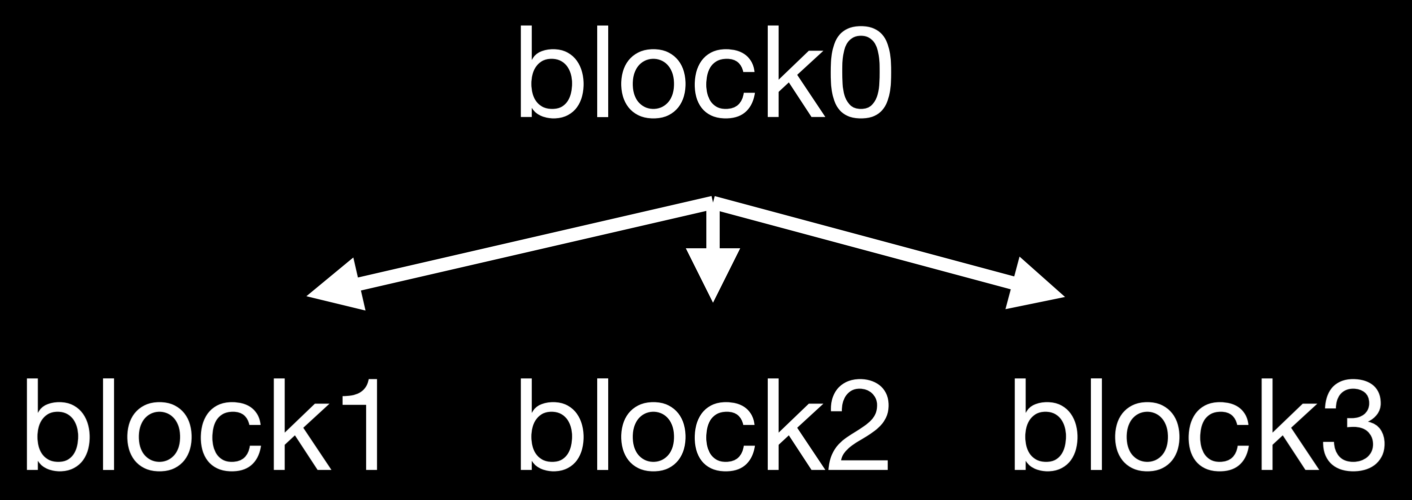


Dominator Tree

SSA



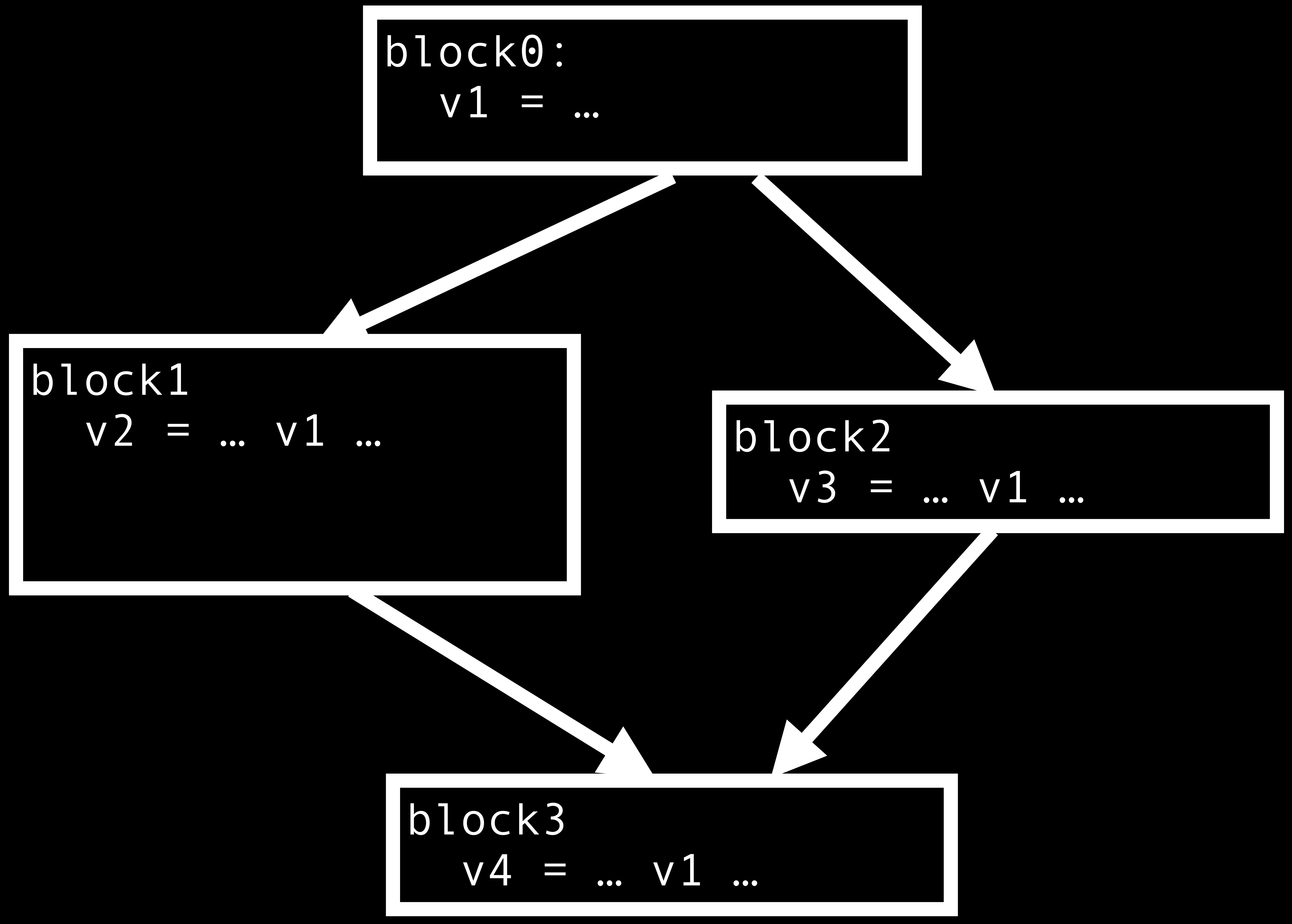
CFG



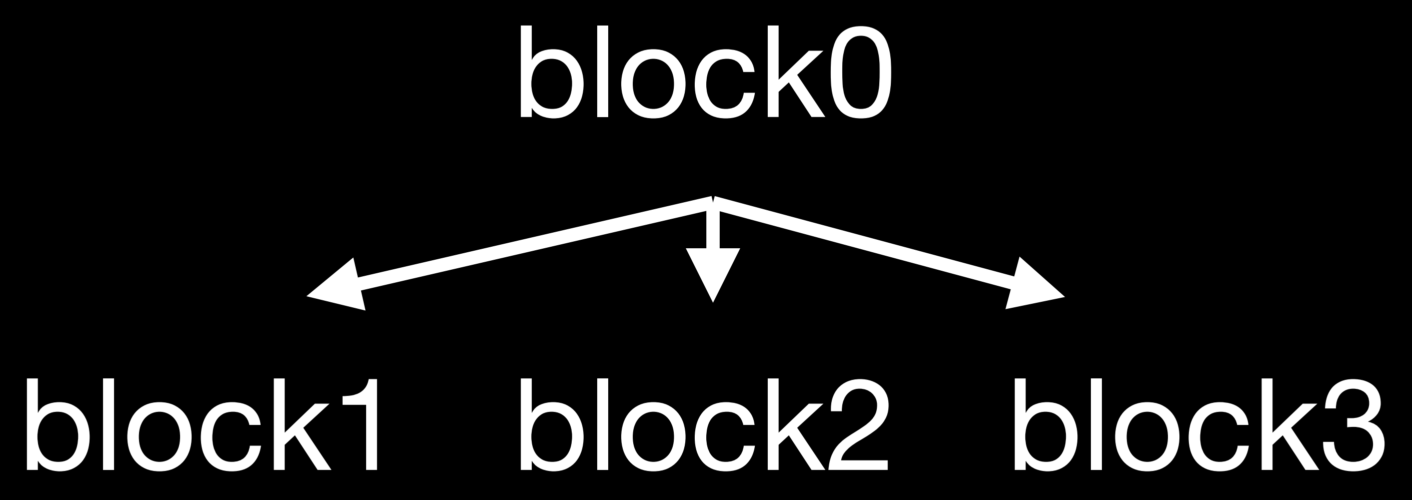
SSA: A value's definition dominates its uses.

Dominator Tree

SSA



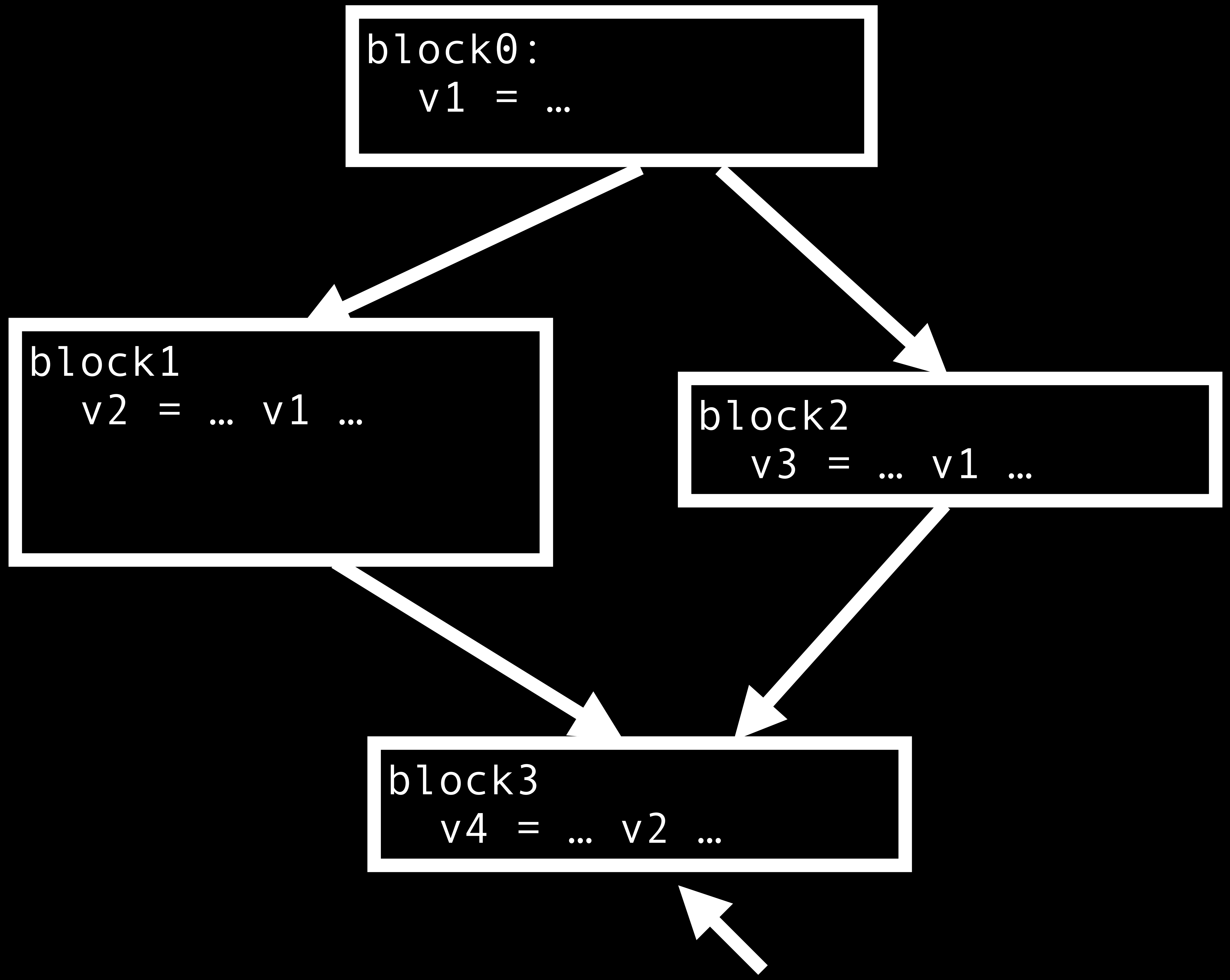
CFG



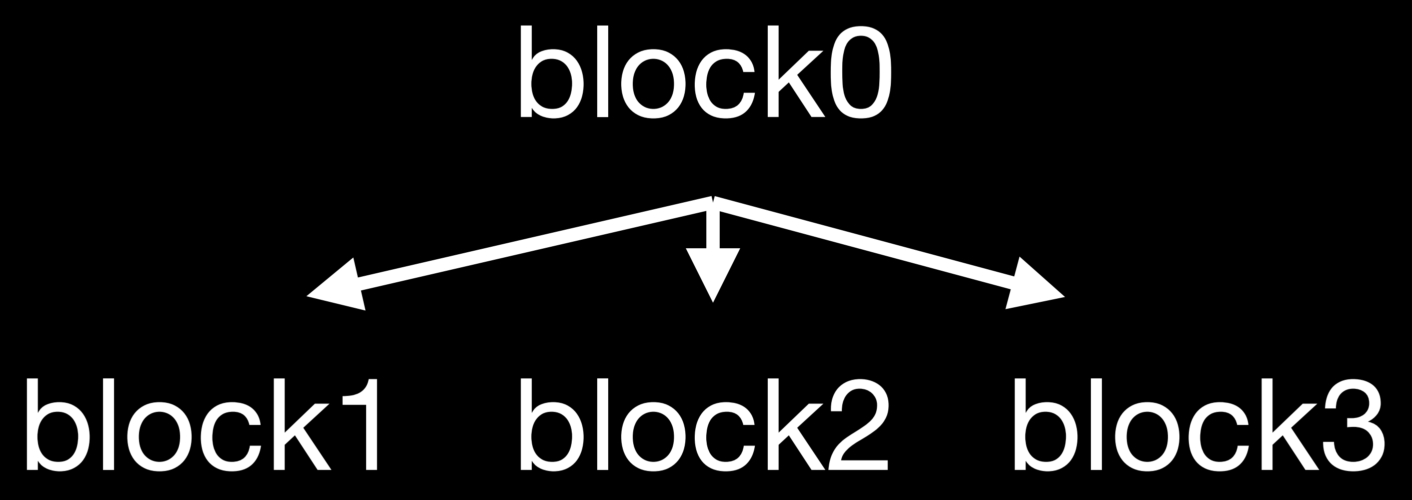
SSA: A value's definition dominates its uses.

Dominator Tree

SSA



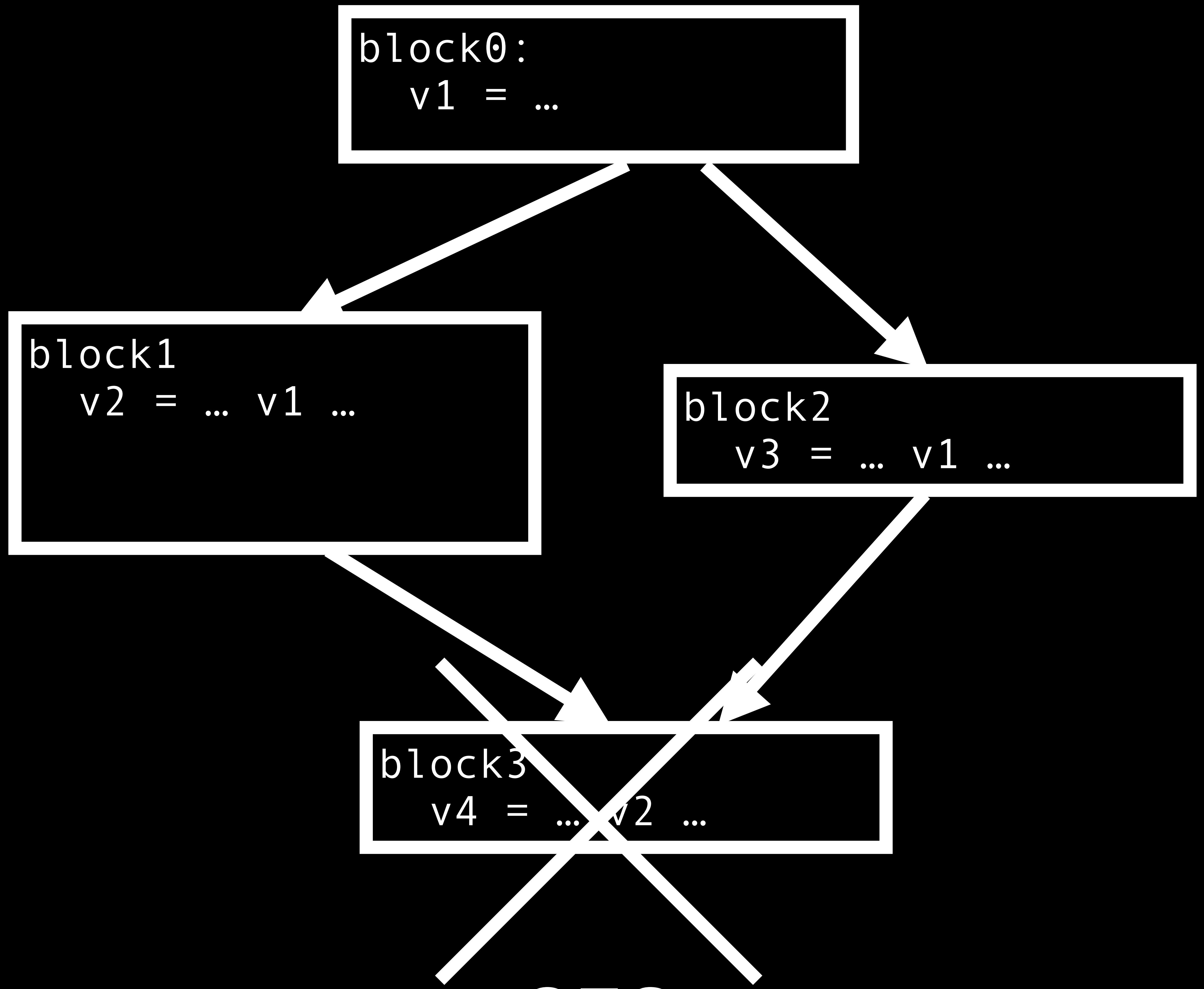
CFG



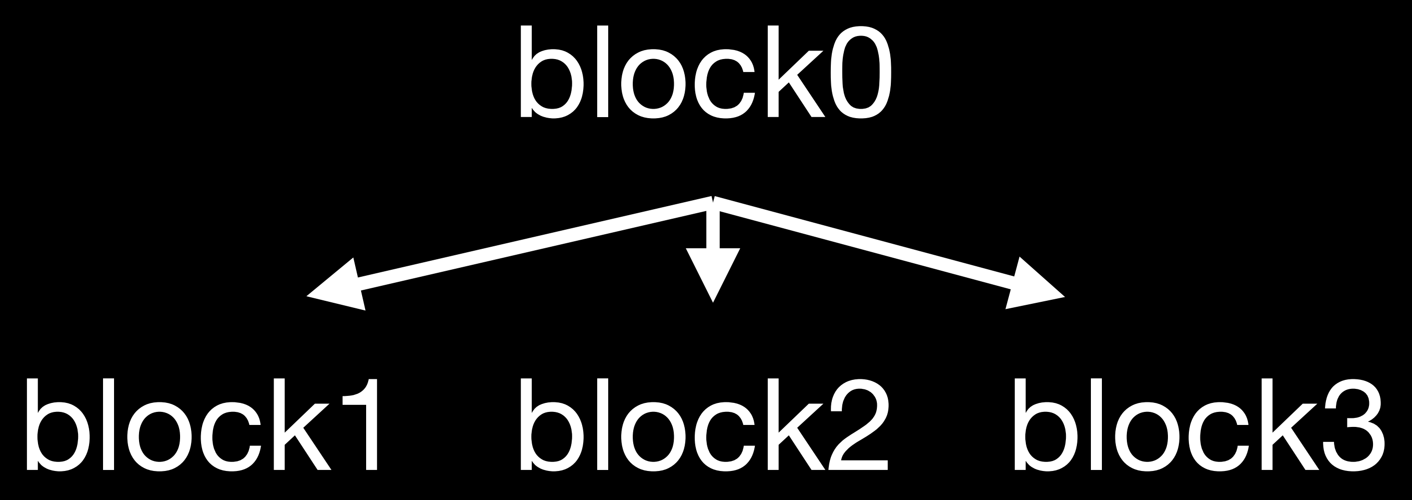
SSA: A value’s definition dominates its uses.

Dominator Tree

SSA



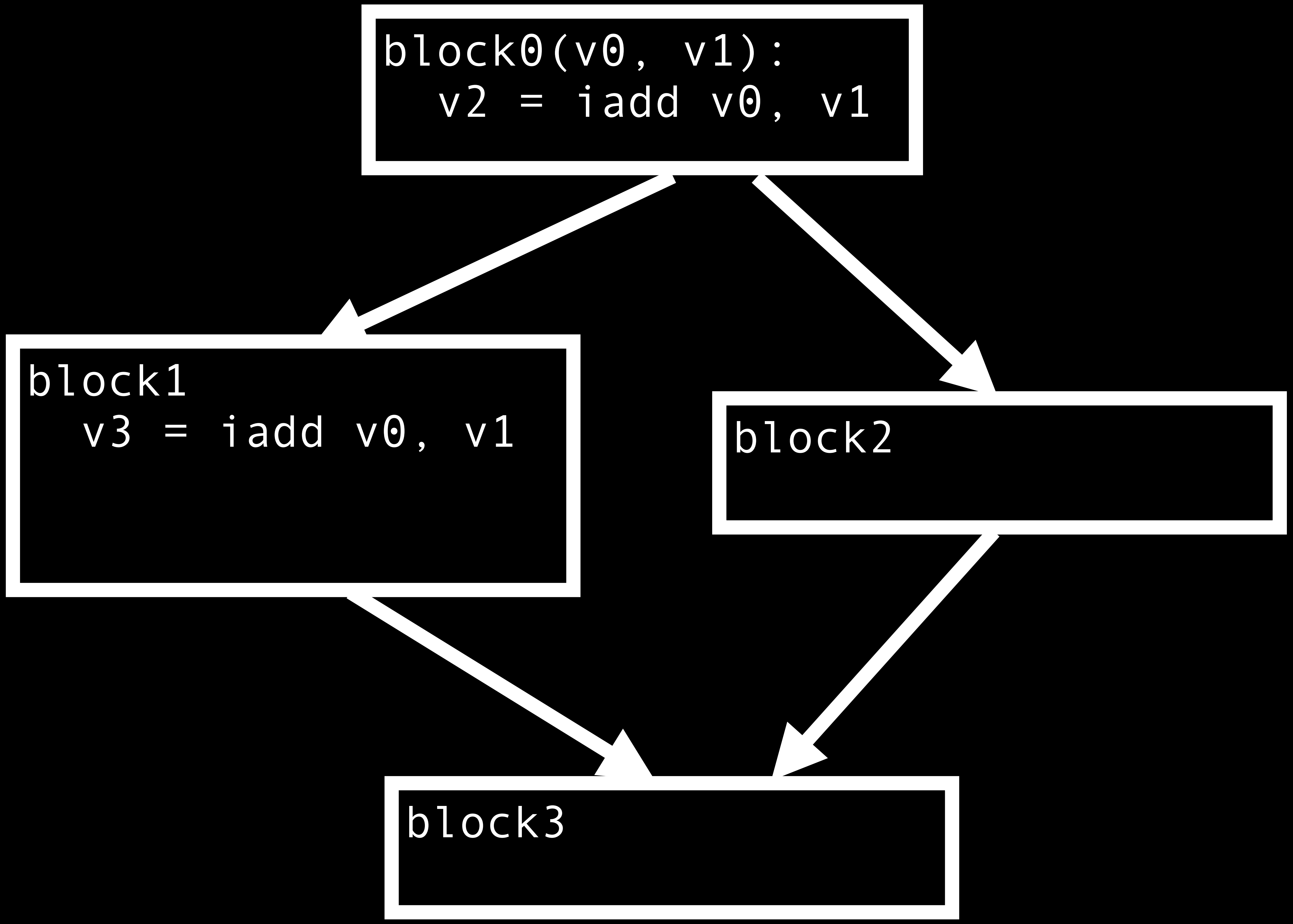
CFG



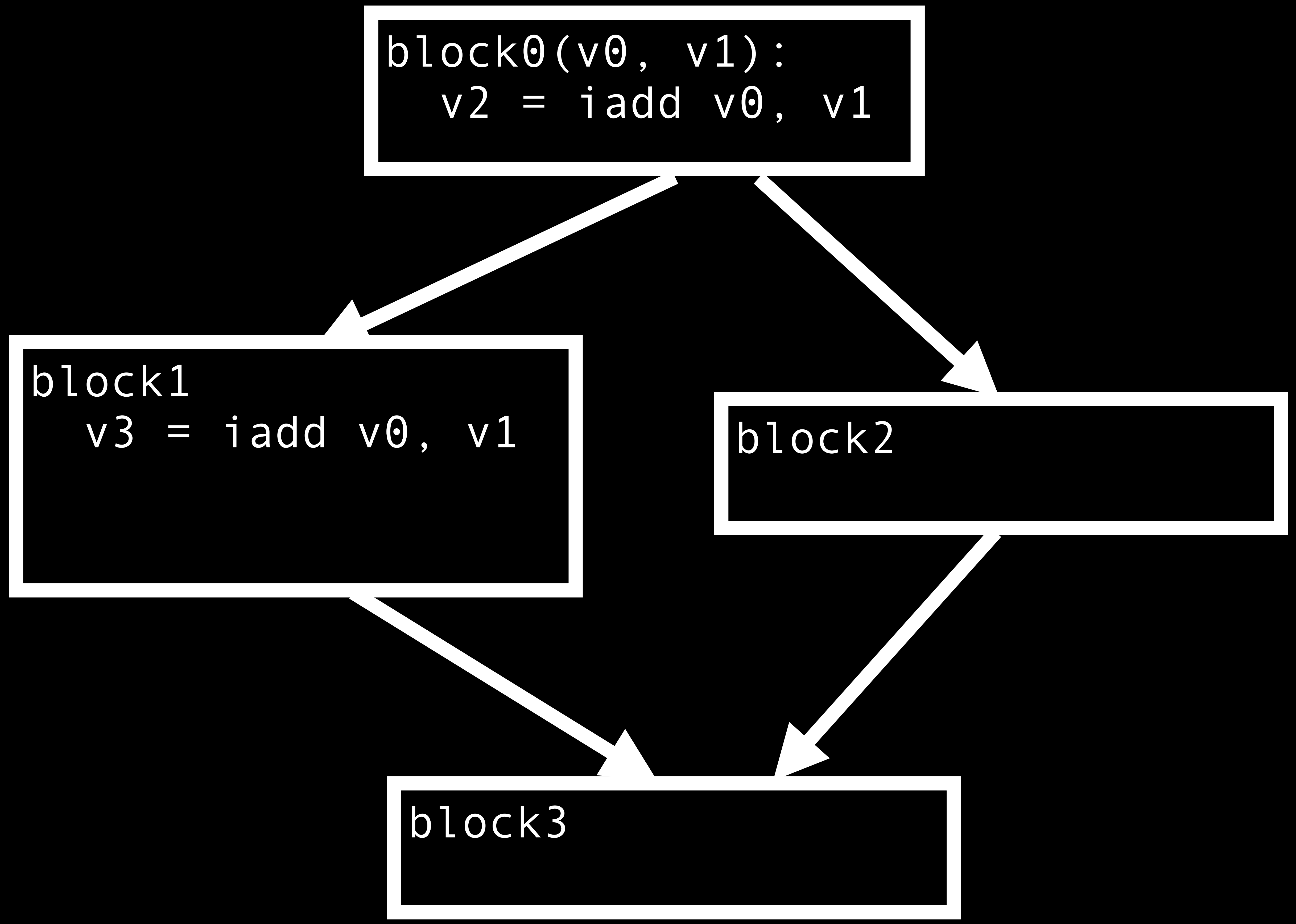
SSA: A value's definition dominates its uses.

Dominator Tree

GVN

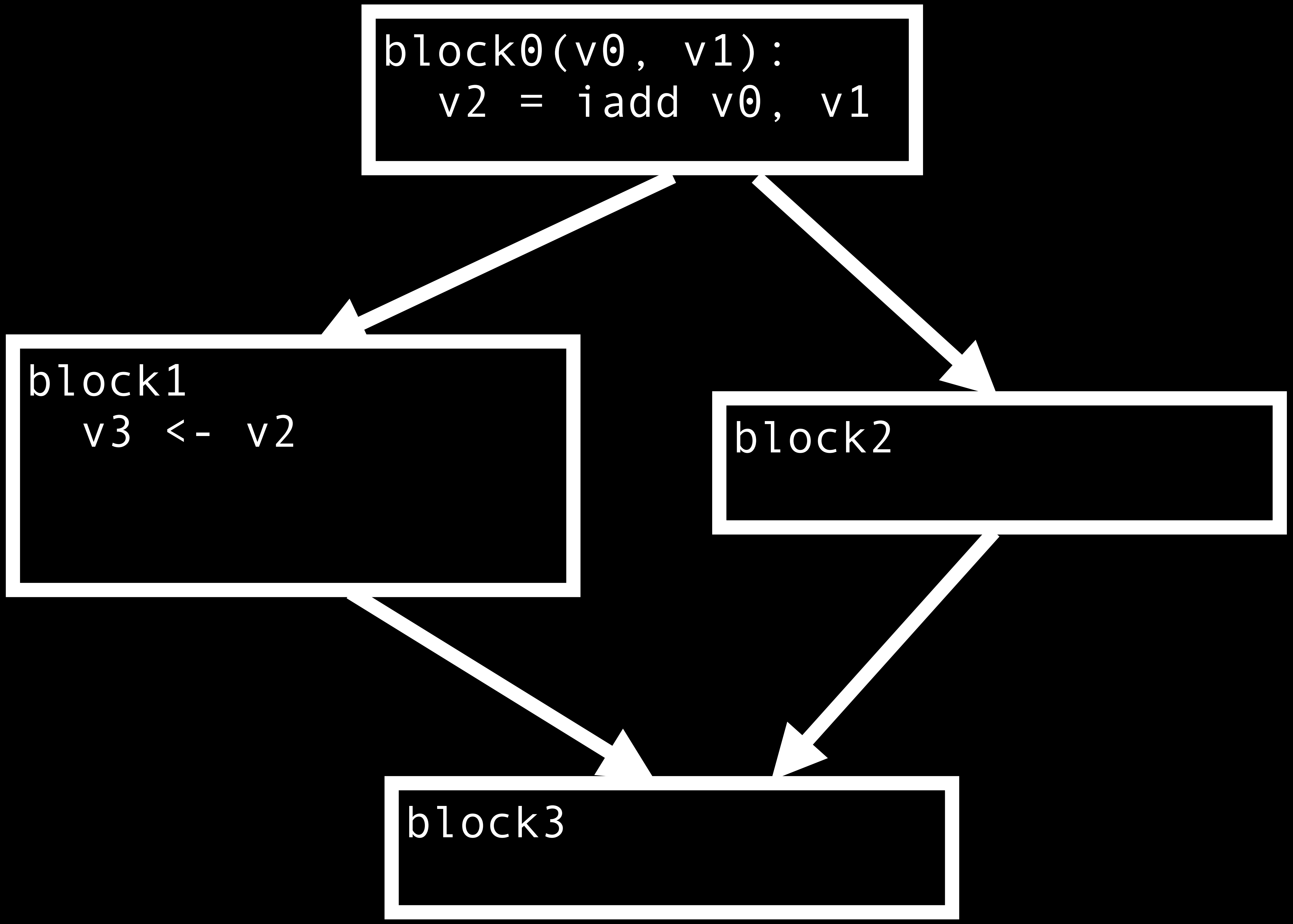


GVN



GVN (Global Value Numbering):
If an operator dominates a duplicate copy of itself, reuse the original.

GVN



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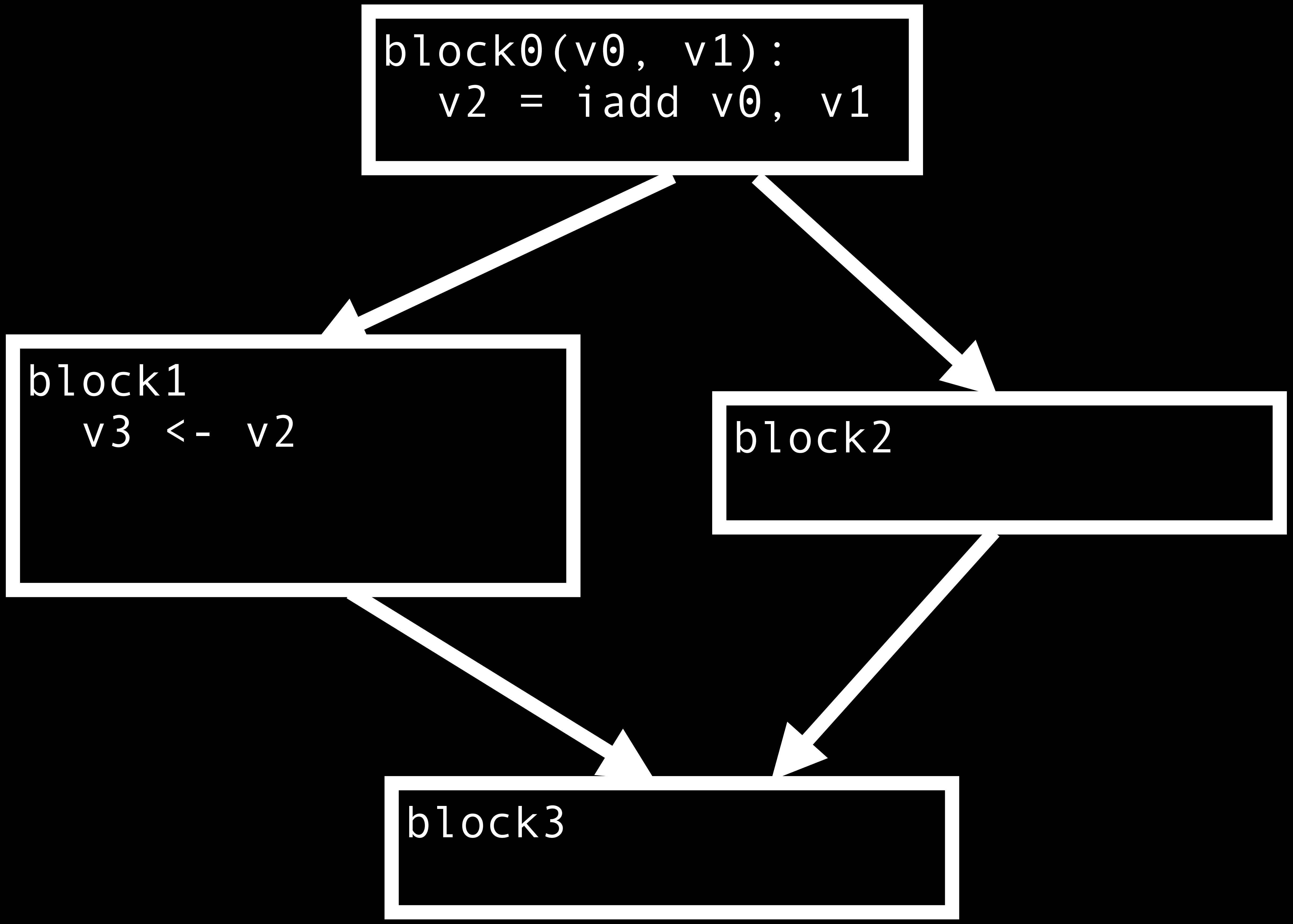
If an operator dominates a duplicate copy of itself, reuse the original.

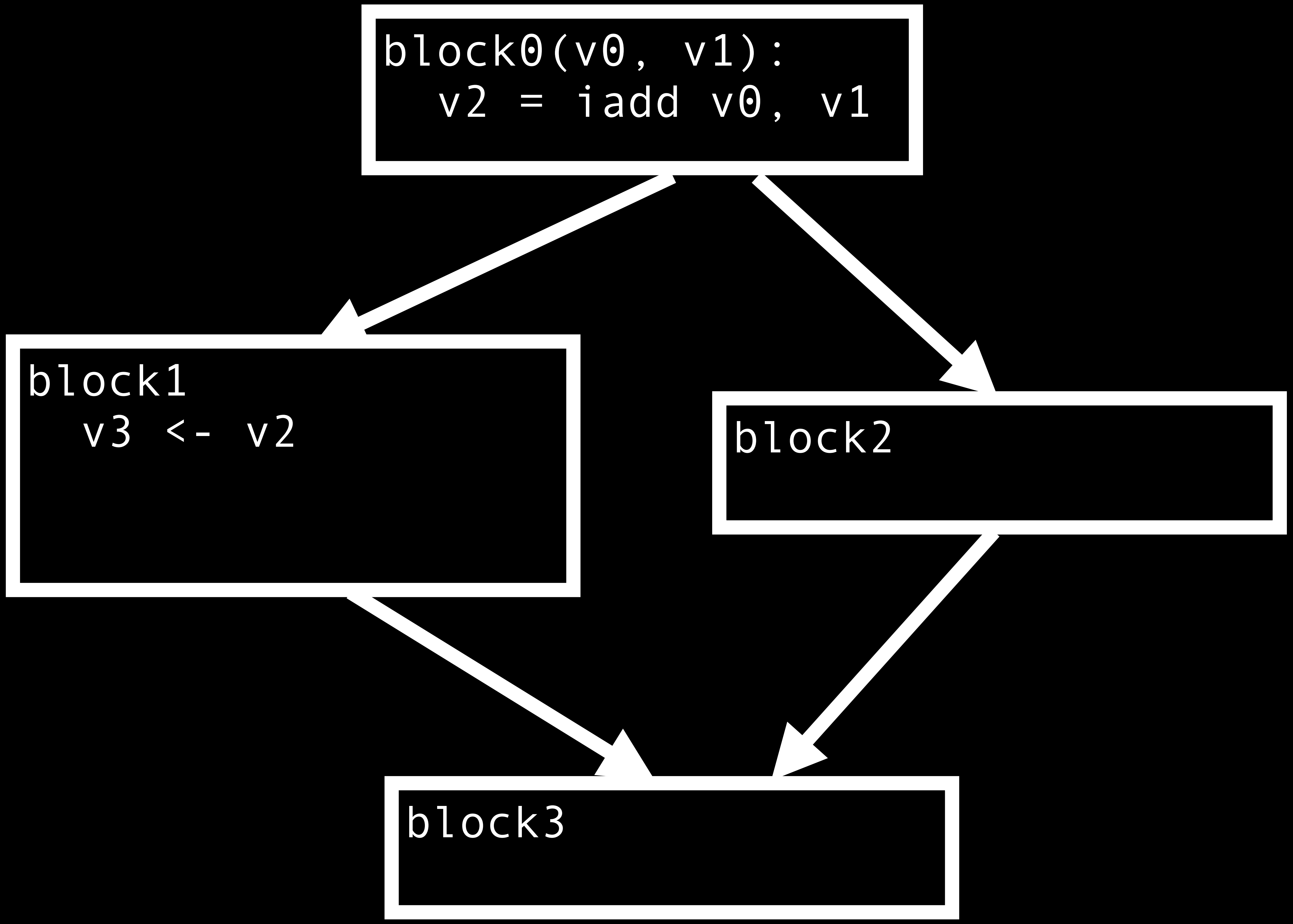
GVN



GVN (Global Value Numbering):
If an operator dominates a duplicate copy of itself, reuse the original.

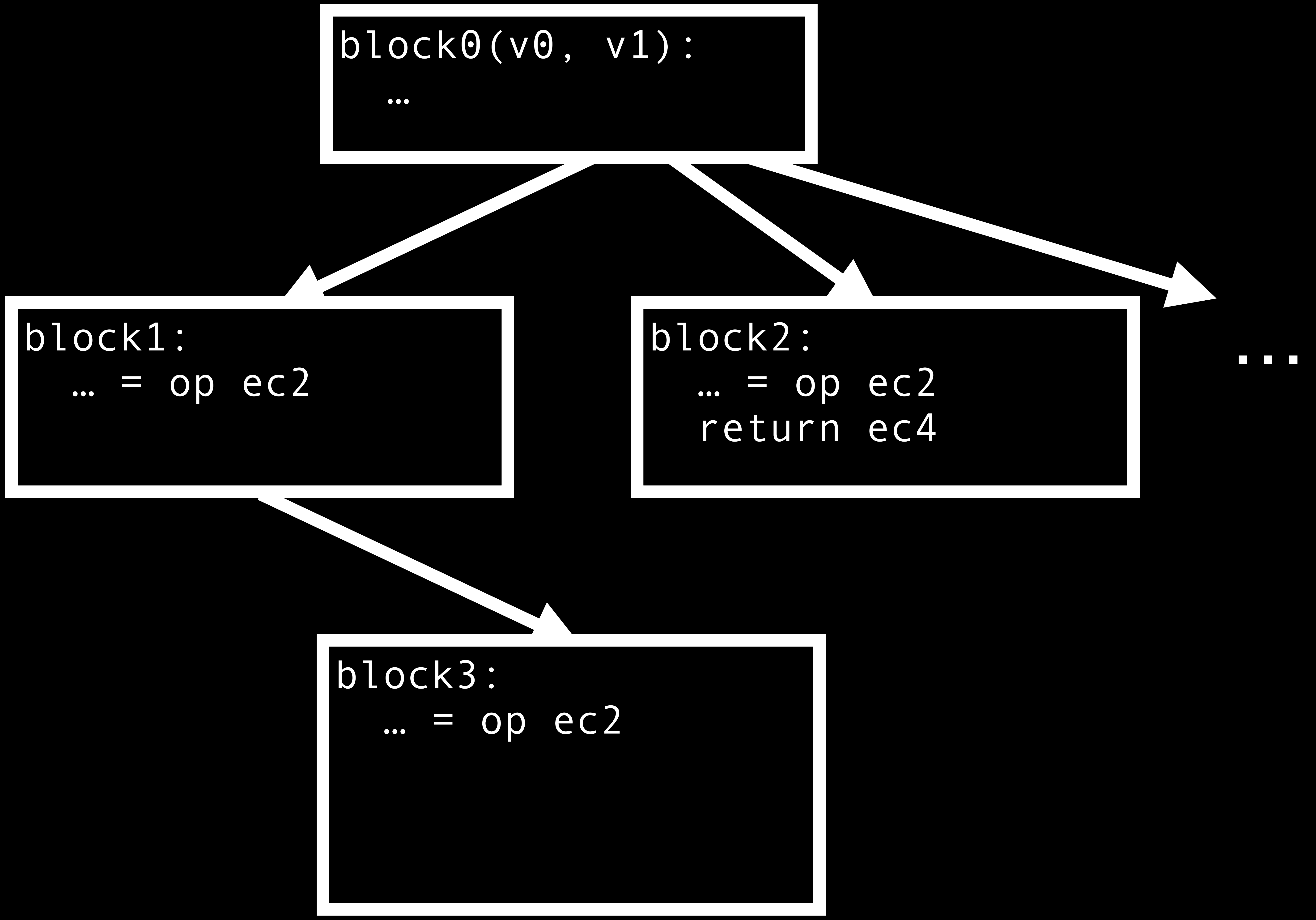
Implement with *domtree preorder traversal* and a *scoped map*.

GVN

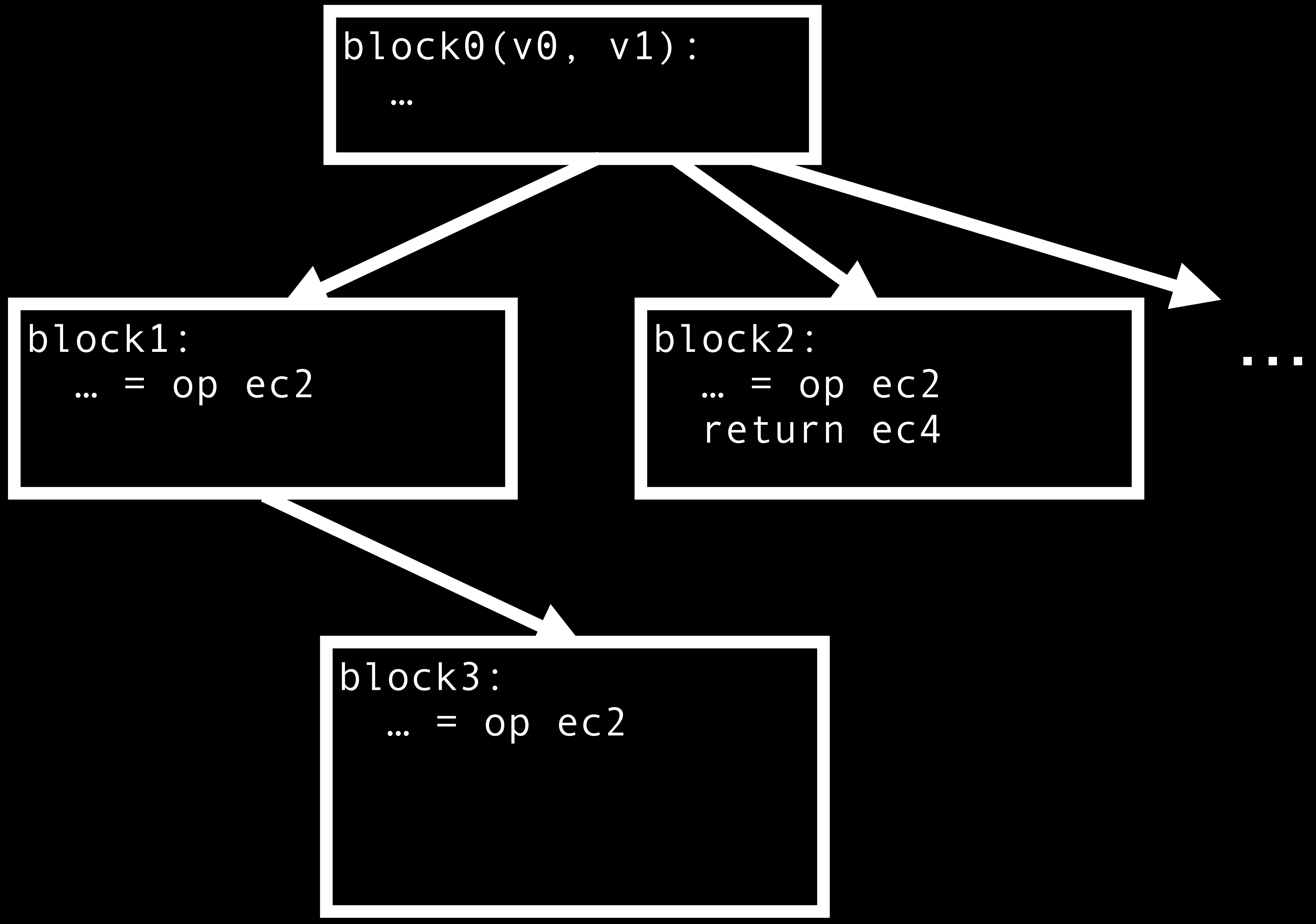


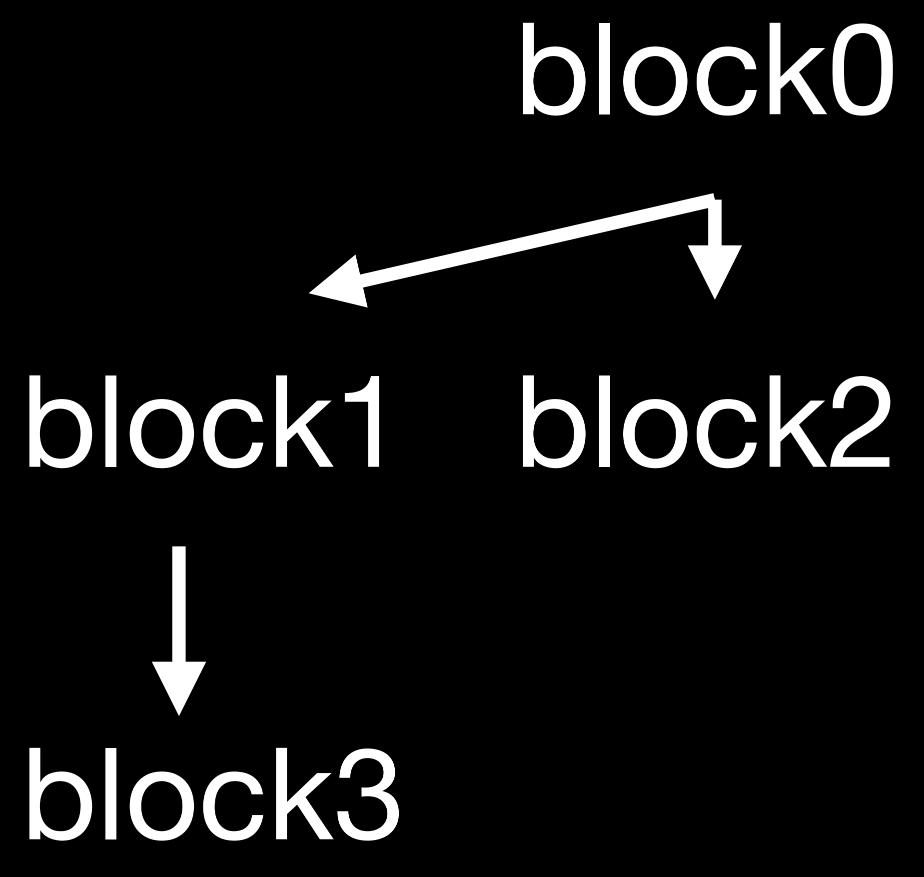
Implement with
domtree preorder traversal
and a *scoped map*.

Scoped Elaboration

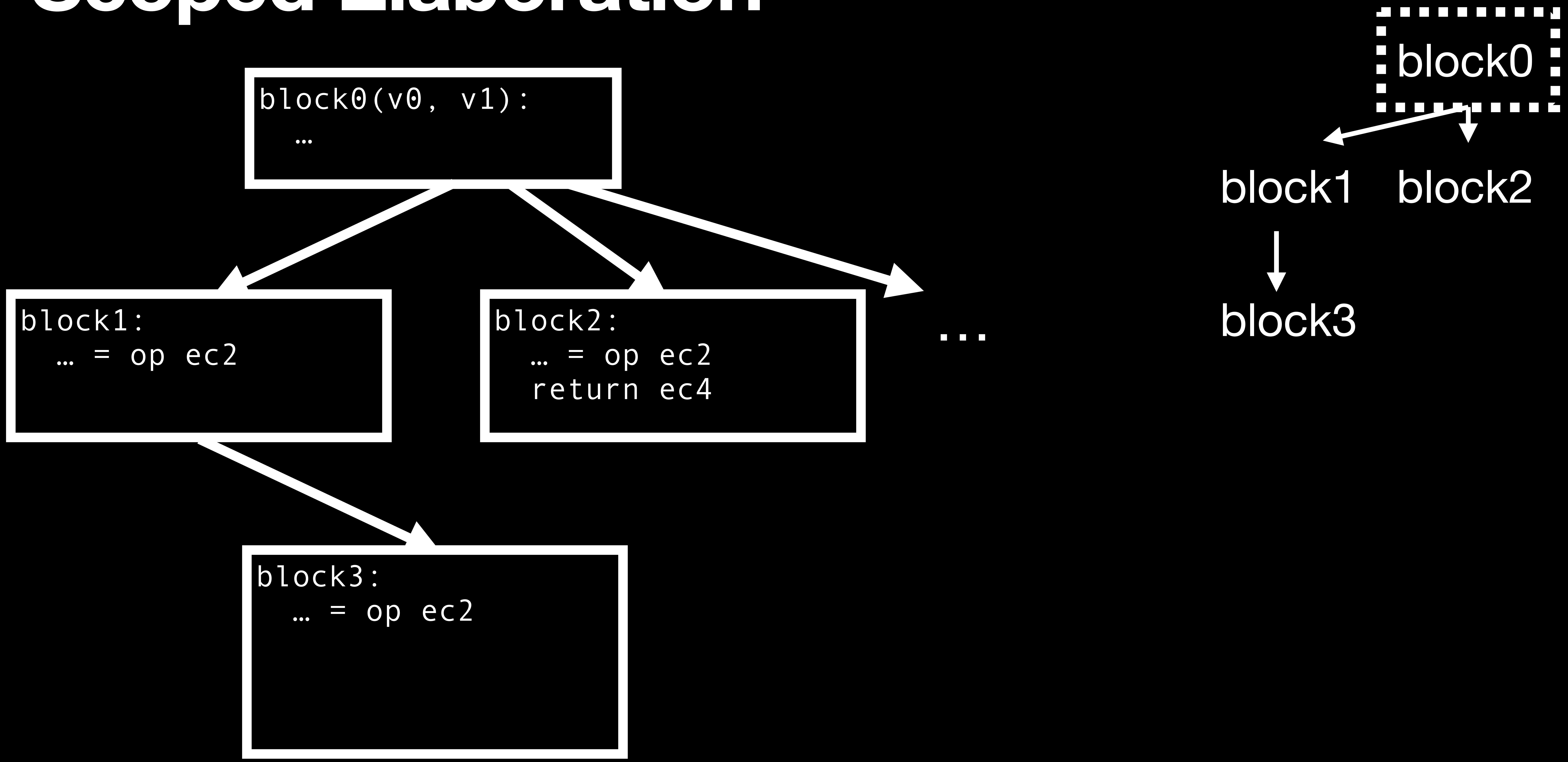


Scoped Elaboration

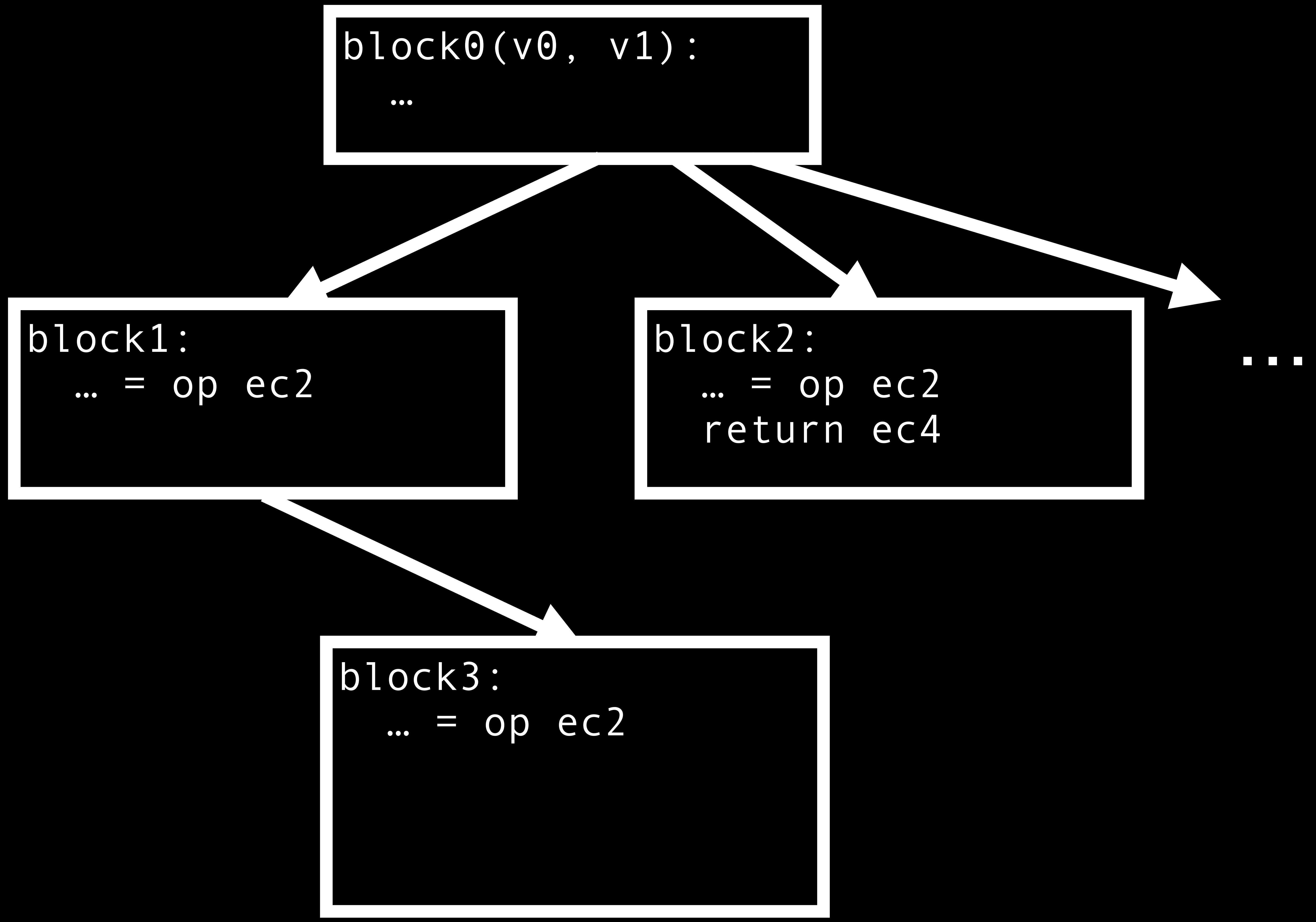


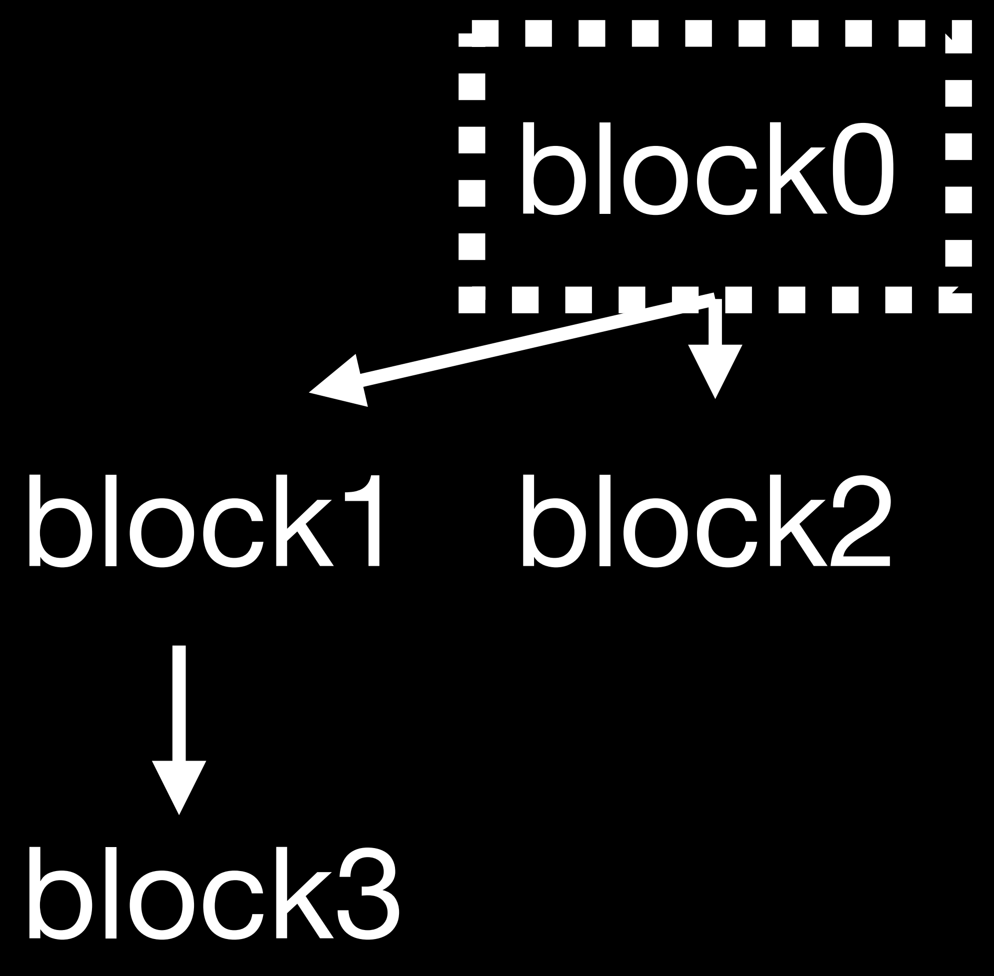


Scoped Elaboration



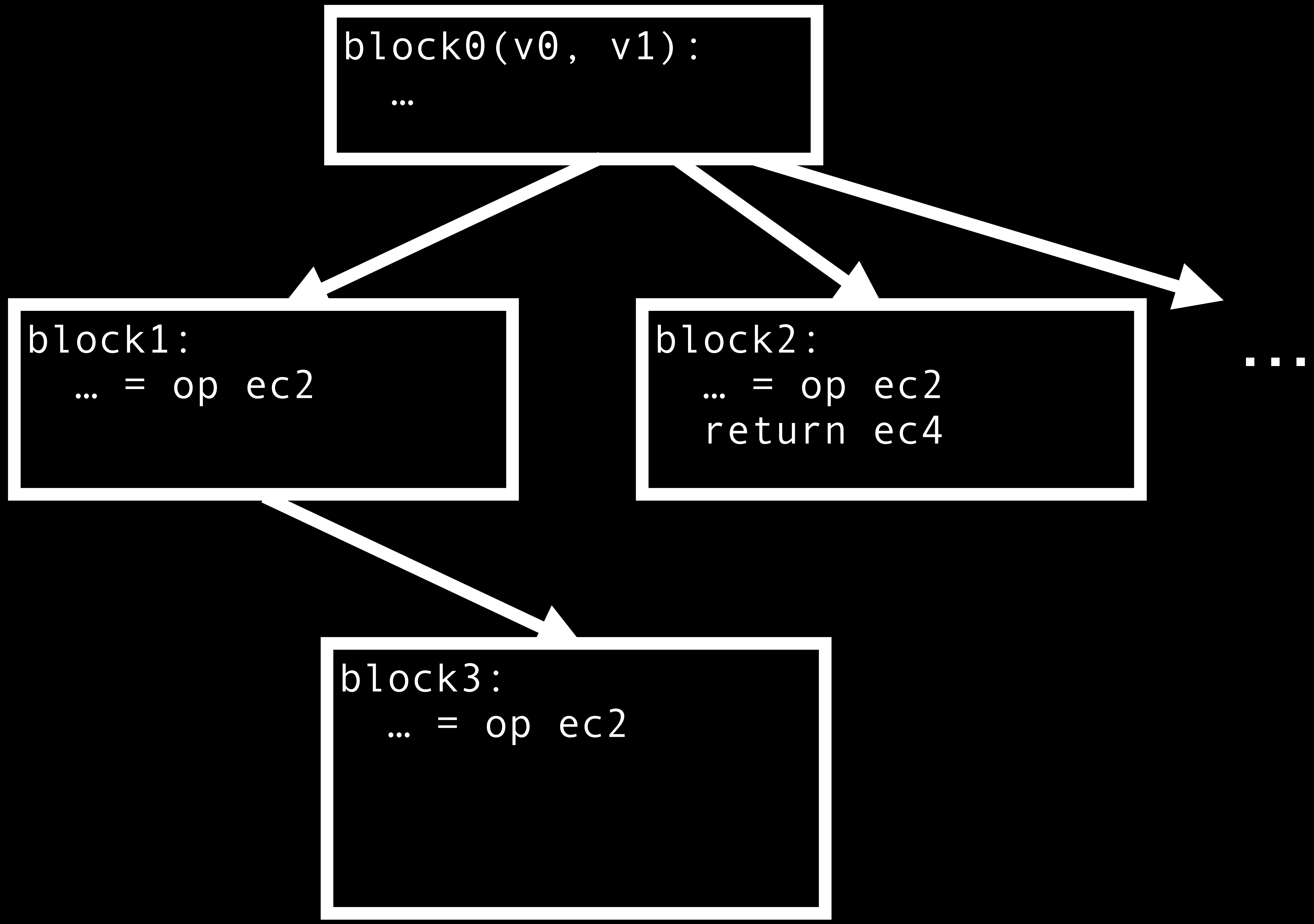
Scoped Elaboration

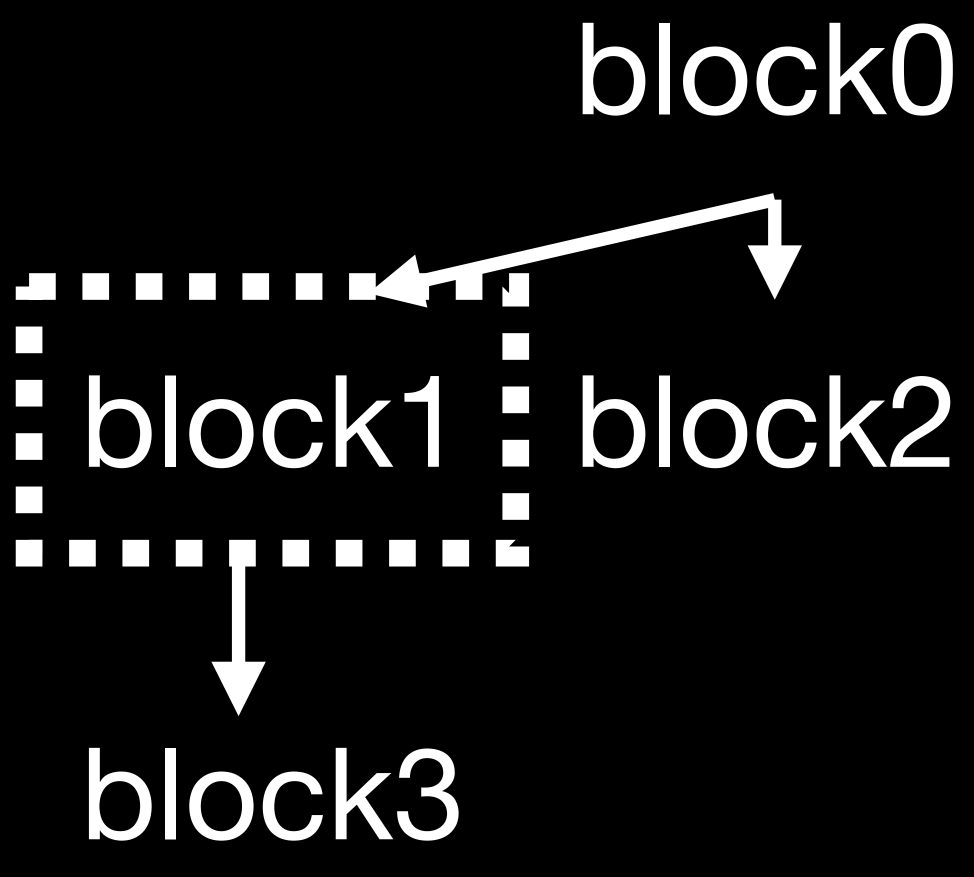




eclass	elaborated
ec0	v0
ec1	v1

Scoped Elaboration





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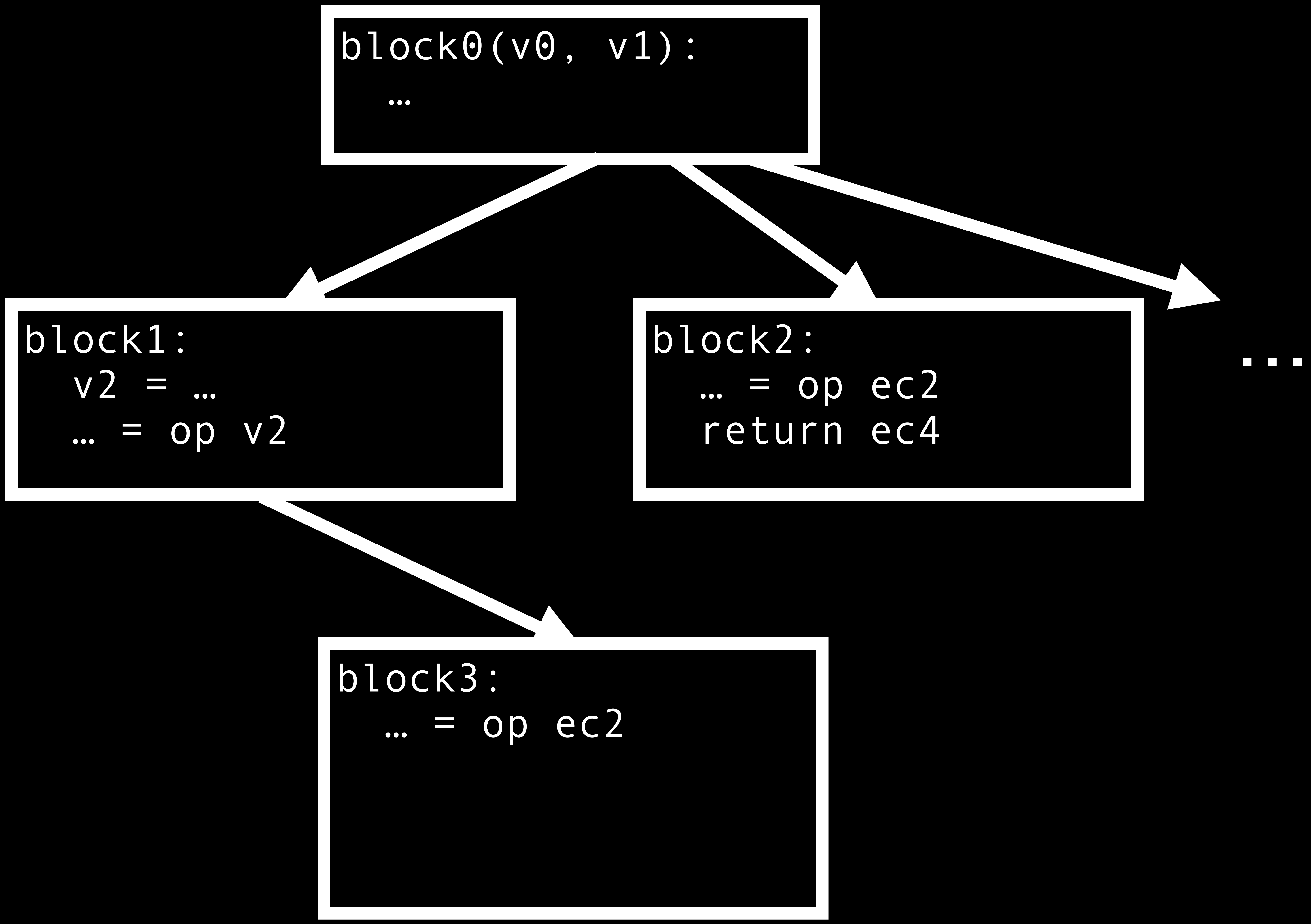
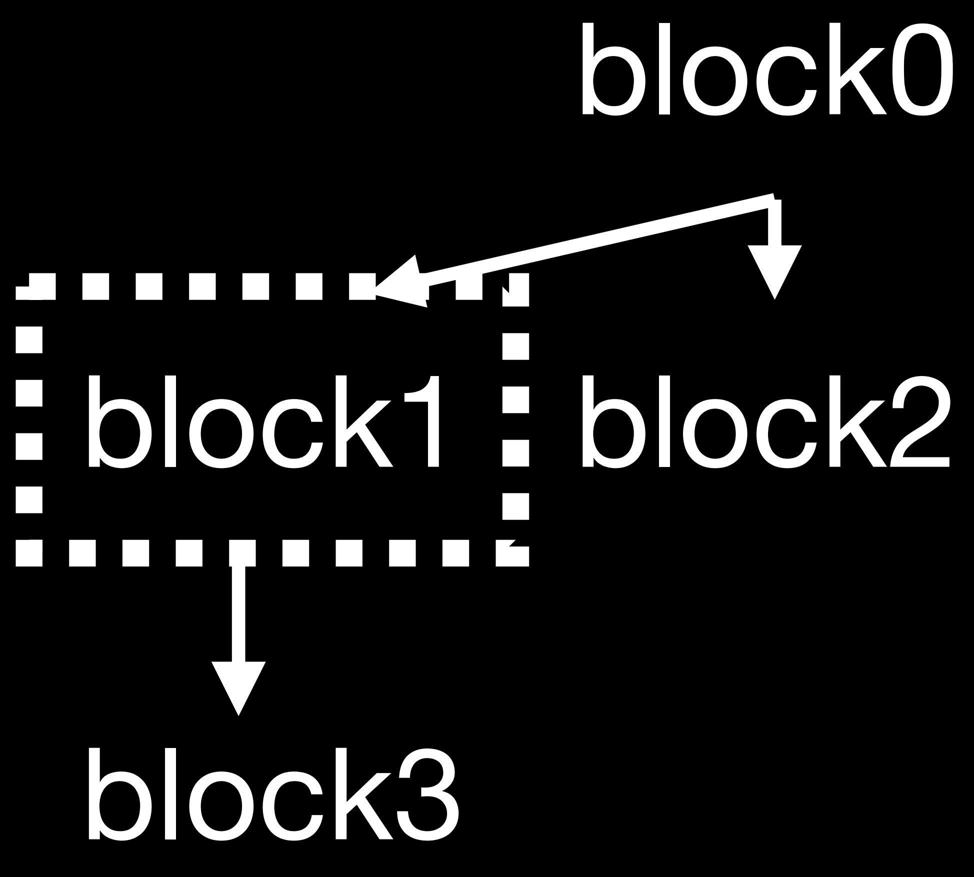
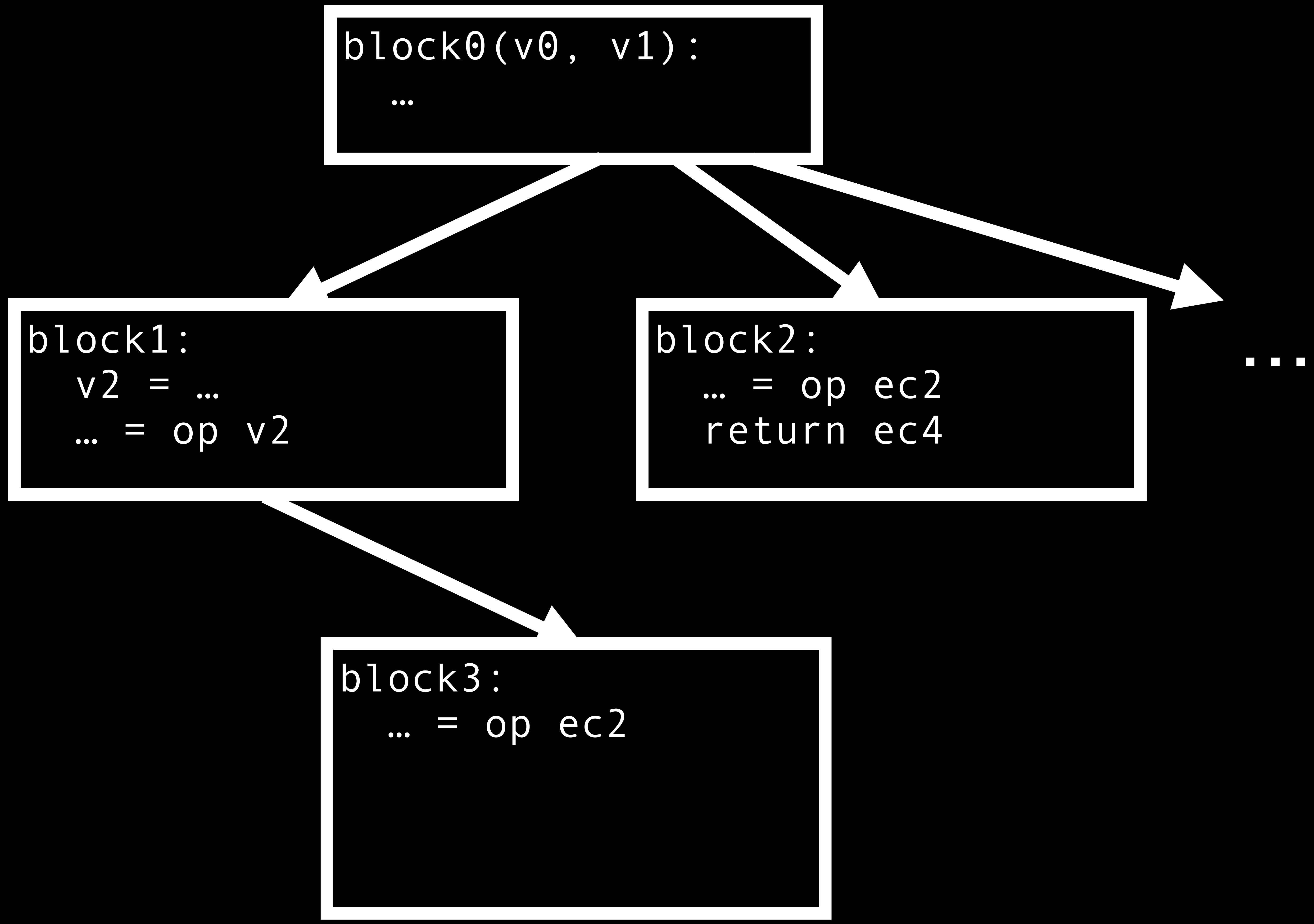
Scoped Elaboration

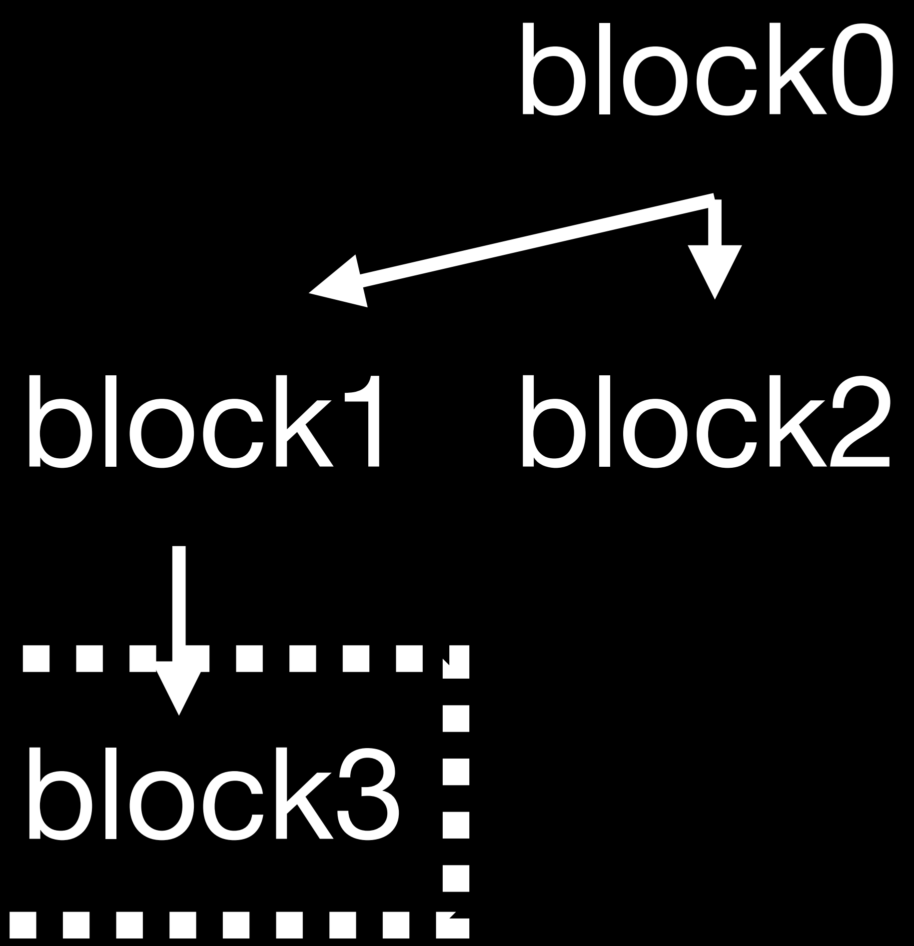




eclass	elaborated
ec0	v0
ec1	v1
ec2	v2

Scoped Elaboration





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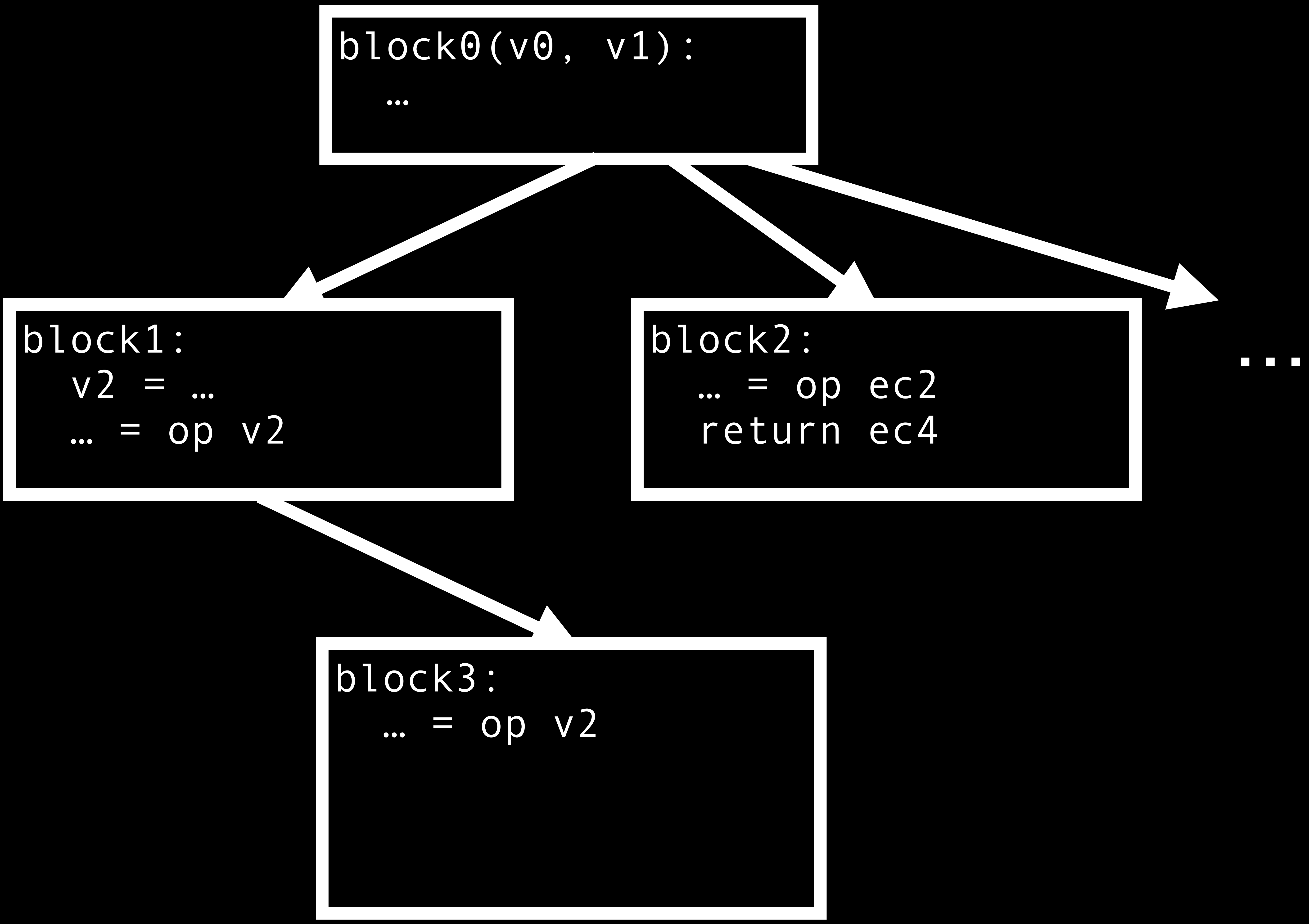
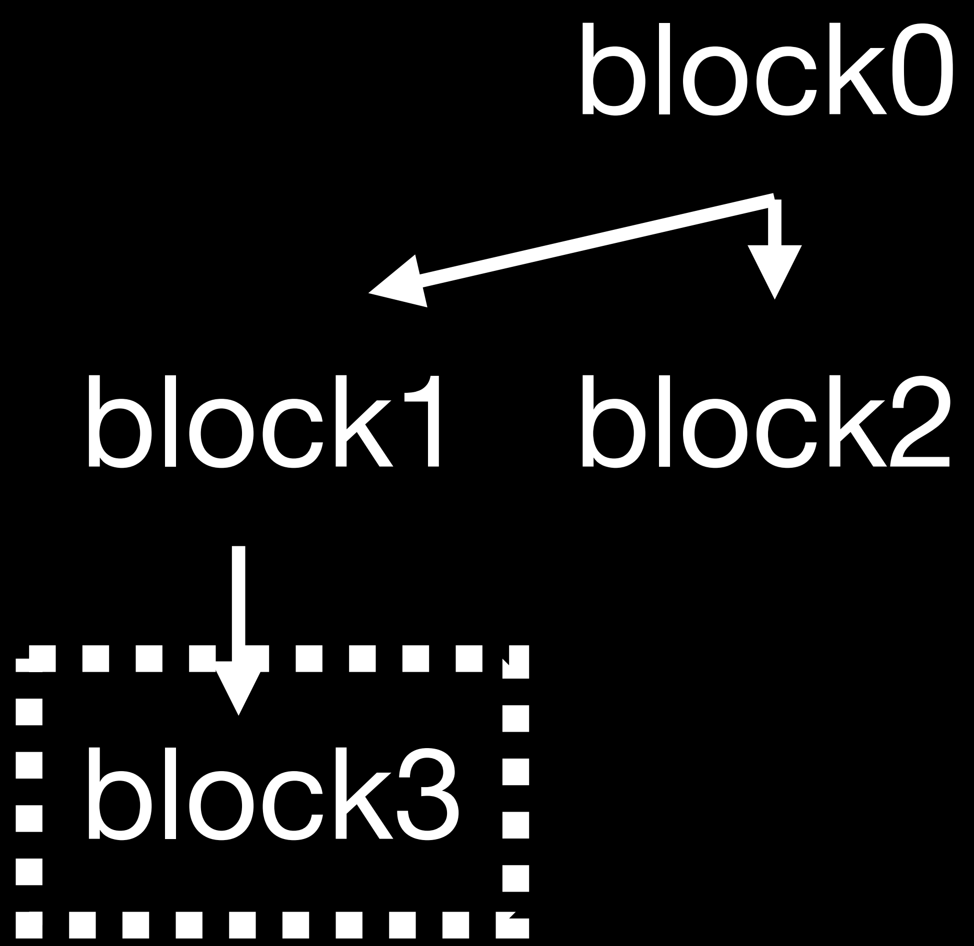
Scoped Elaboration





eclass	elaborated
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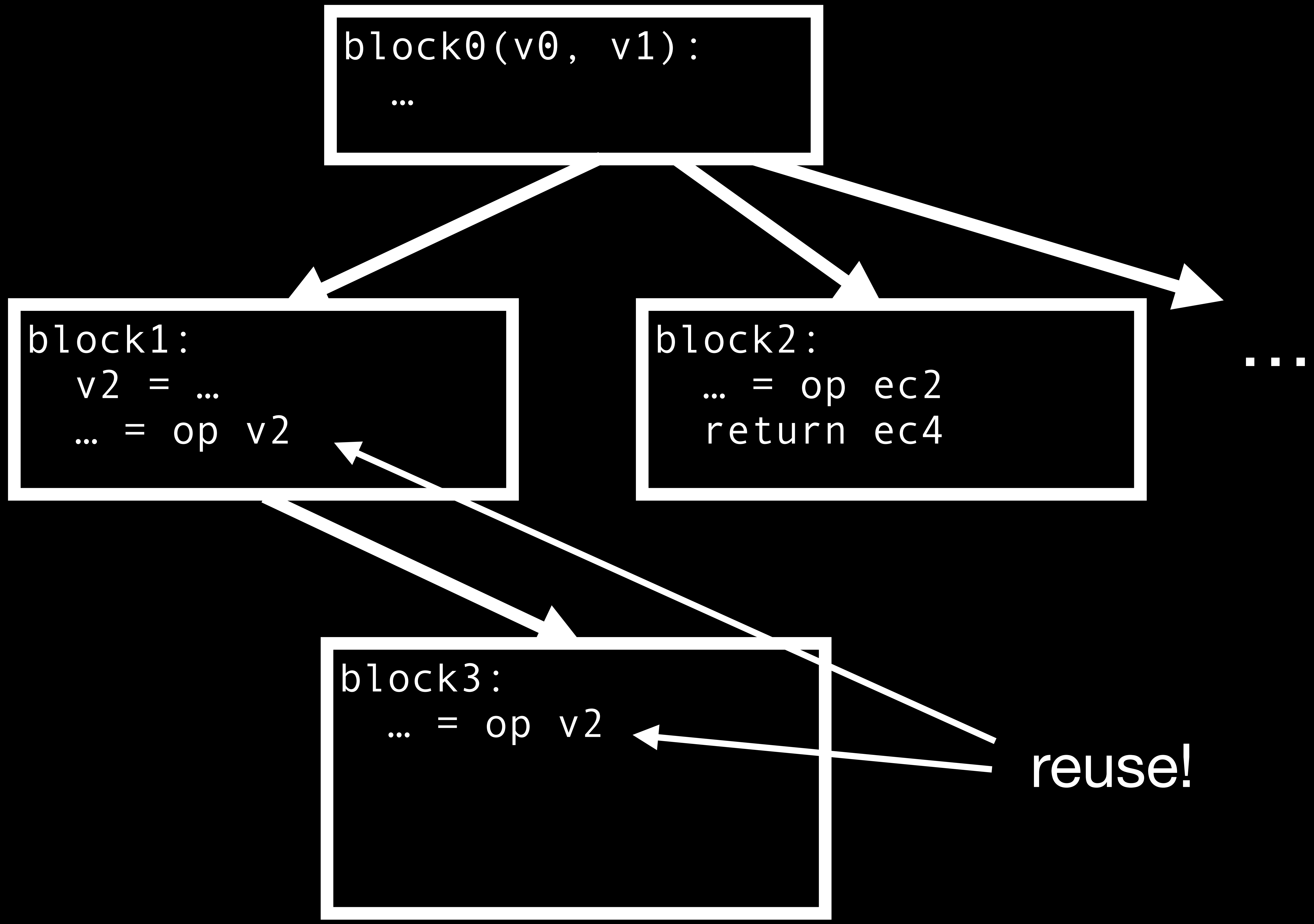
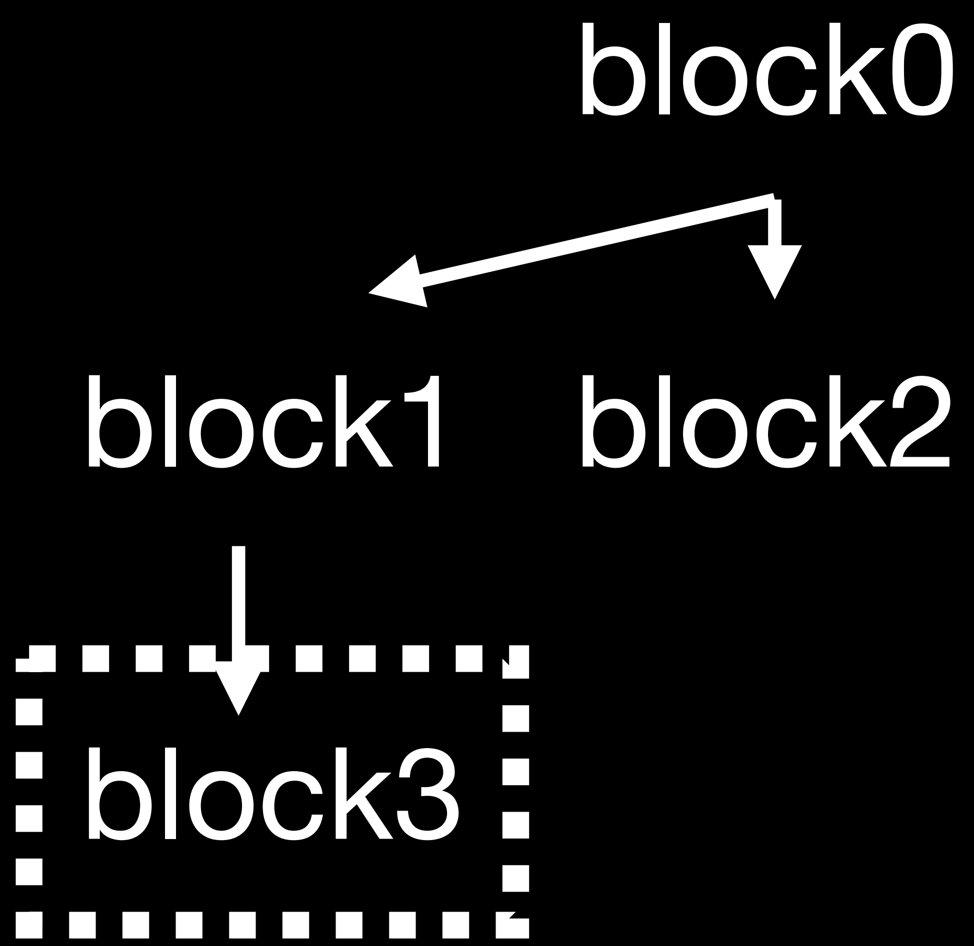
Scoped Elaboration





eclass	elaborated
ec0	v0
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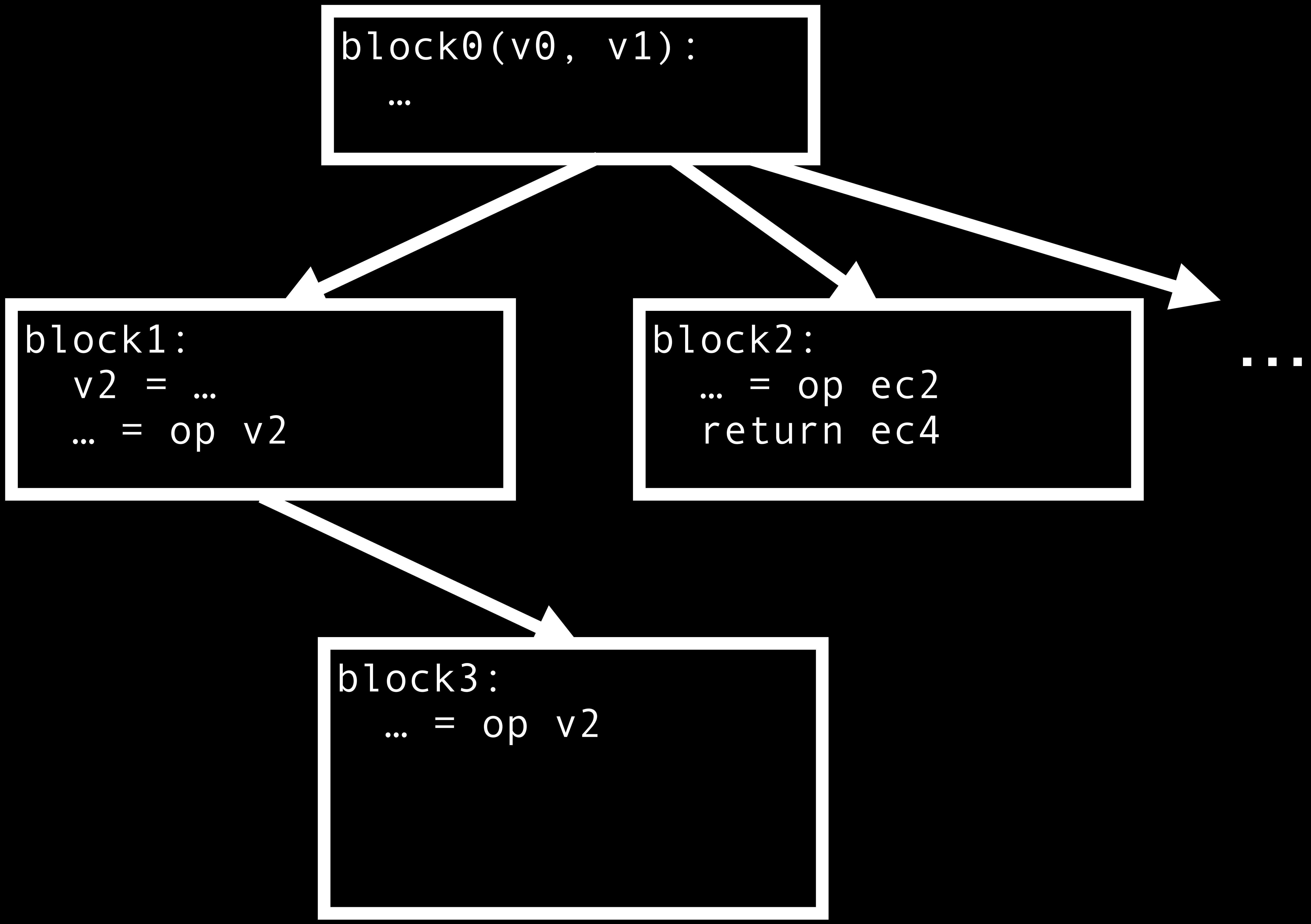
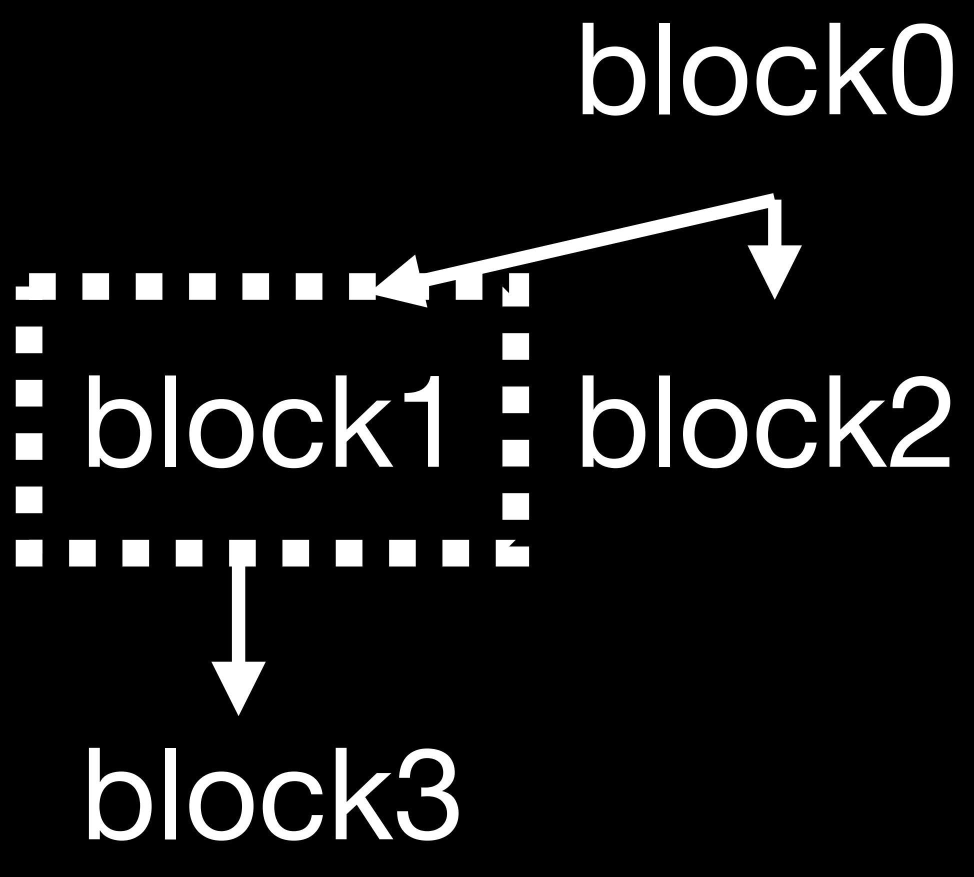
Scoped Elaboration





eclass	elaborated
ec0	v0
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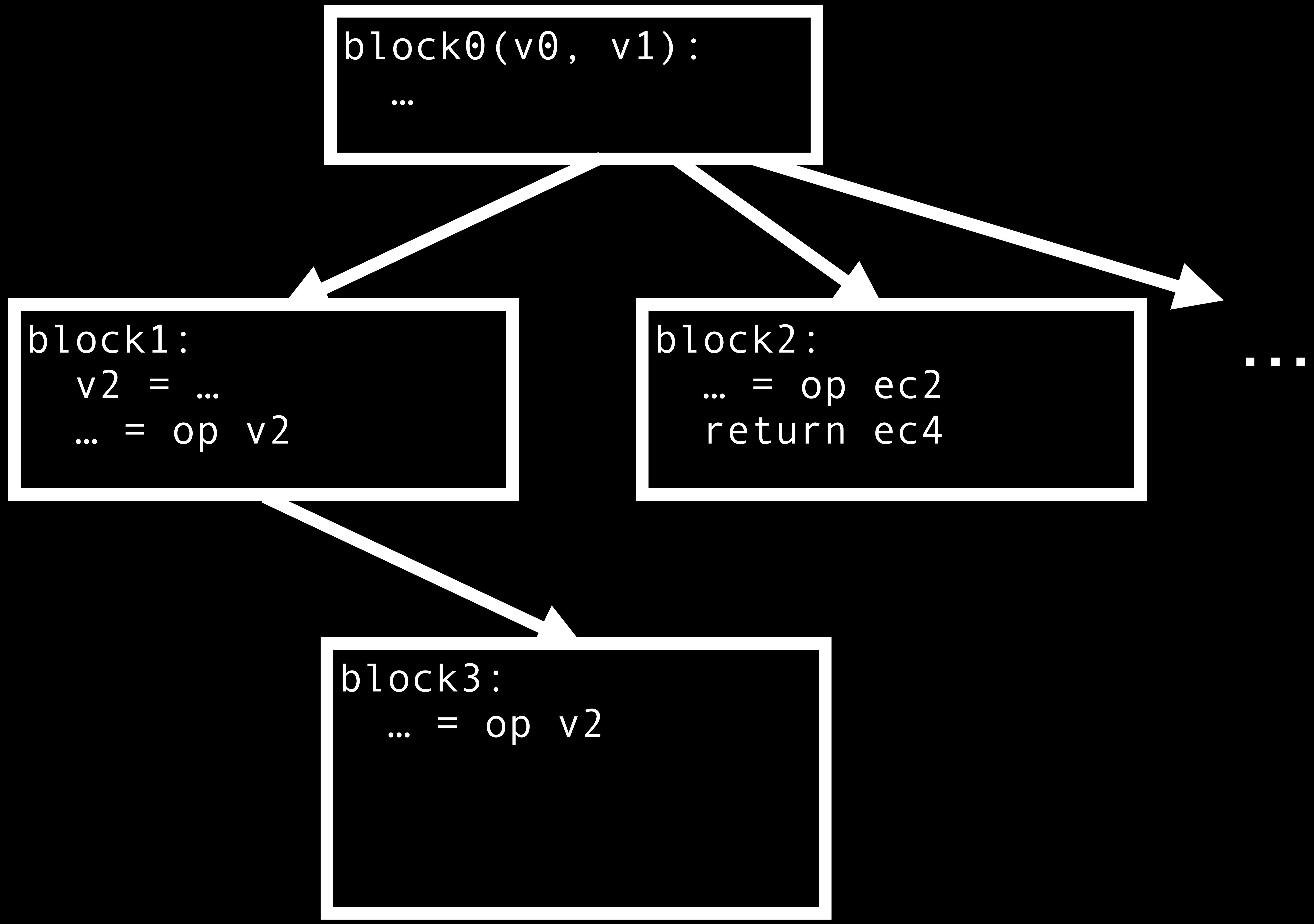
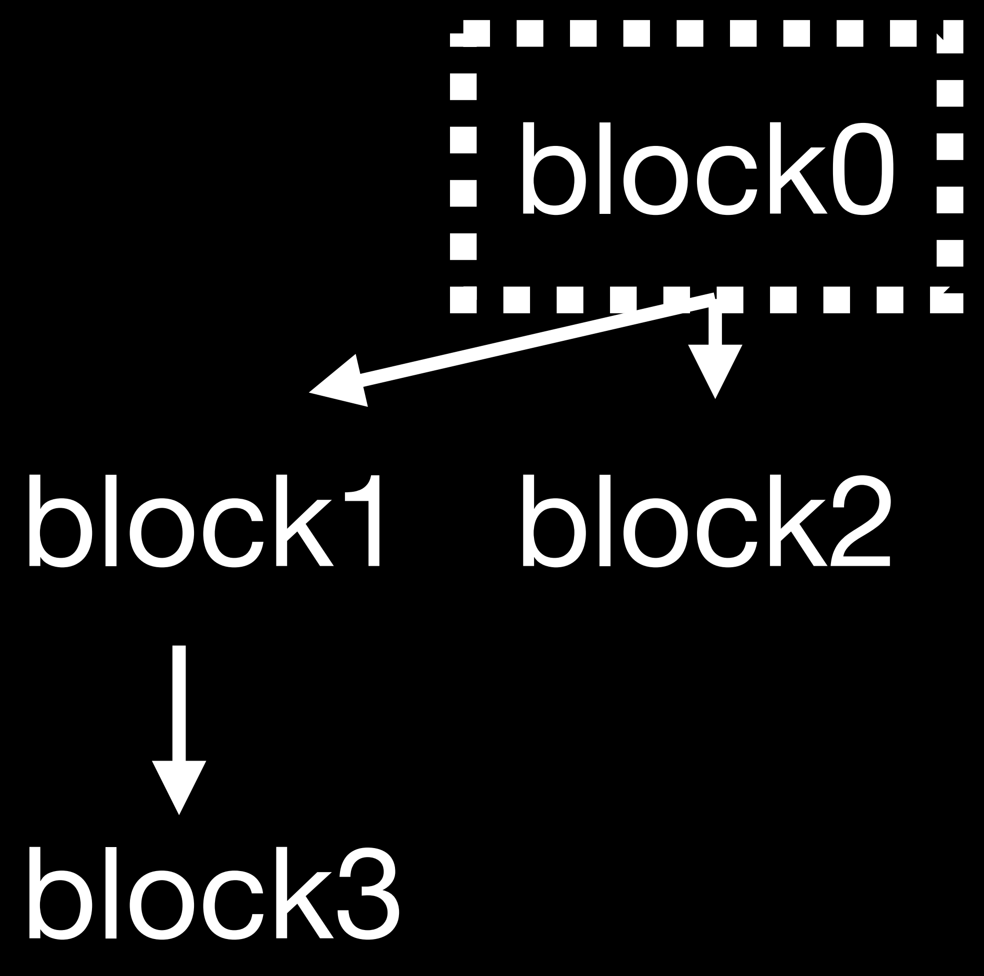
Scoped Elaboration





eclass	elaborated
ec0	v0
ec1	v1
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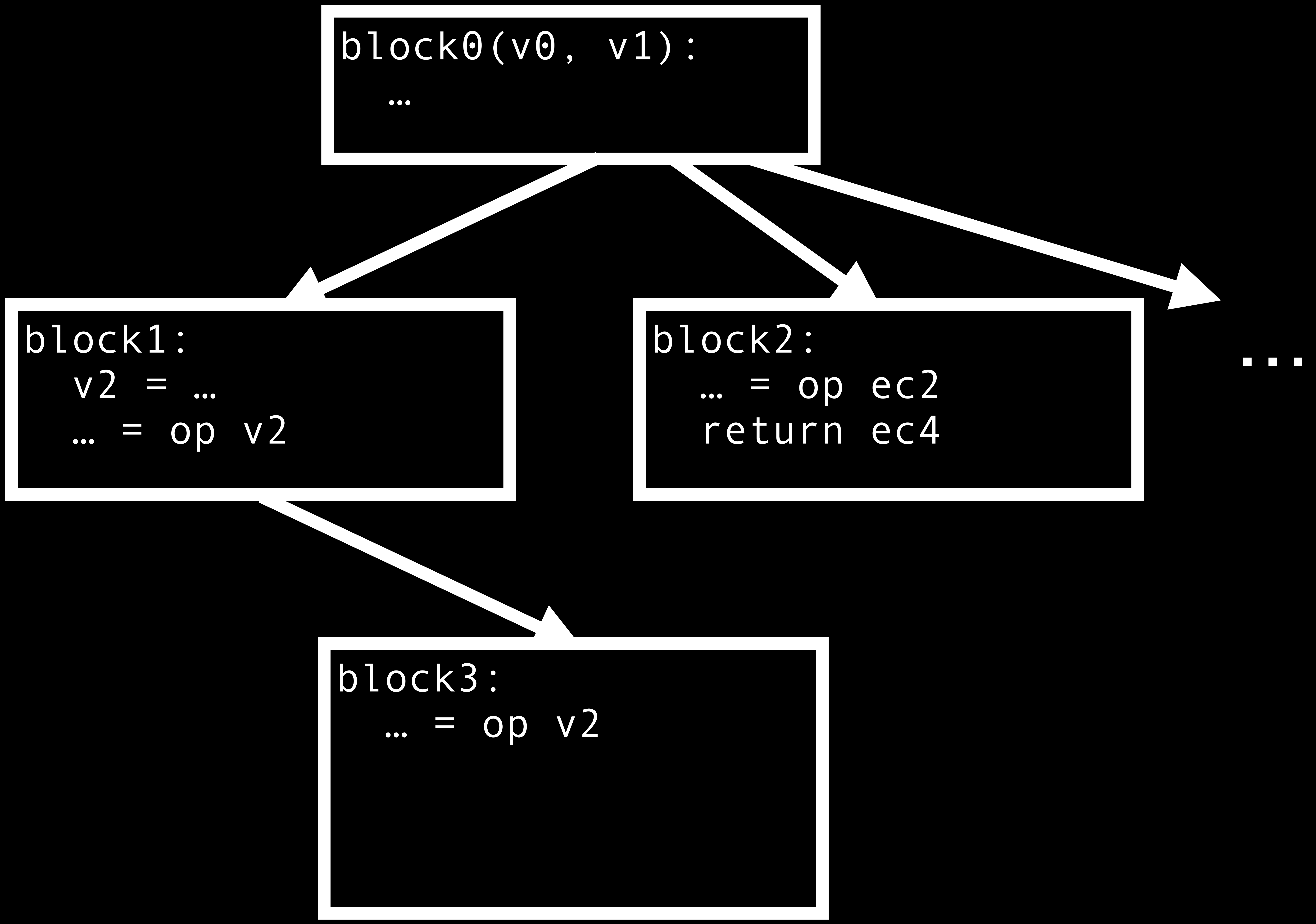
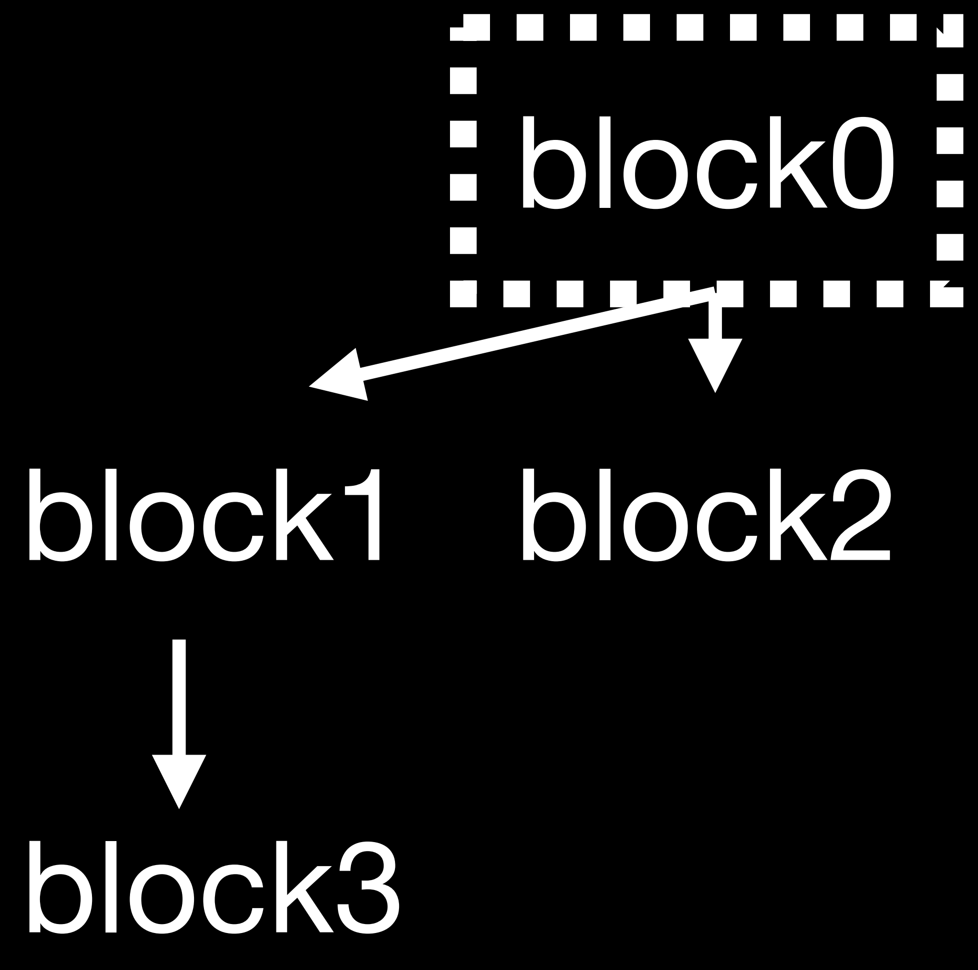
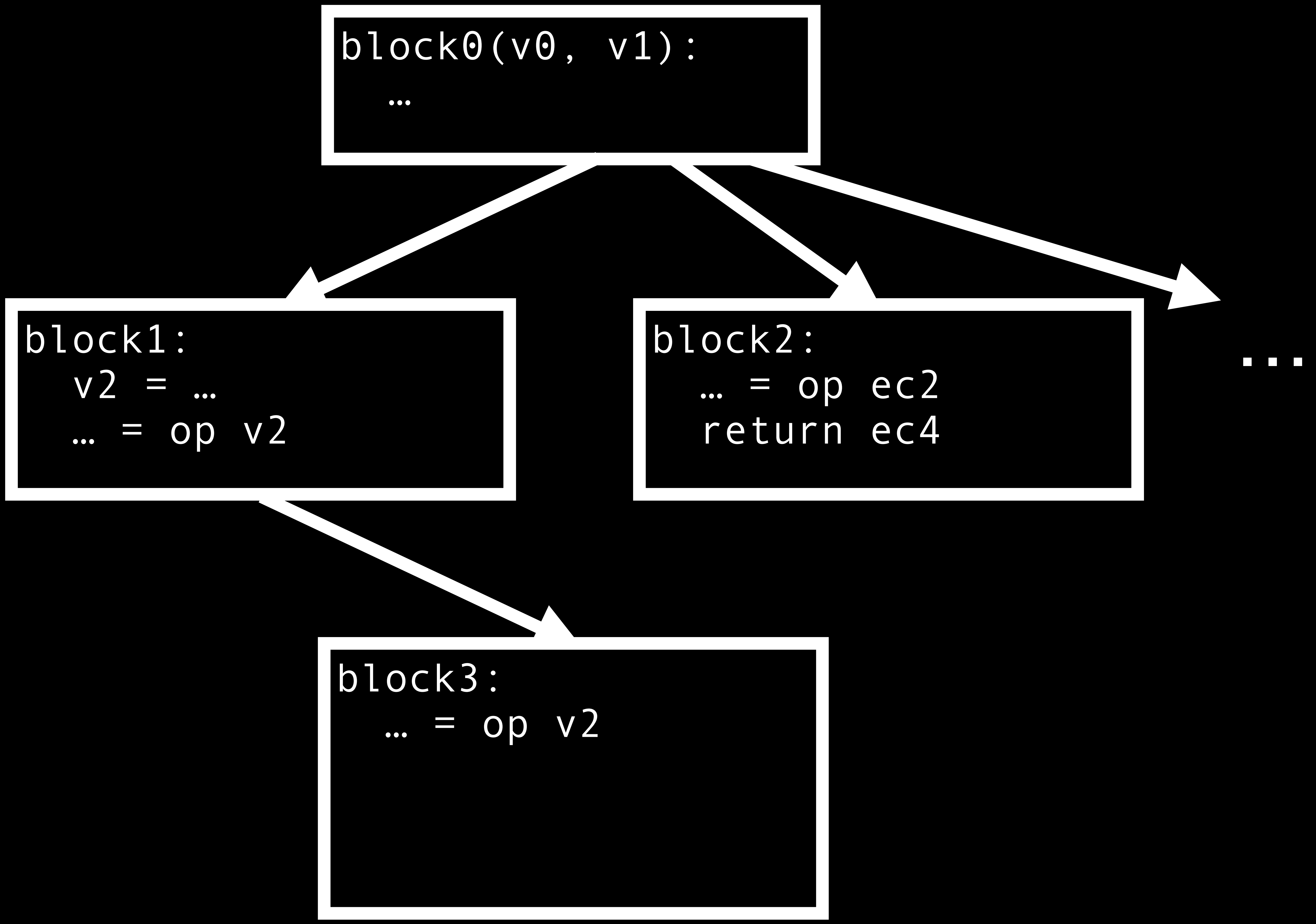
Scoped Elaboration

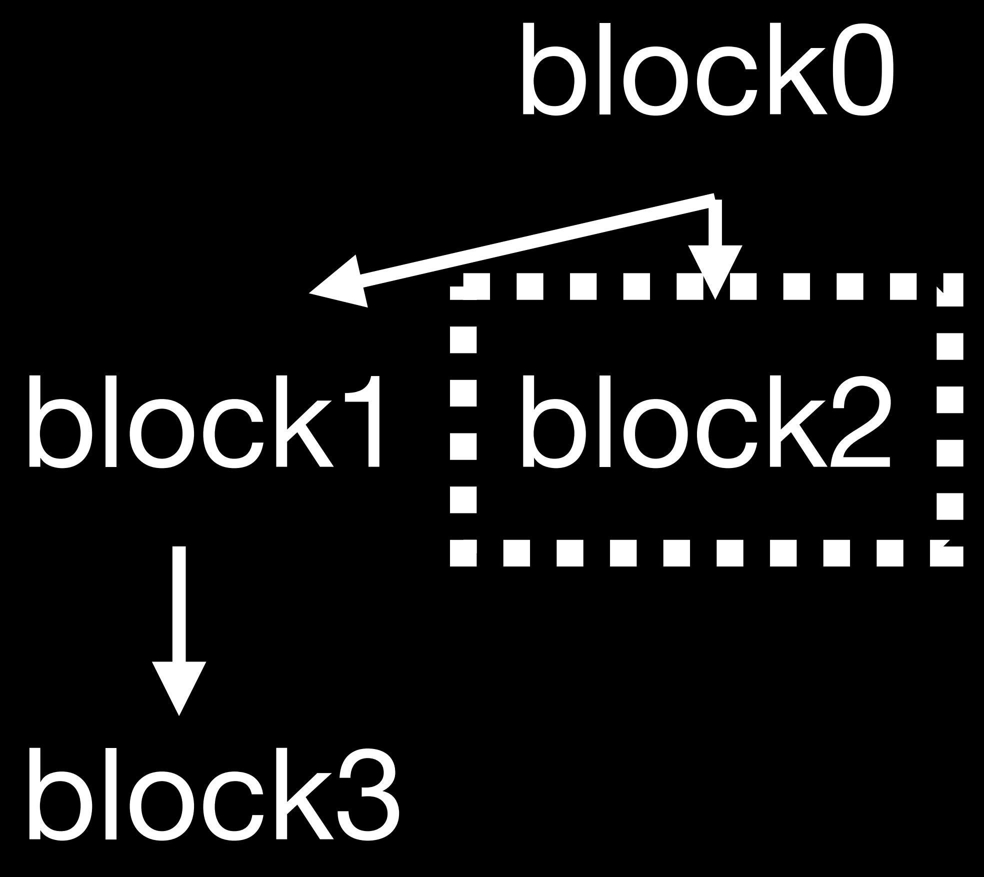




eclass	elaborated
ec0	v0
ec1	v1

Scoped Elaboration





eclass	elaborated
ec0	v0
ec1	v1

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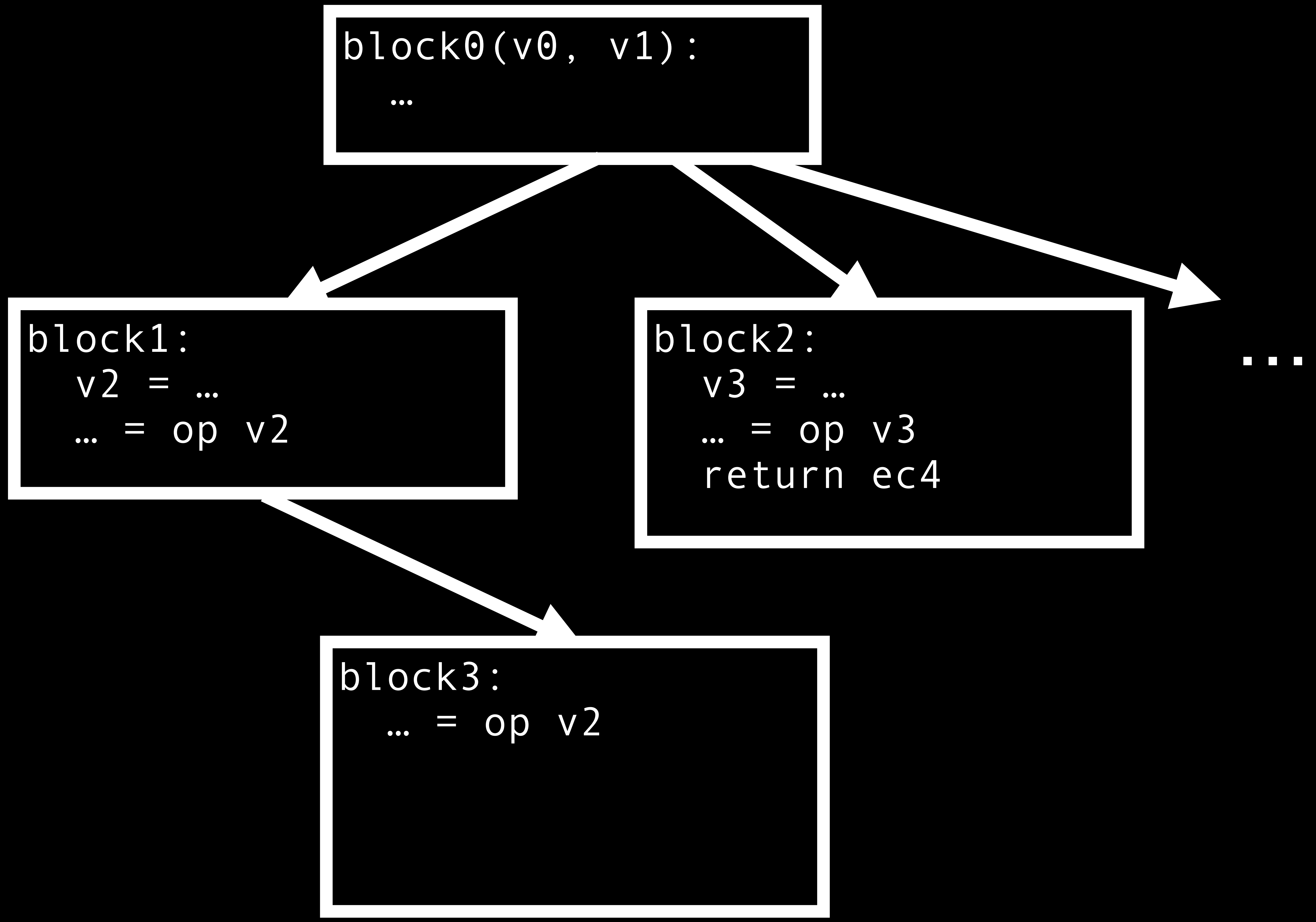

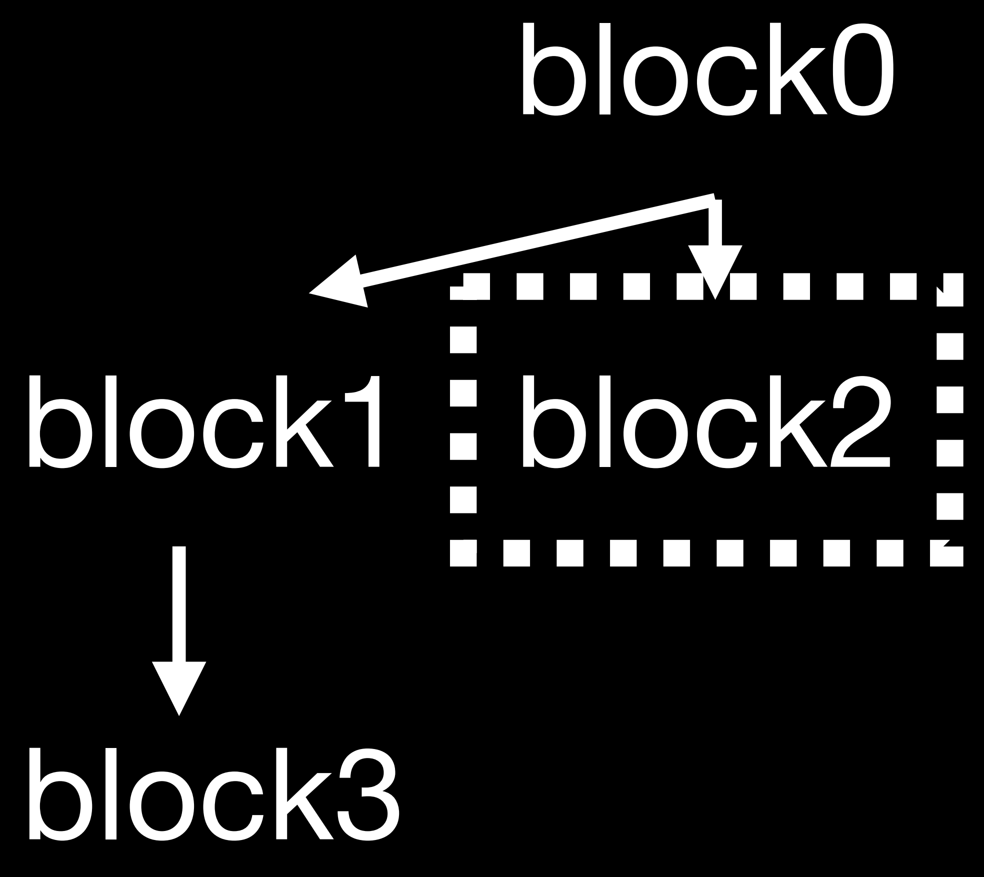

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ec2	v3

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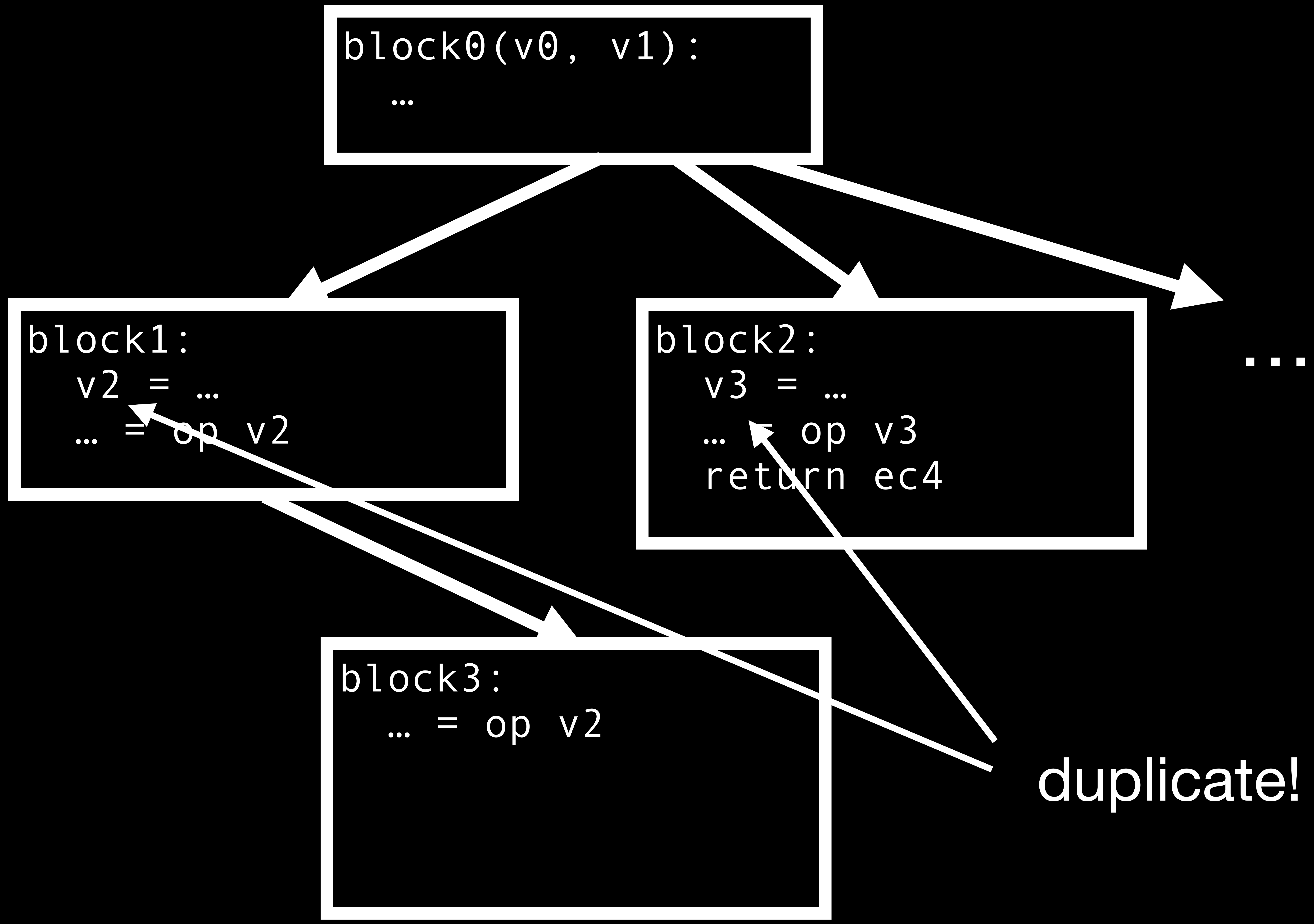

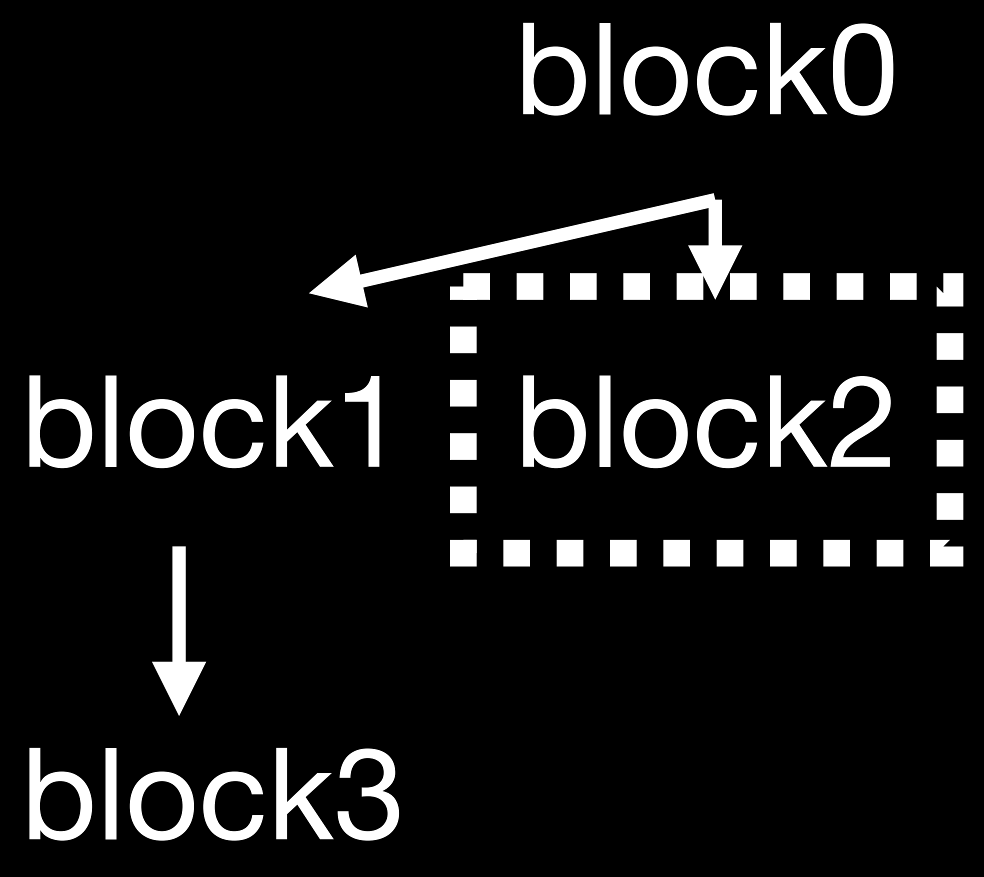

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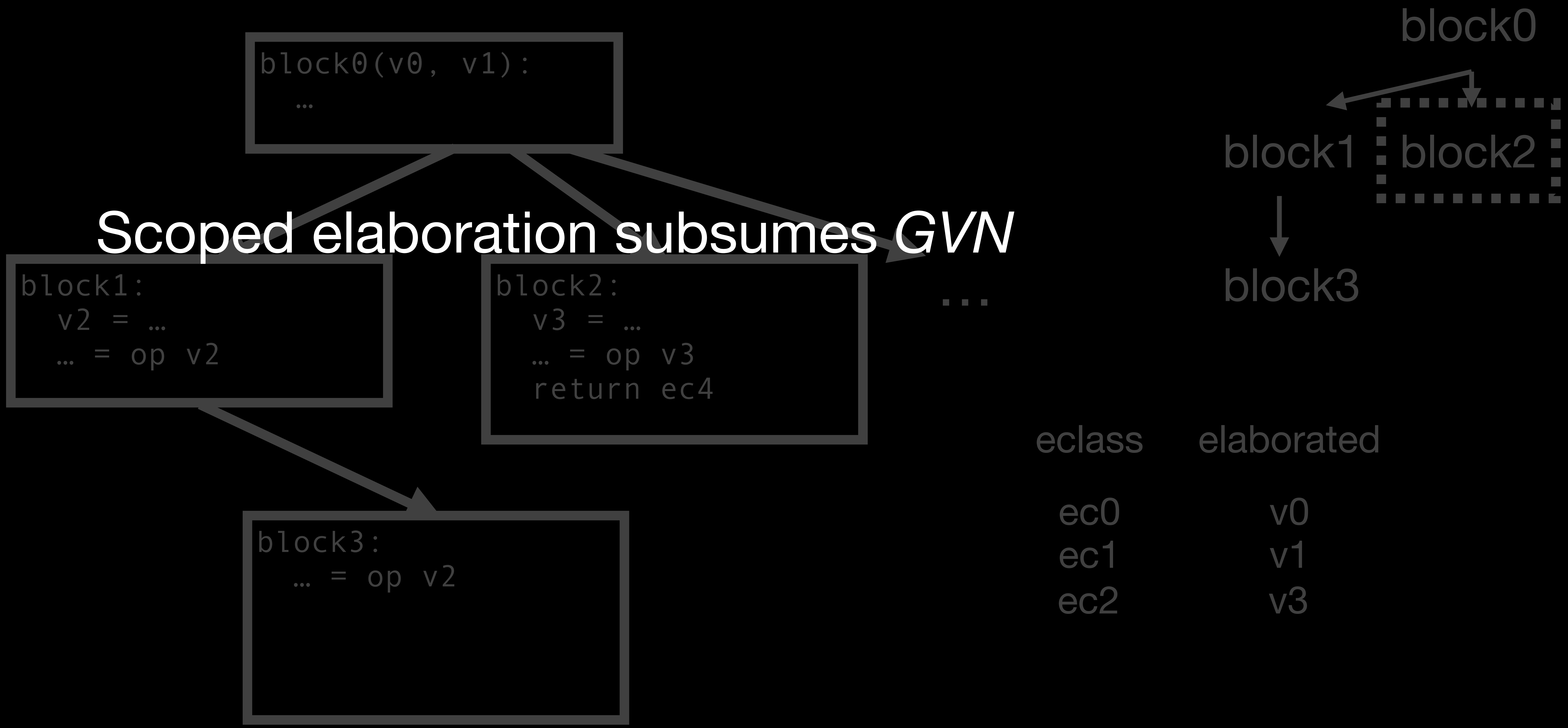
Scoped elaboration subsumes *GVN*



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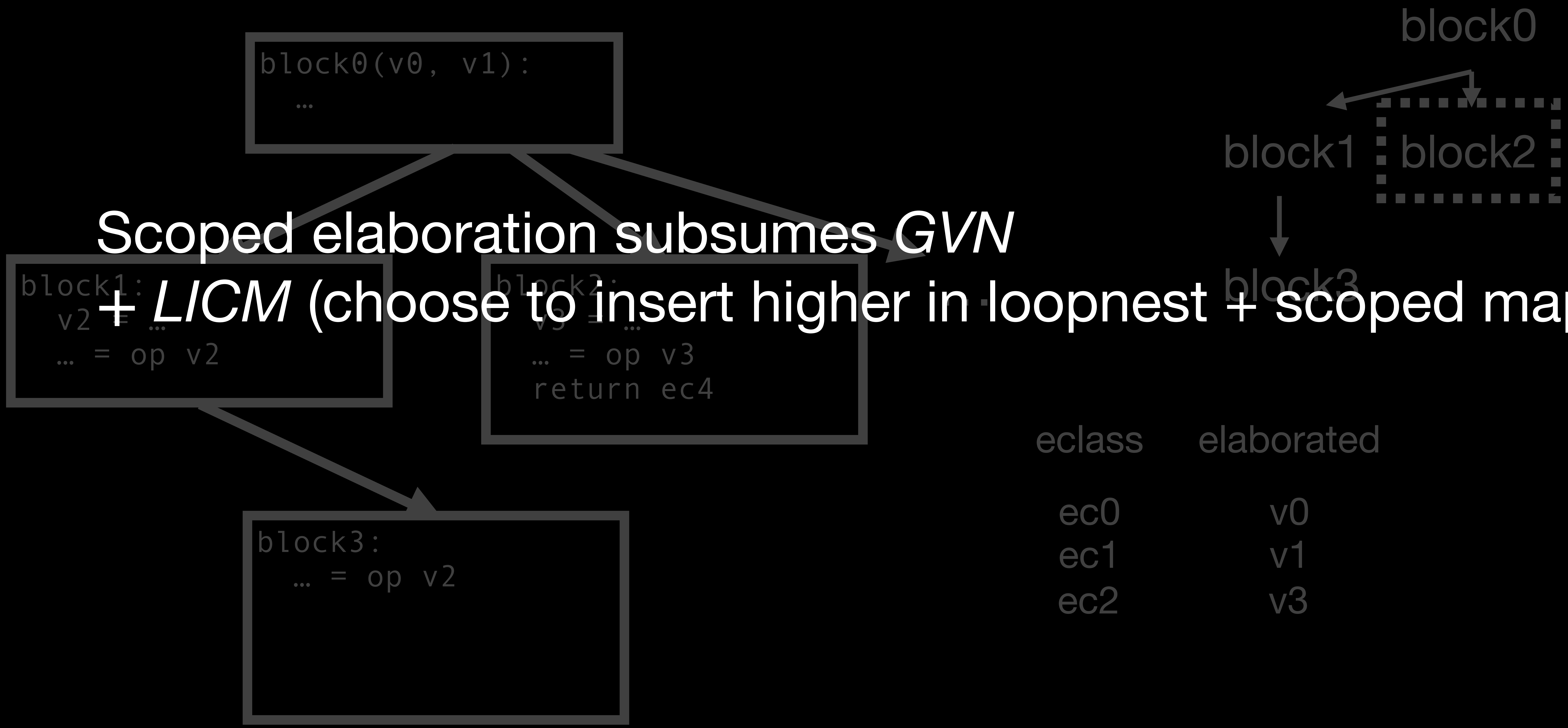

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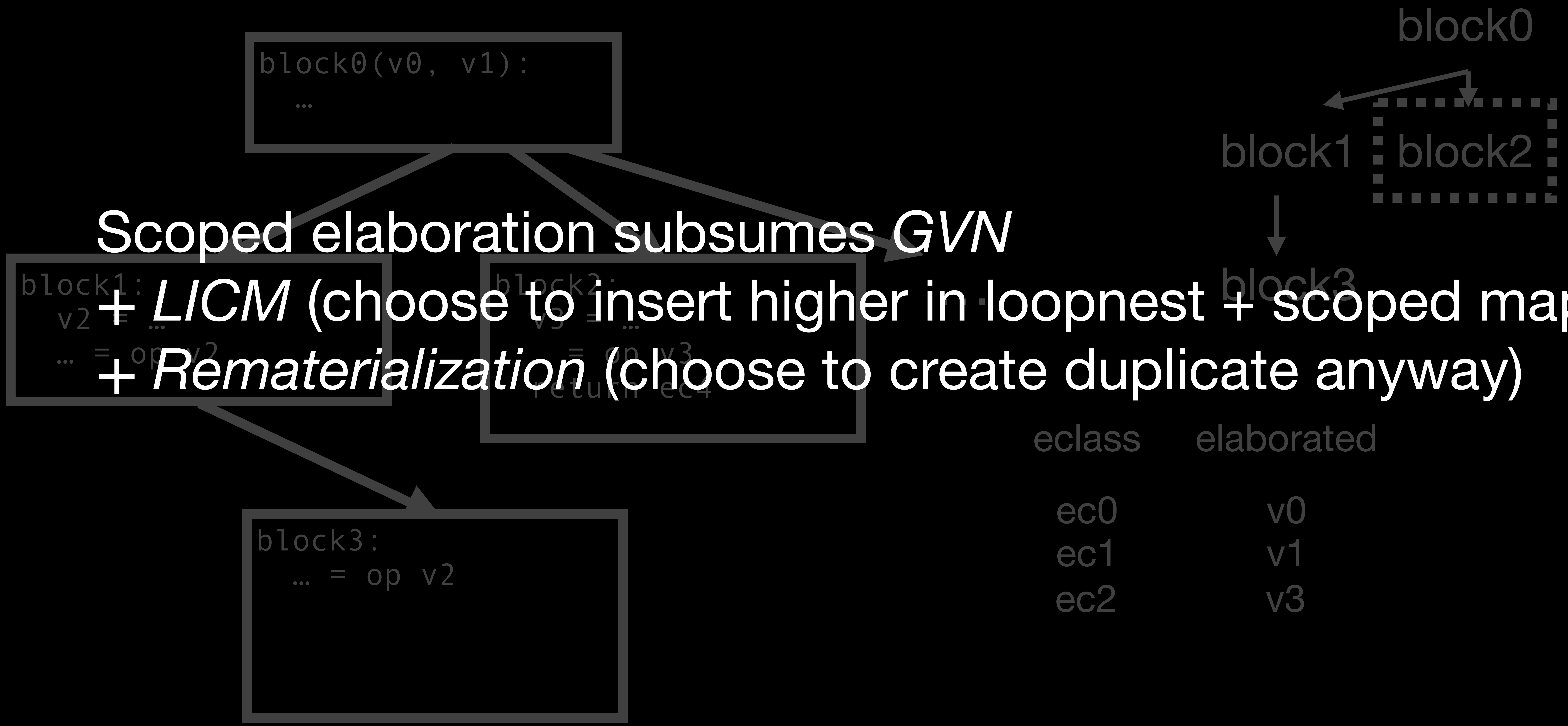

Scoped elaboration subsumes *GVN*
+ *LICM* (choose to insert higher in loopnest + scoped map)
+ *Rematerialization* (choose to create duplicate anyway)

1. **Why** *we want a rewrite-based optimizer*

2. **How** *to turn a CFG into an egraph and back again*

3. **Cycles** *why they occur, and what to do about them*

4. **Results** *how well does it work?*

5. **Lessons** *in translating research to production*

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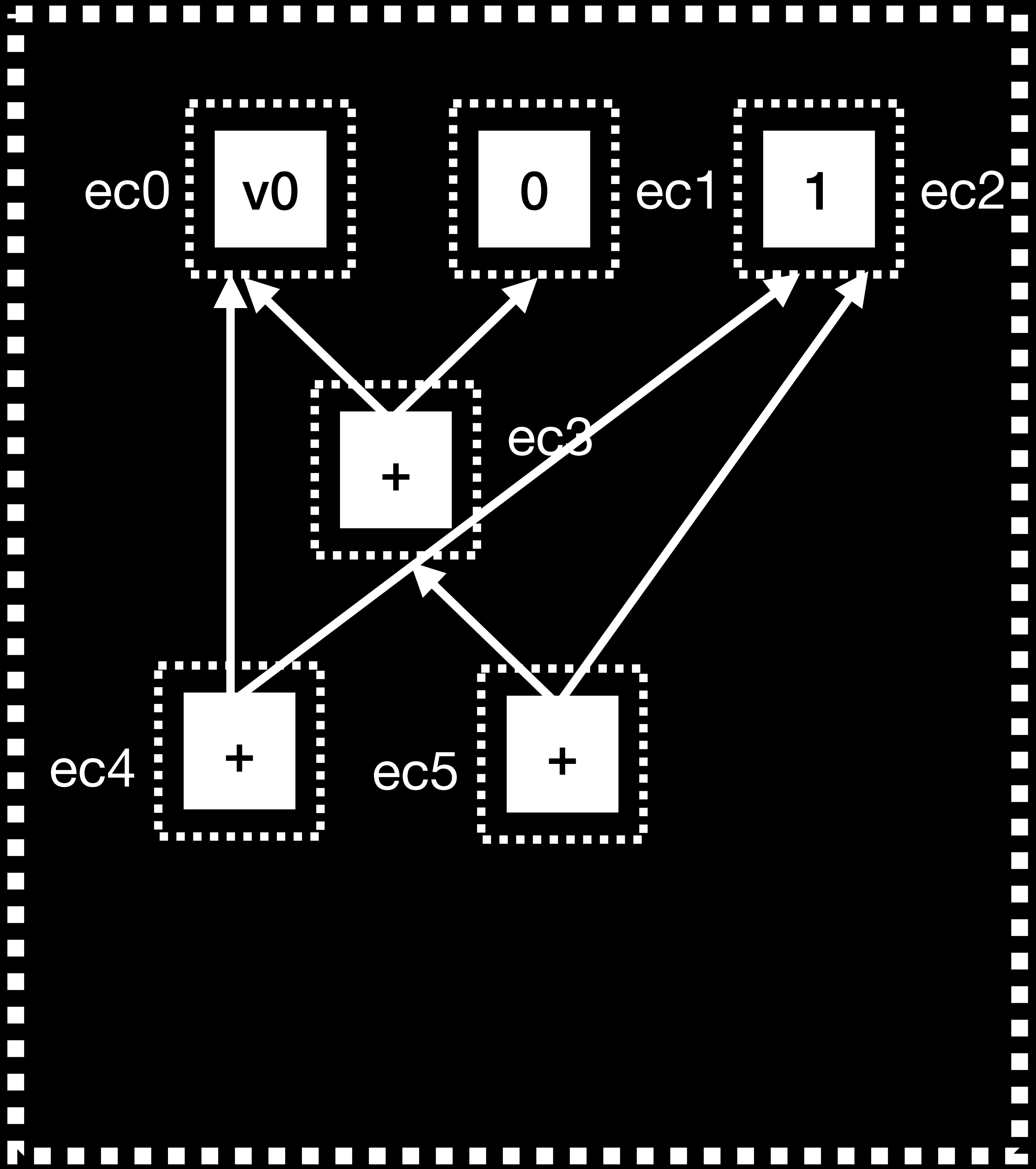
Rewrites and Repair



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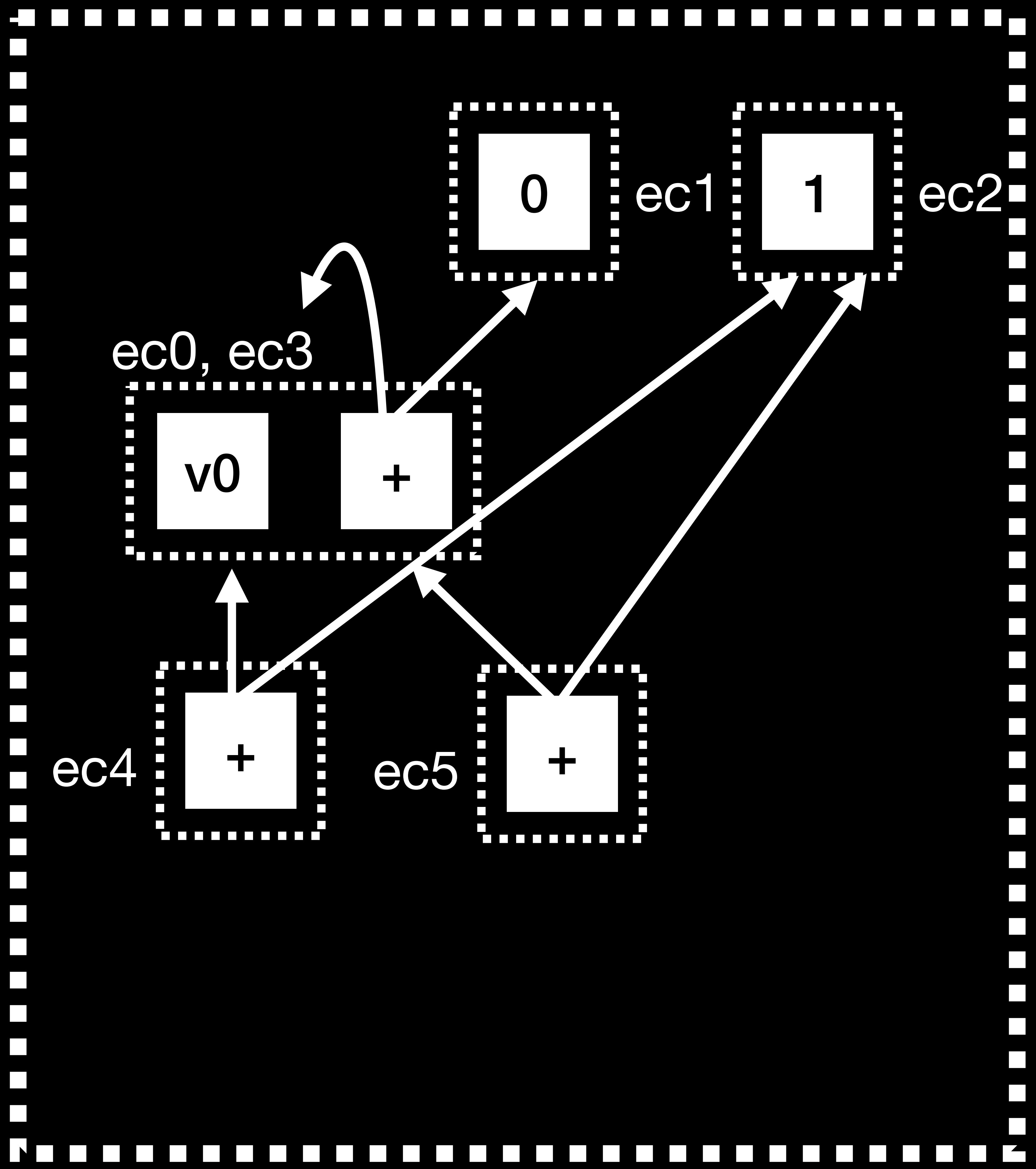

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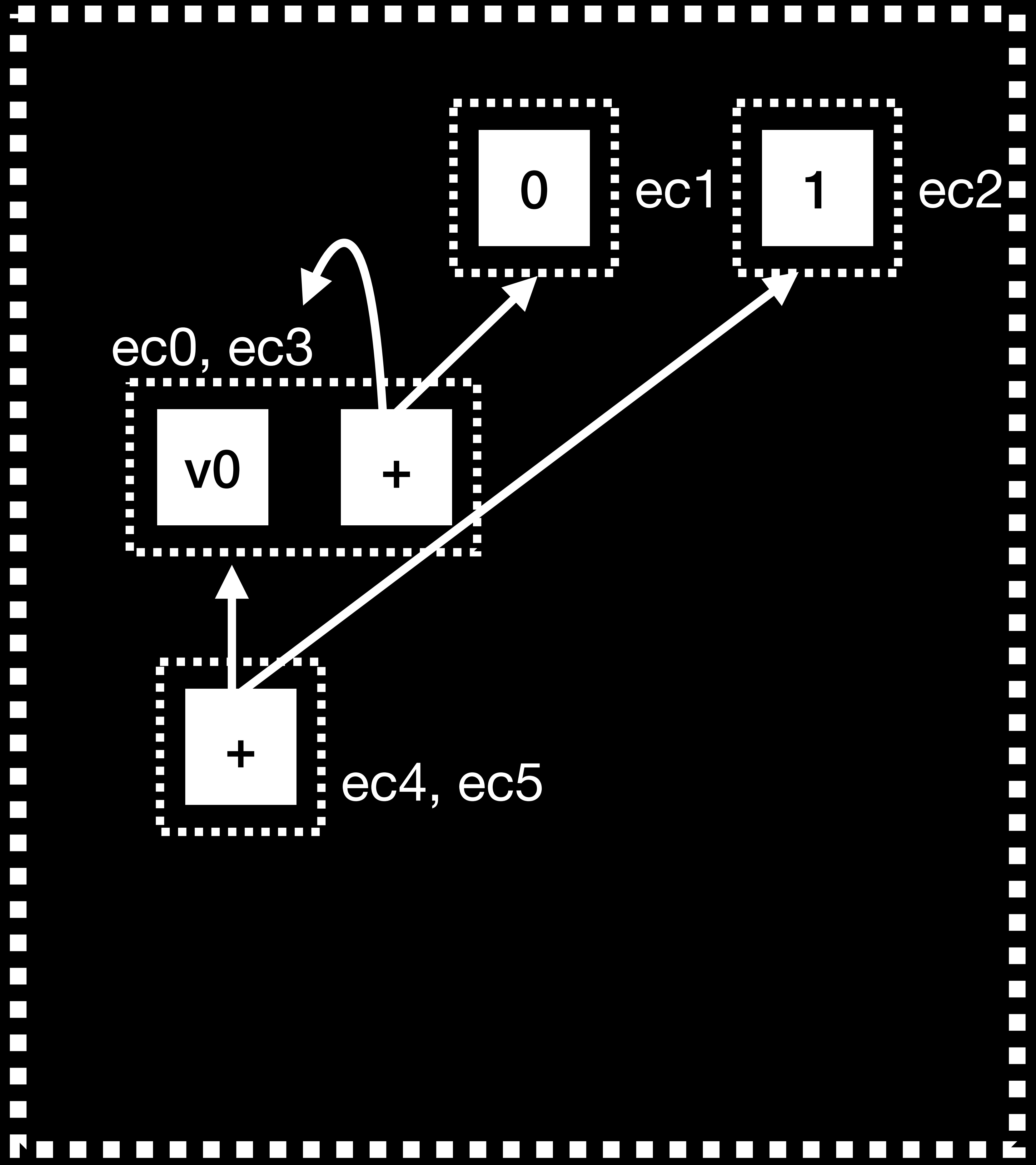

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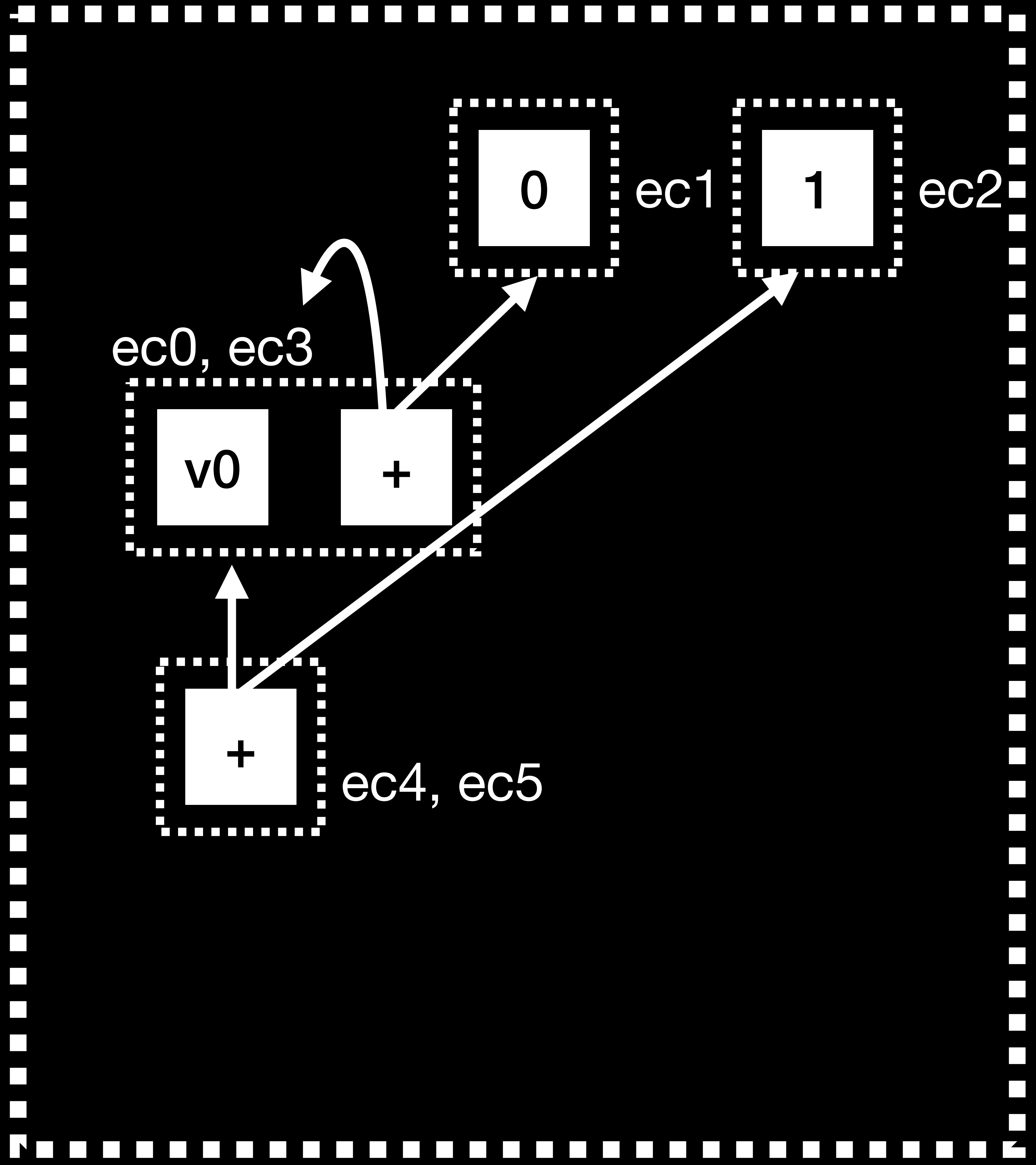

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Fixup requires backlinks (parent pointers) and re-interning, which are *costly*

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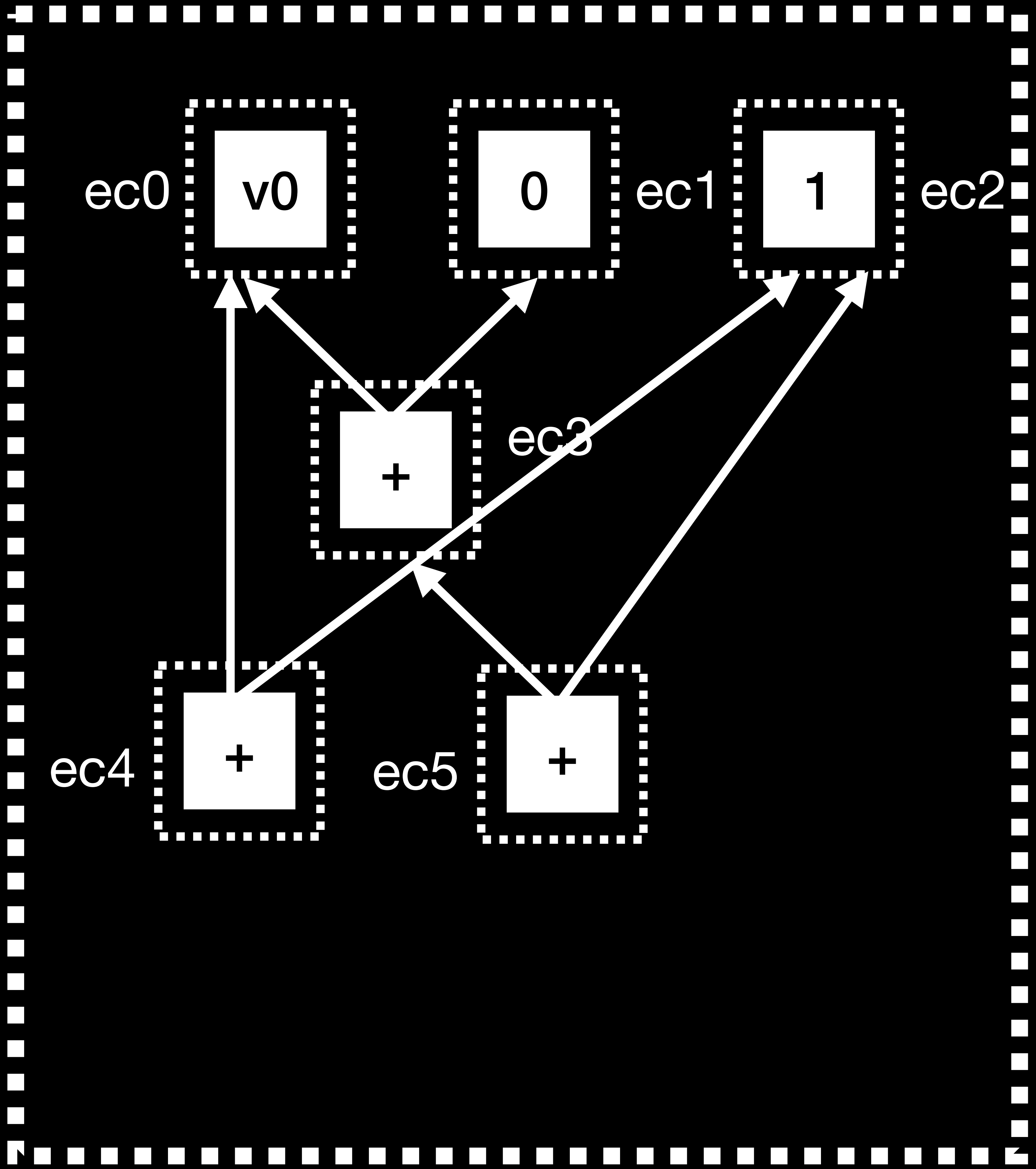

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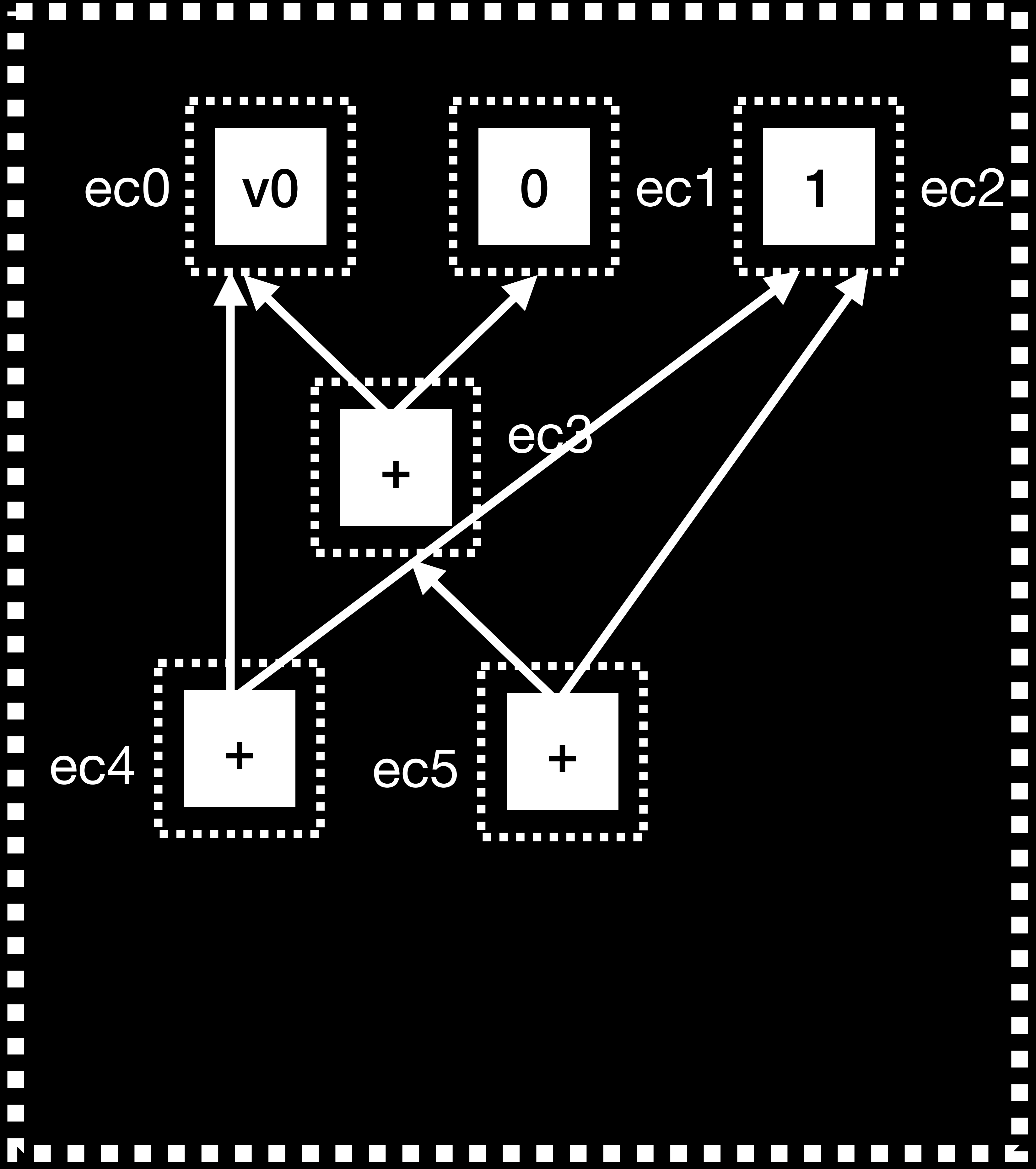

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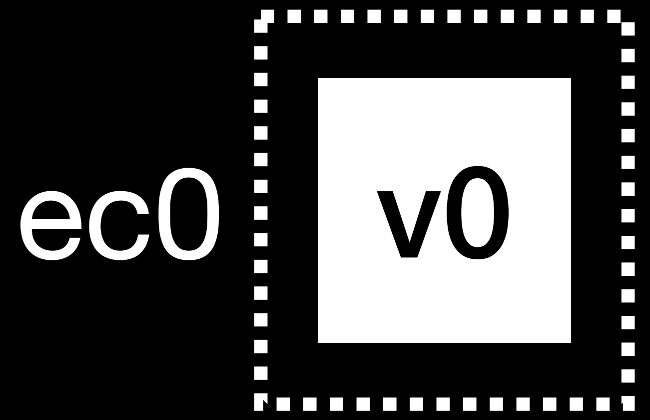

Parents:
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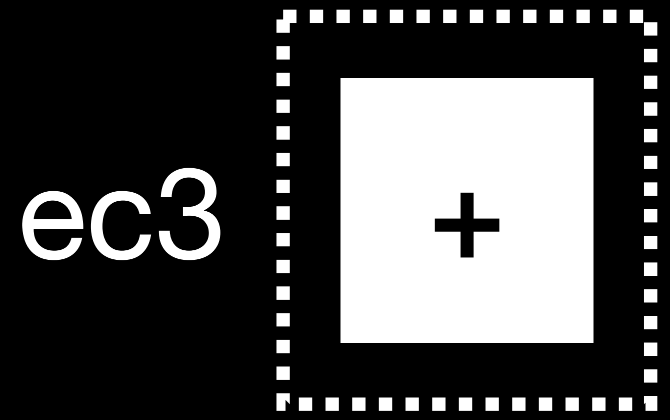
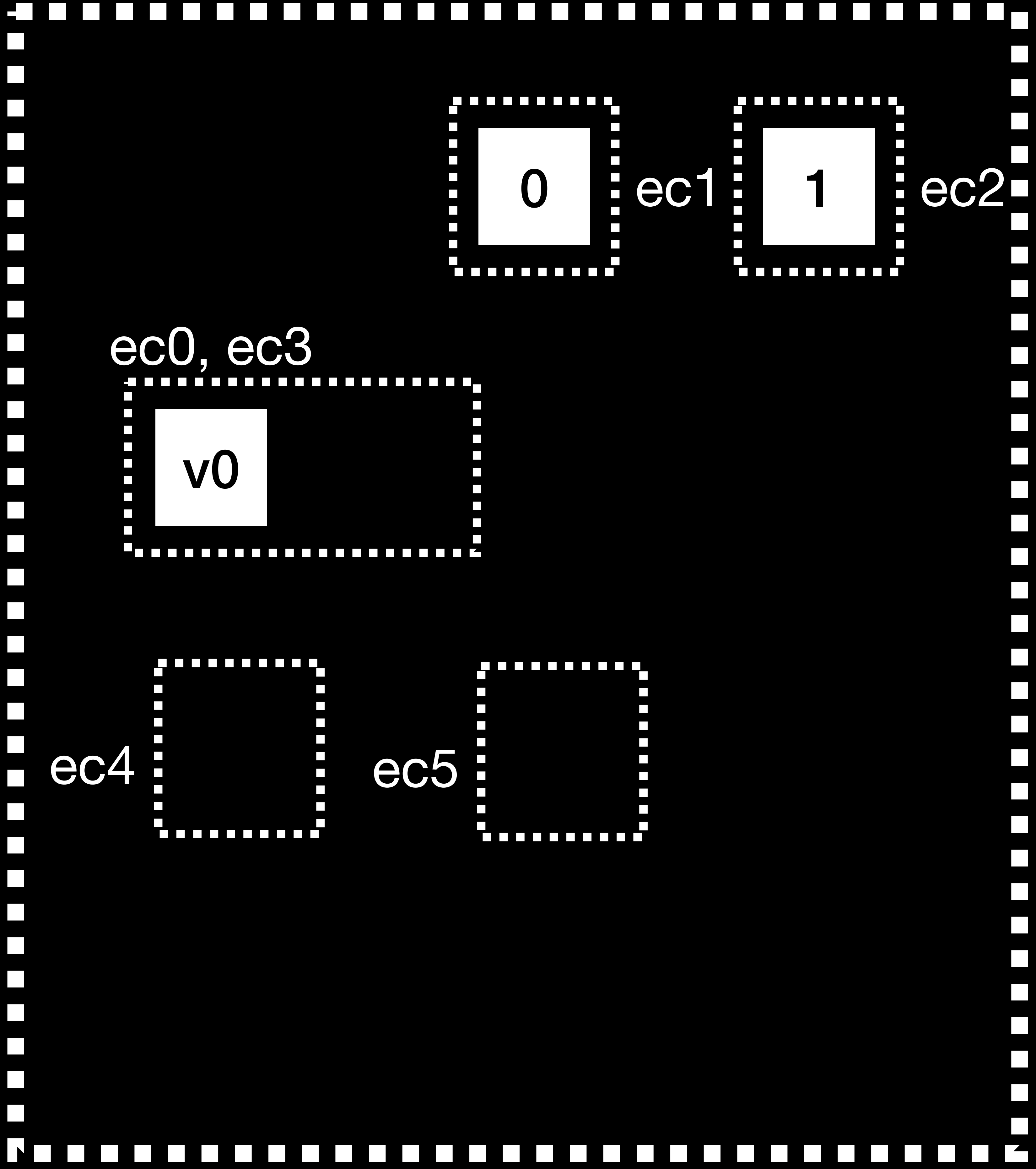


Parents:
{ec5 := (+ ec3 ec2)}

Rewrites and Repair



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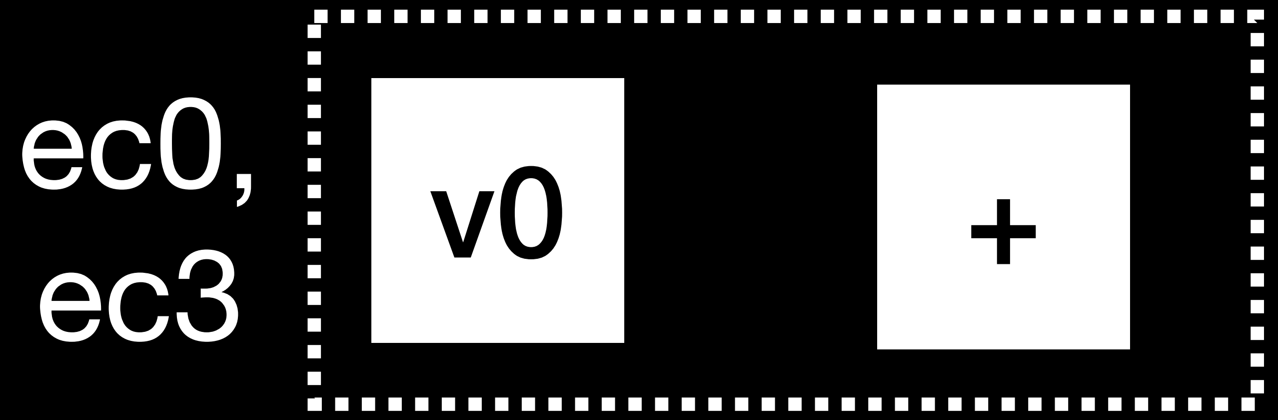

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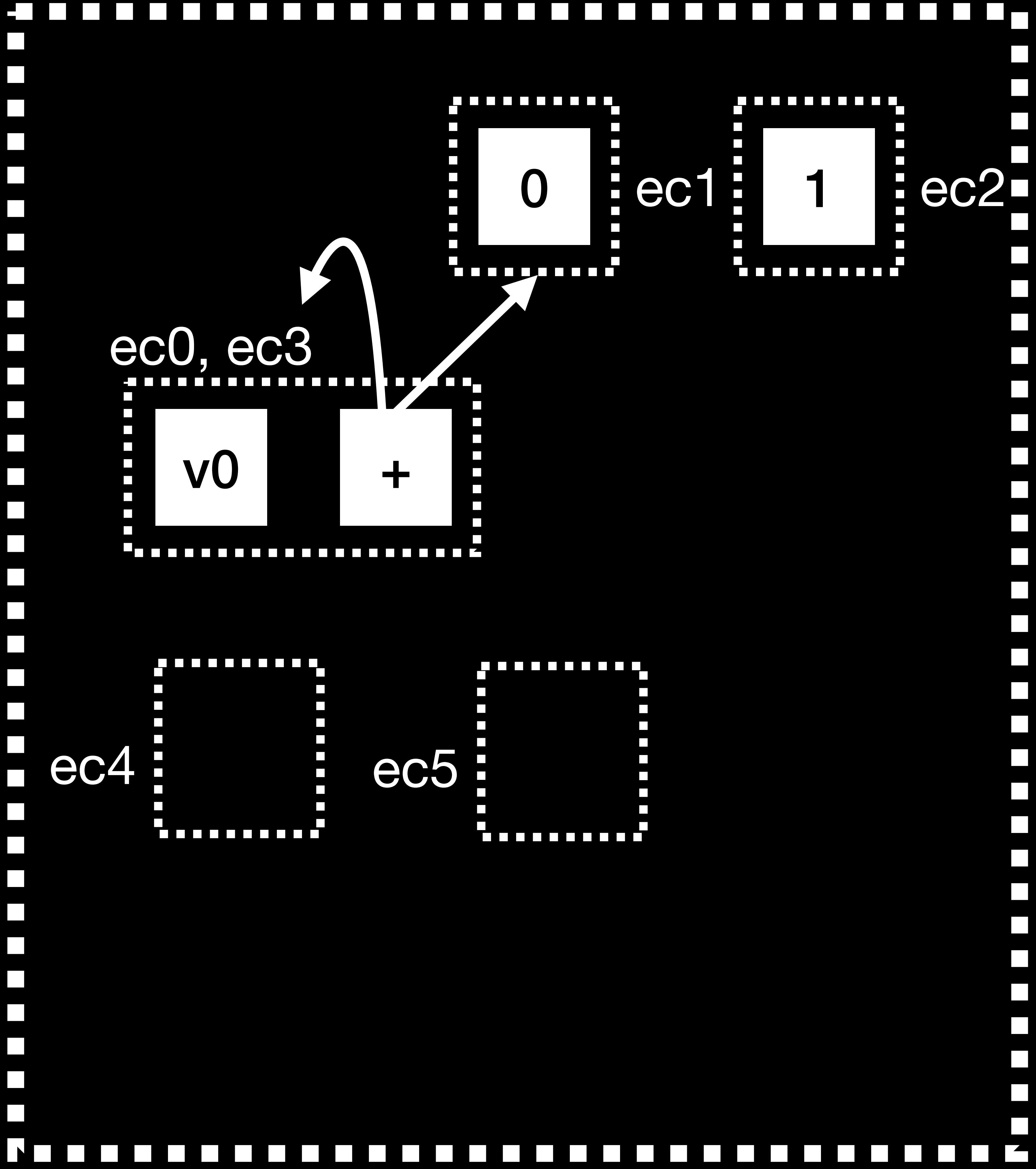

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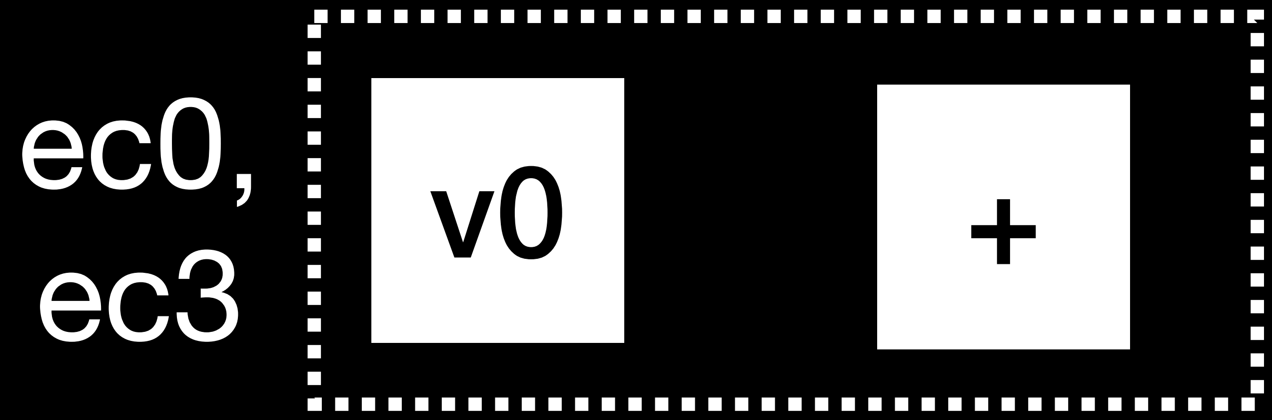

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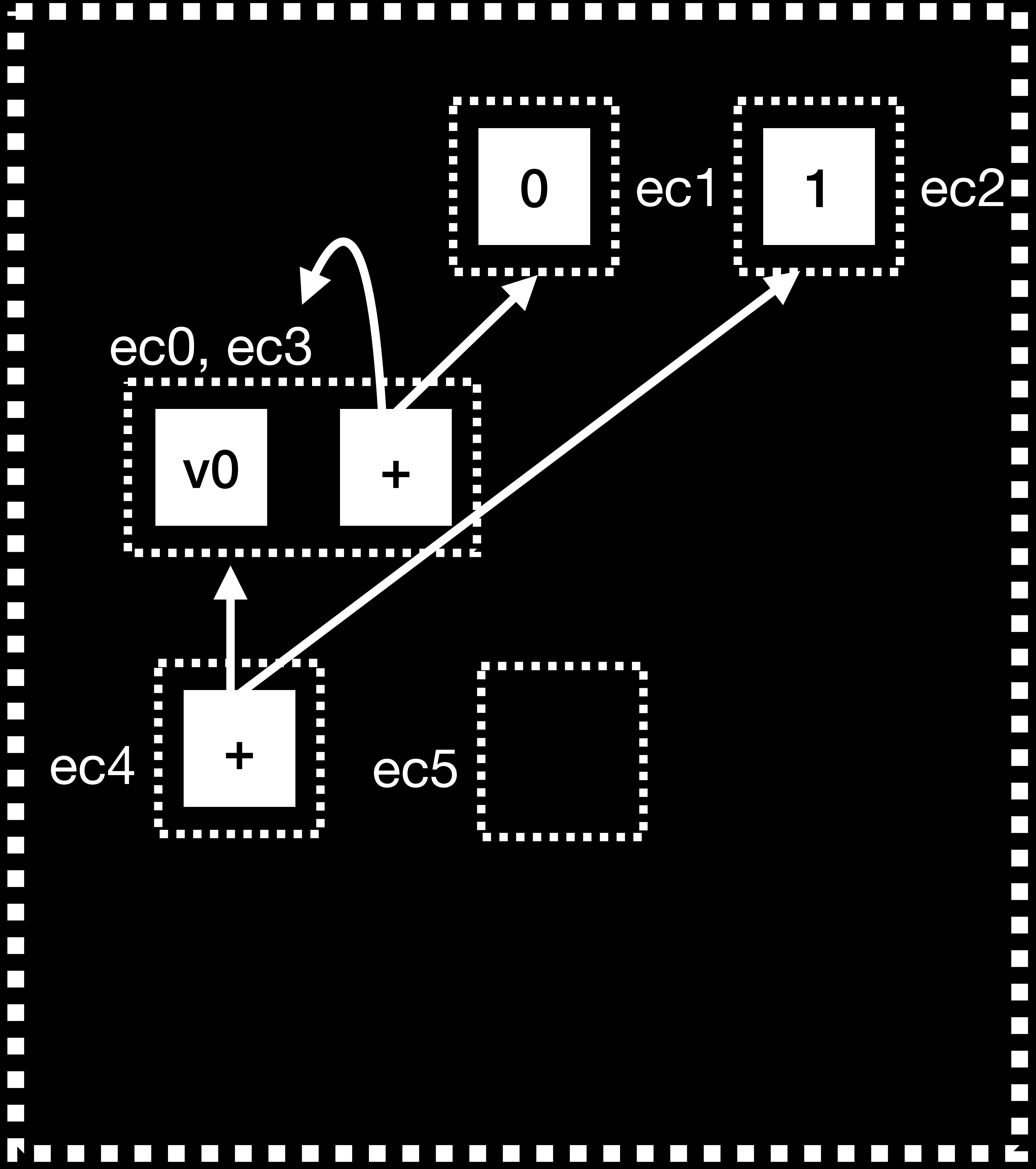

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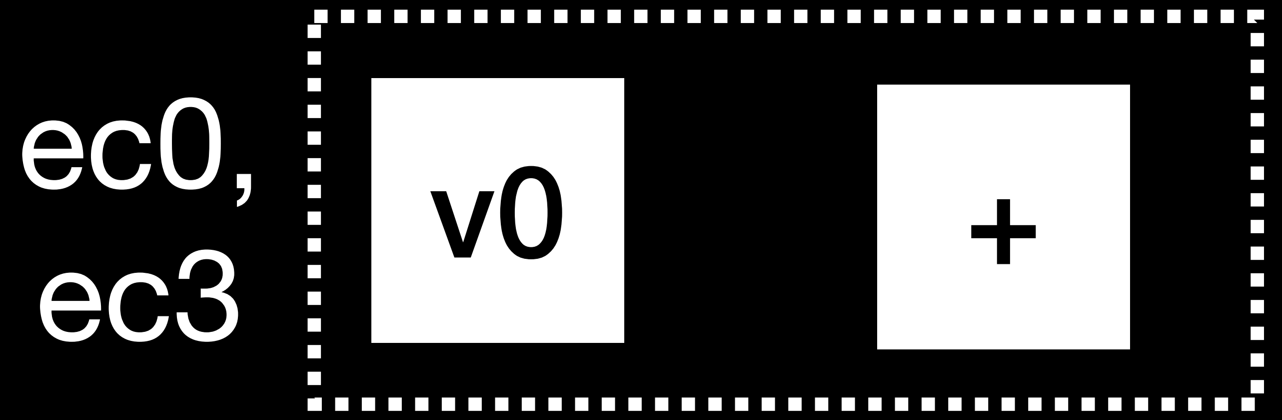

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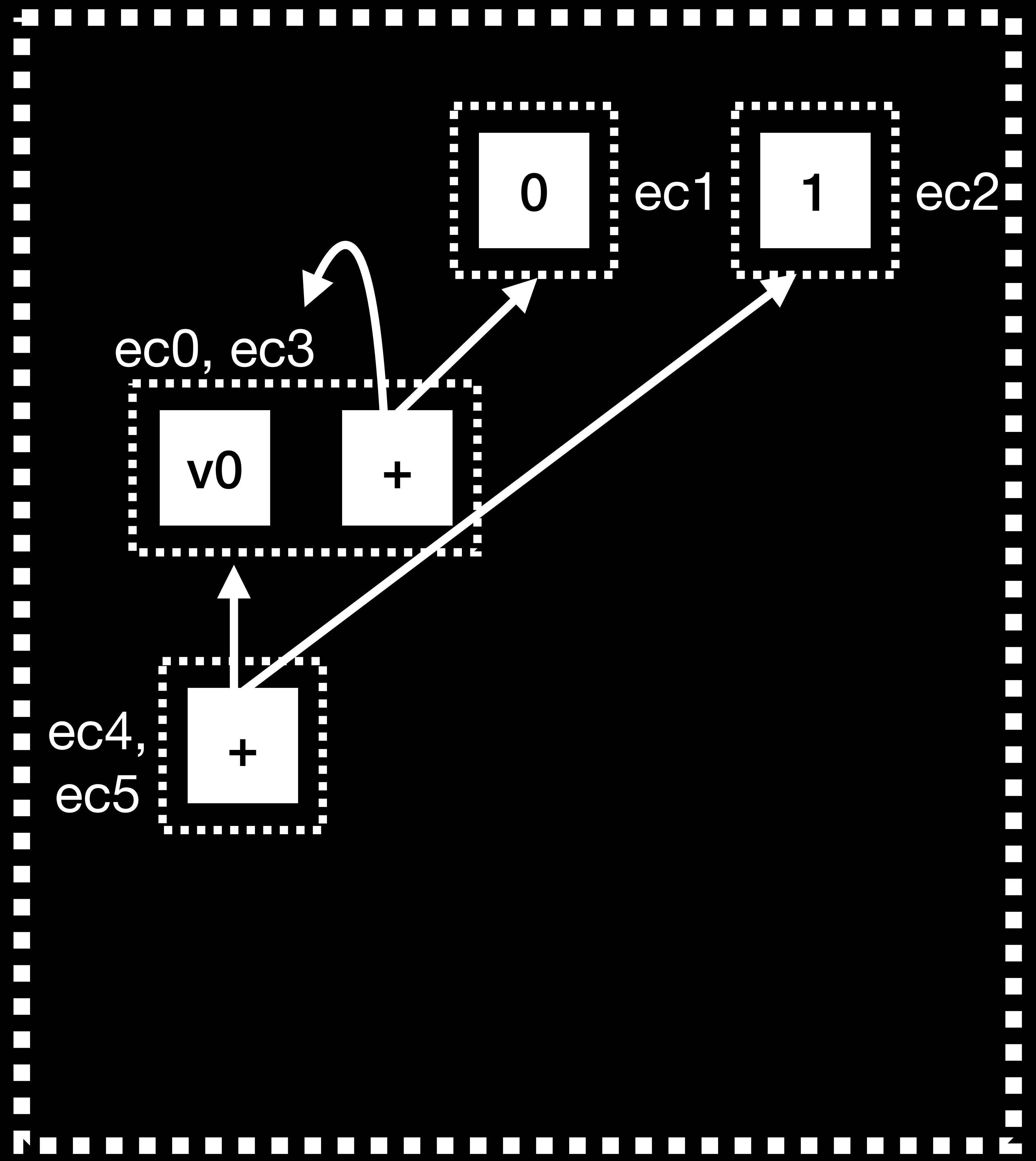

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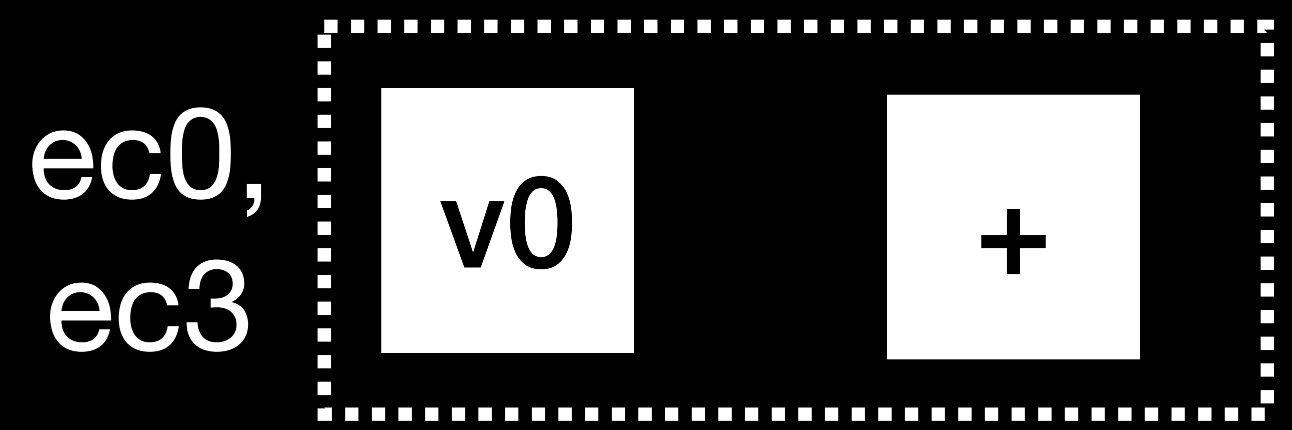

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= (+ ec0 ec2)
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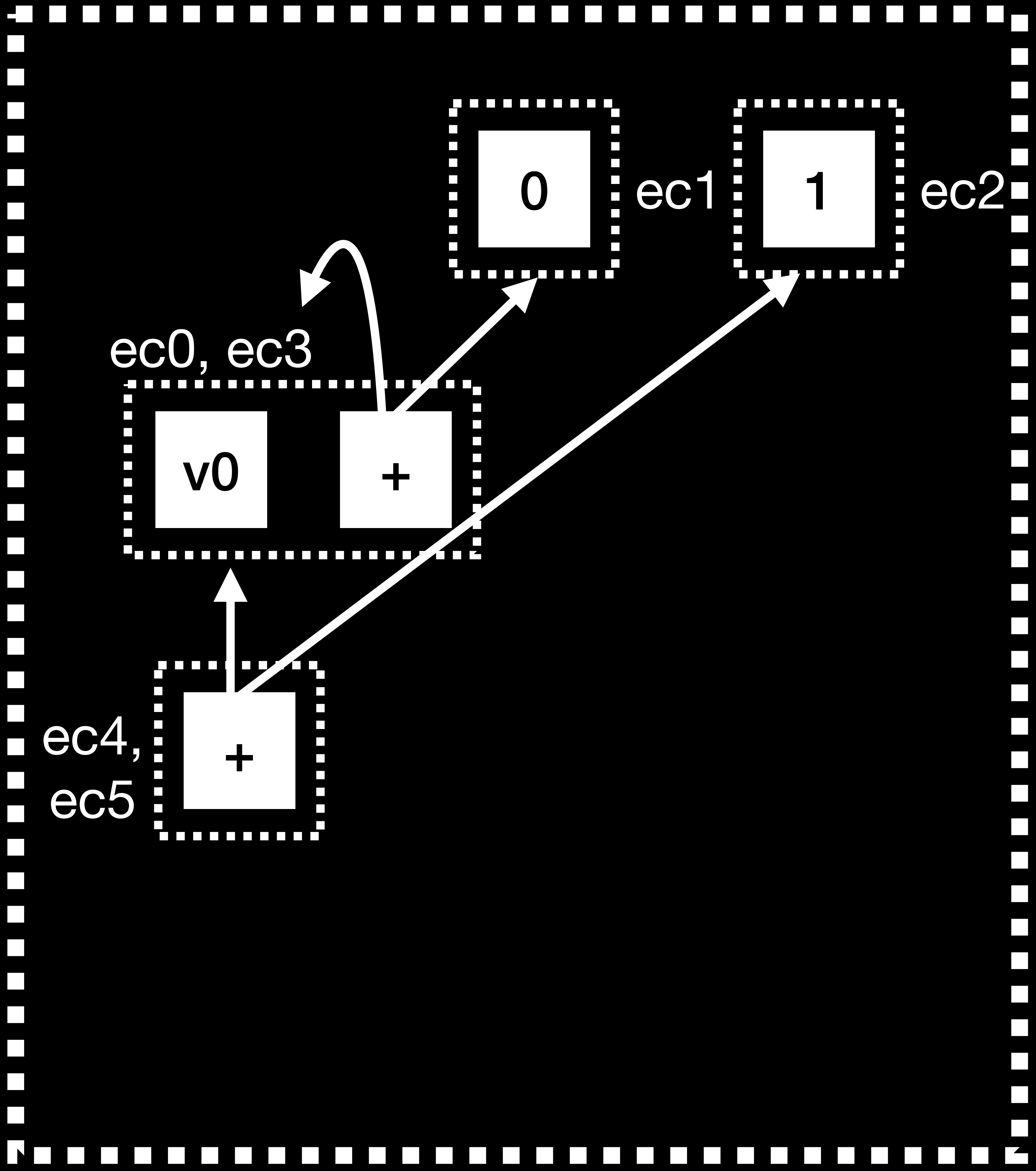

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Eliminate:
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- Duplicated storage of nodes?
- Merging of parent lists, with dedup’ing?

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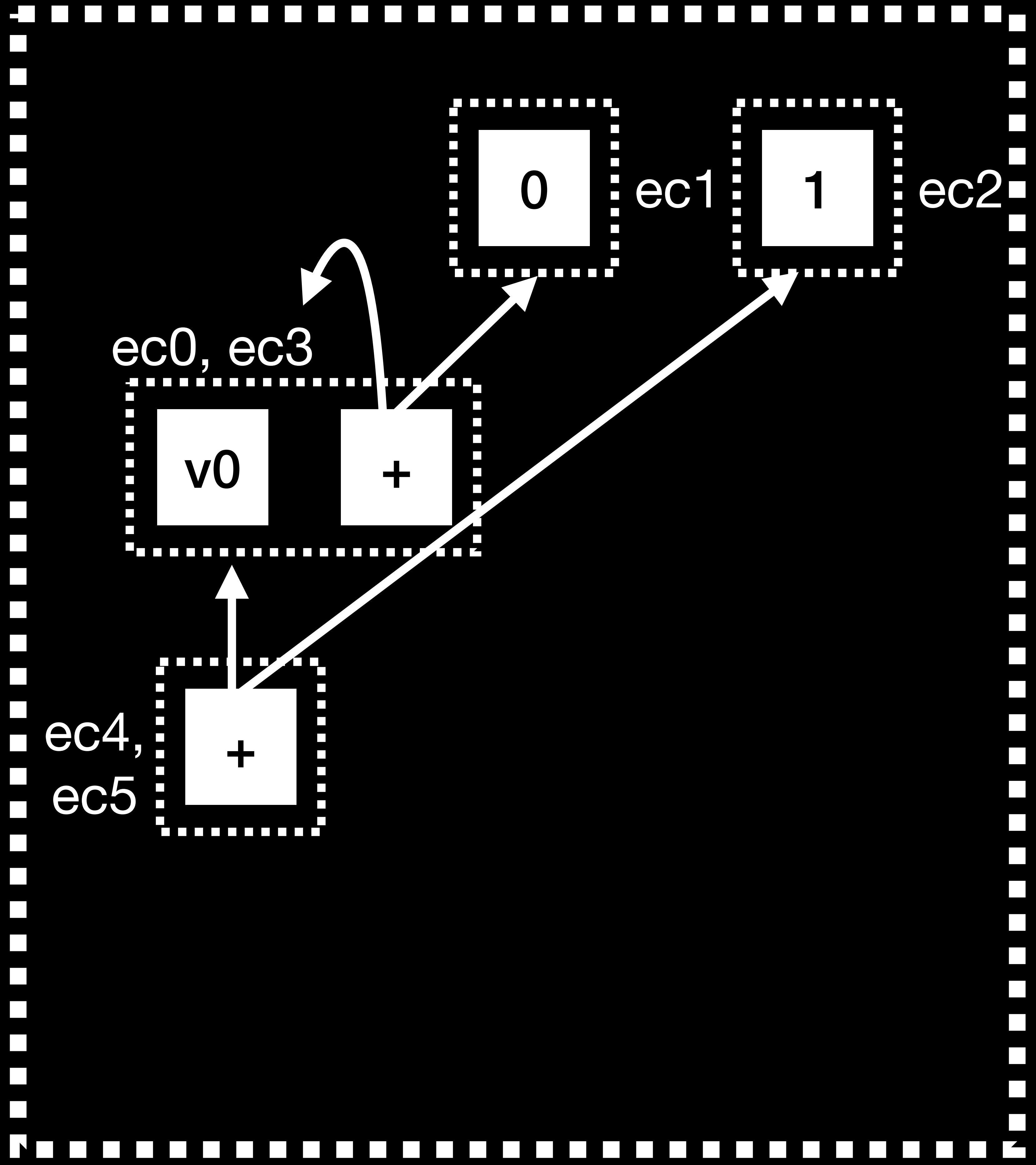

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—> compile + memory overhead too high
vs. traditional compiler pipeline

Rewrites and Repair

Idea: no need to repair uses if eclass is in *final form* before we use it!

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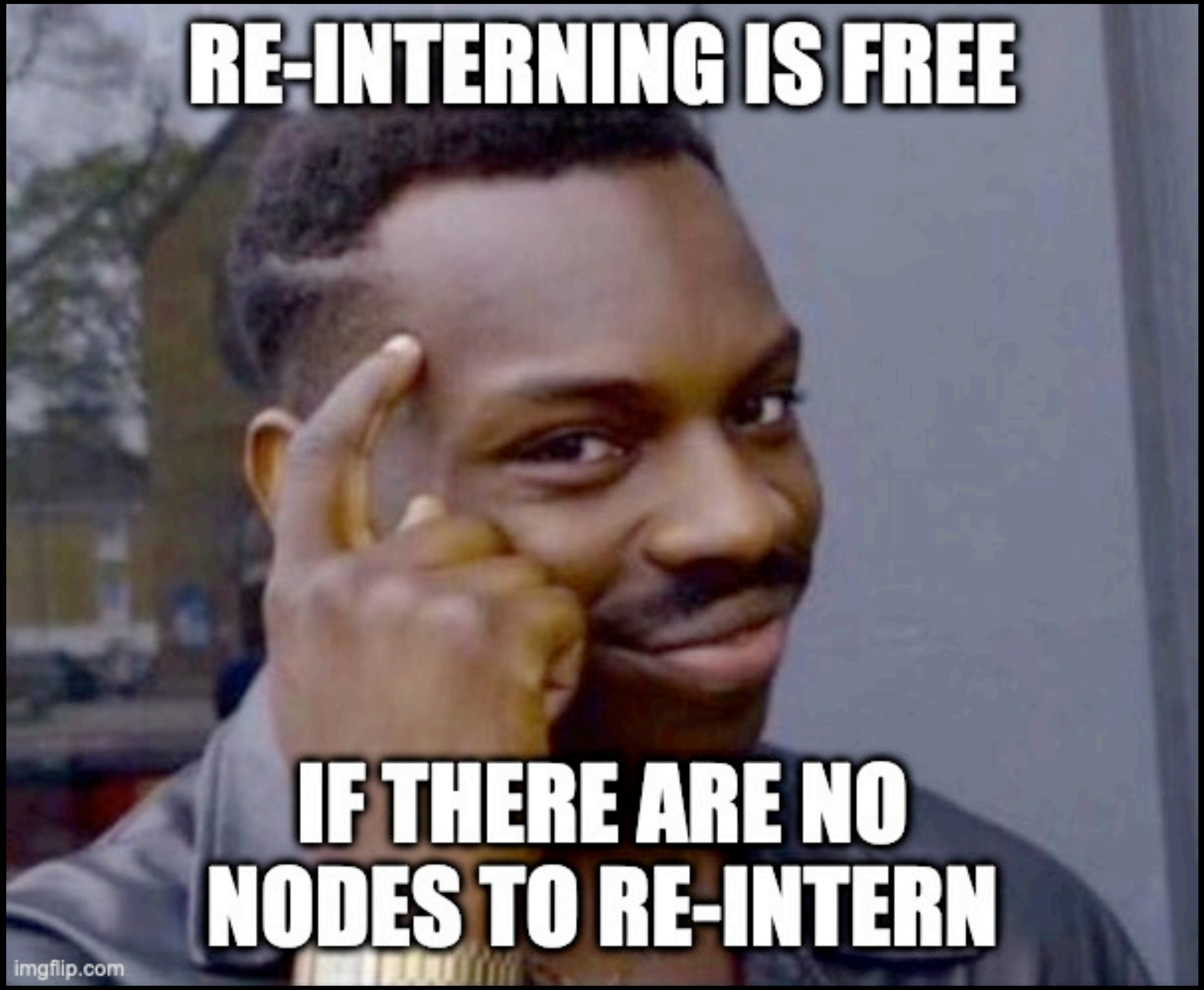
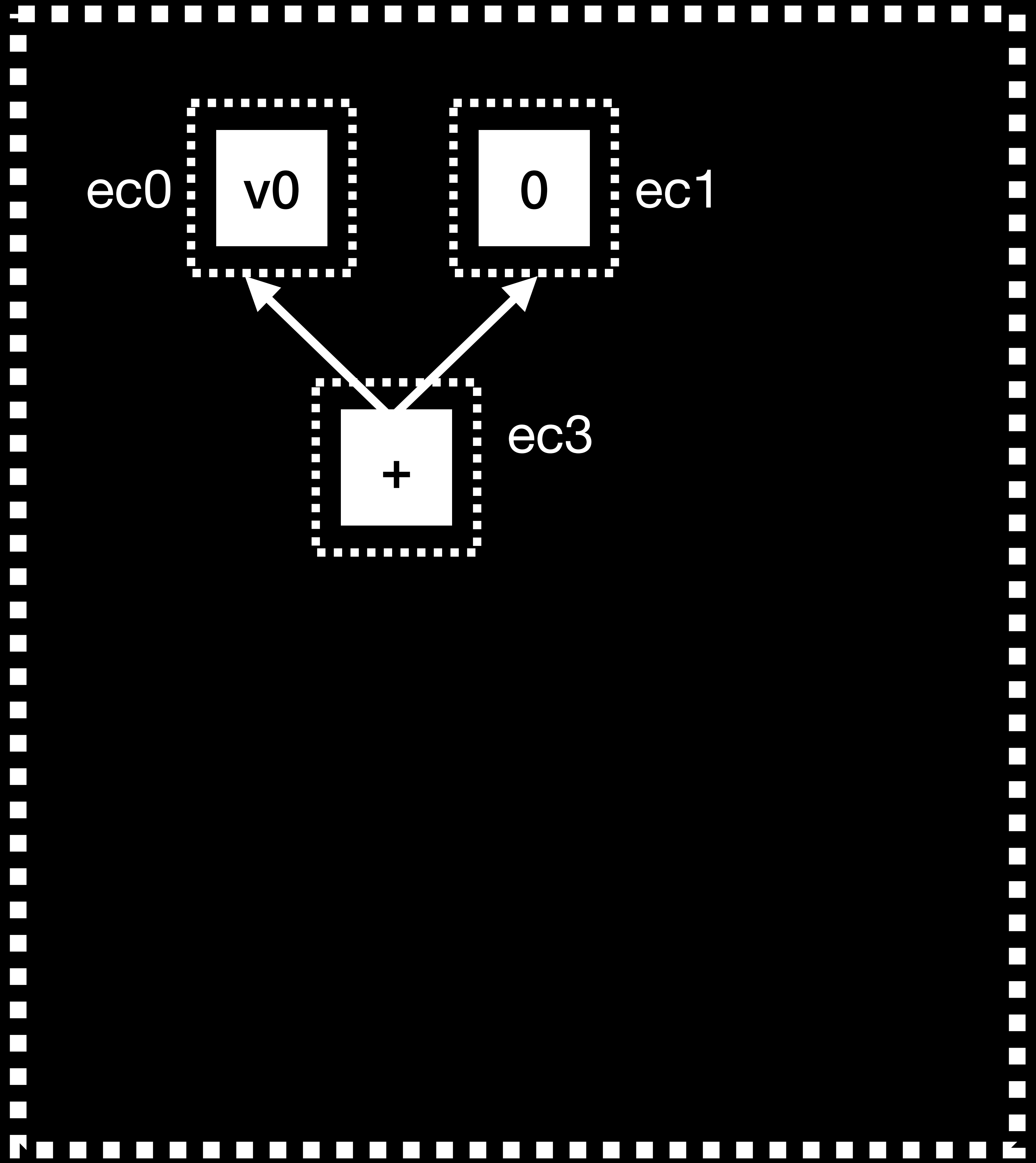


Rewrite eagerly?!



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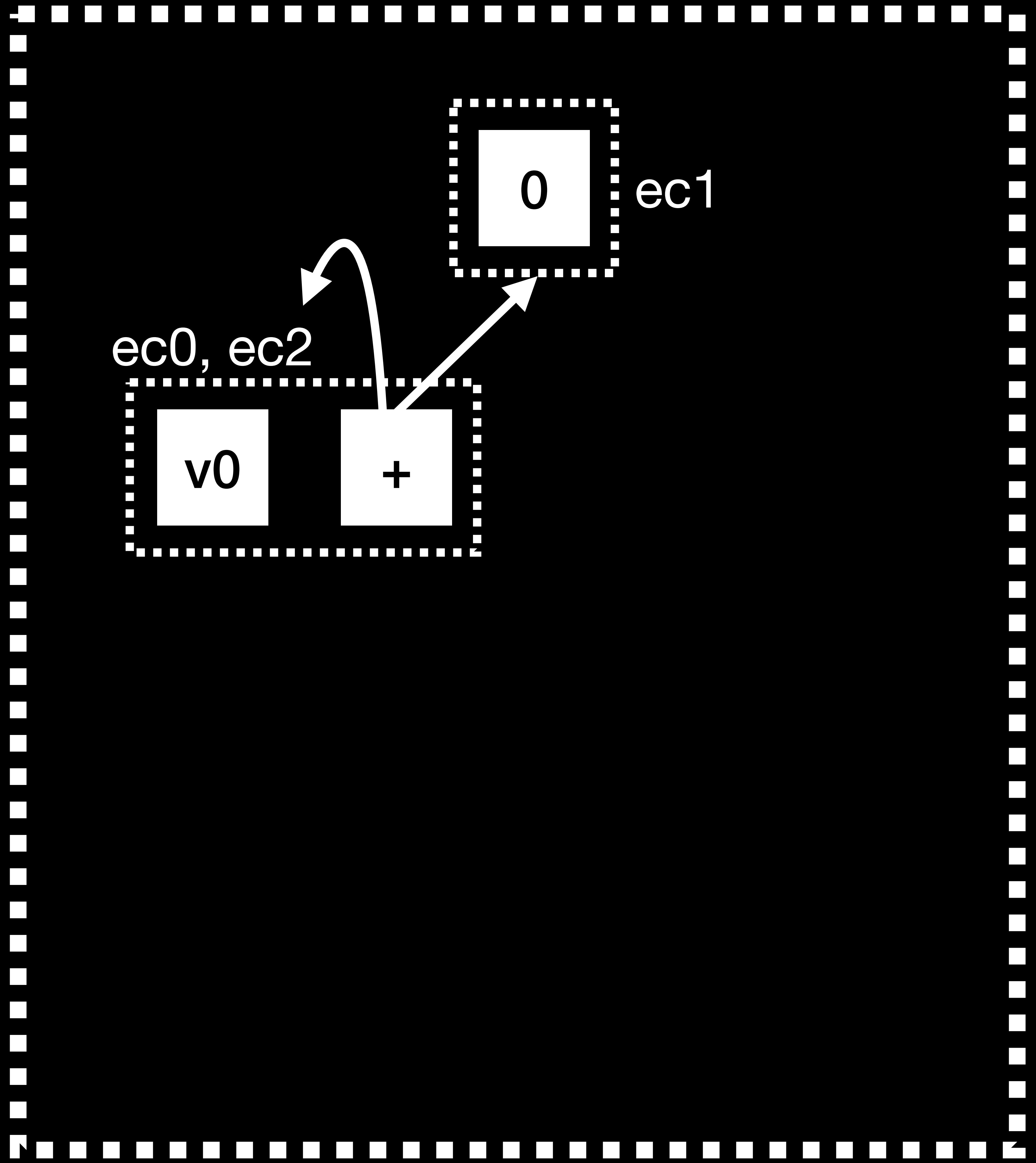

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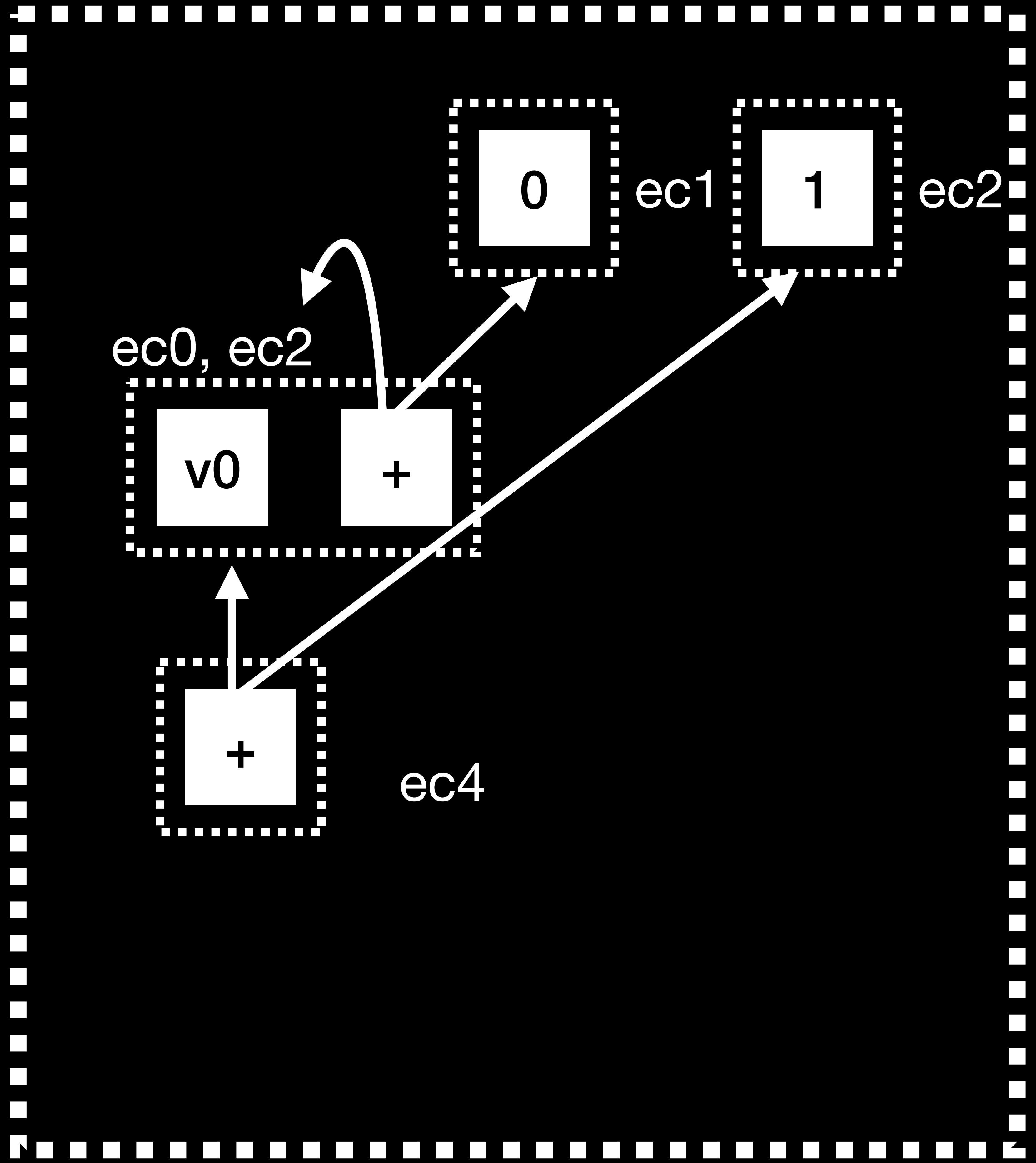

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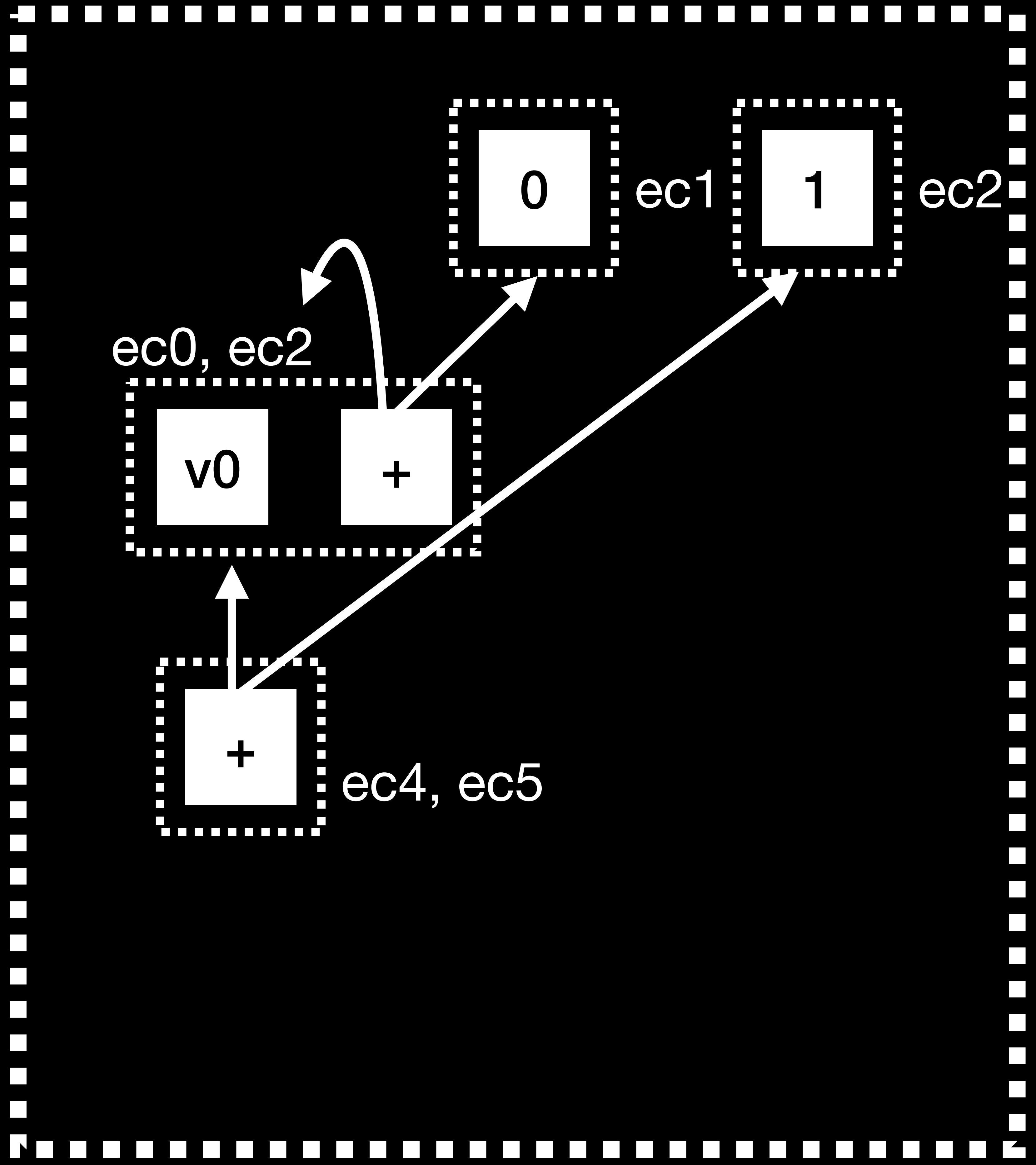
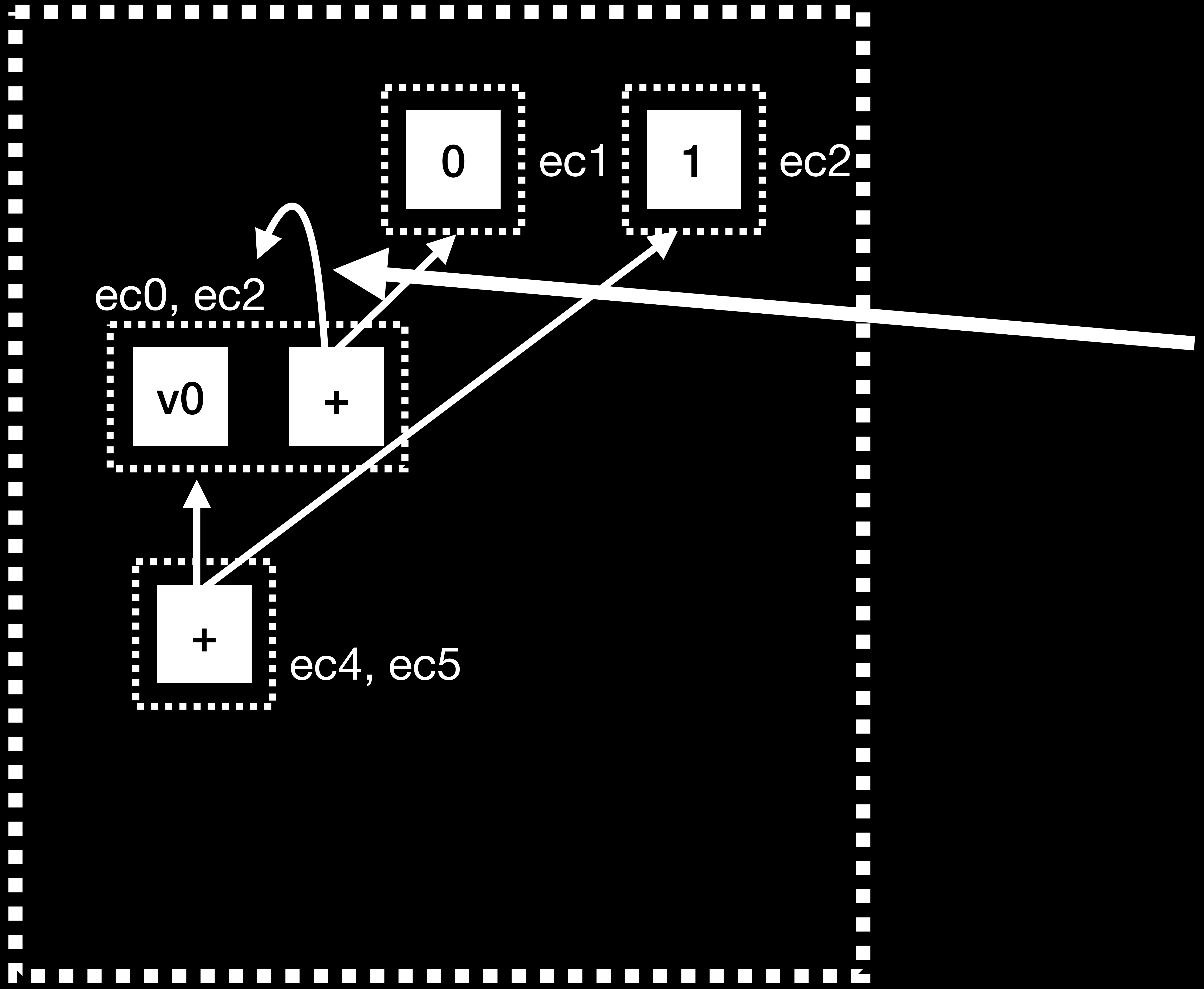


Rewrite already occurred
→ ec5 hash-conses to ec4

Rewrite eagerly?!



How do we handle this cycle?

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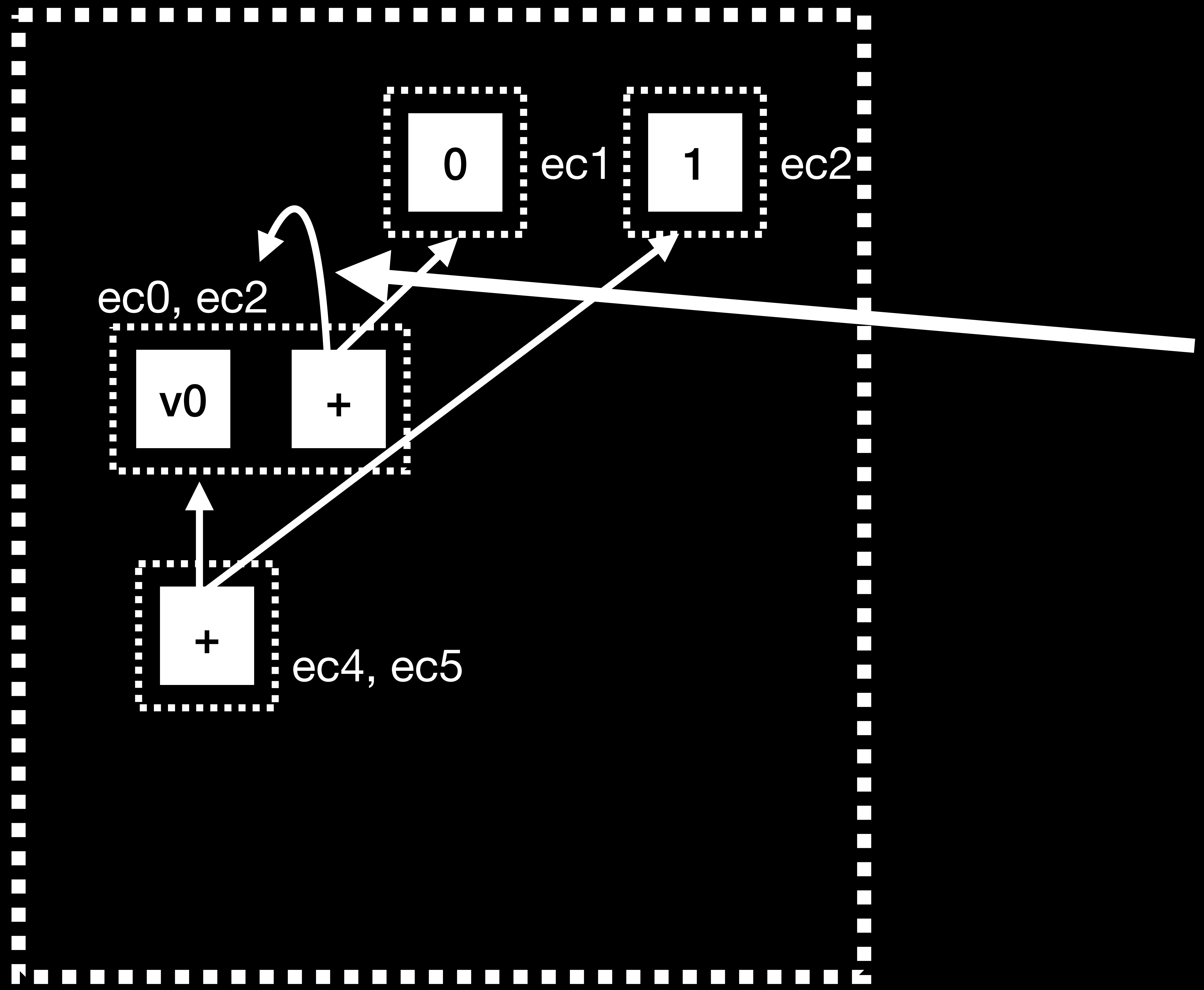

How do we handle this cycle?
- Cycles preclude single pass (imply fixpoint algorithm)

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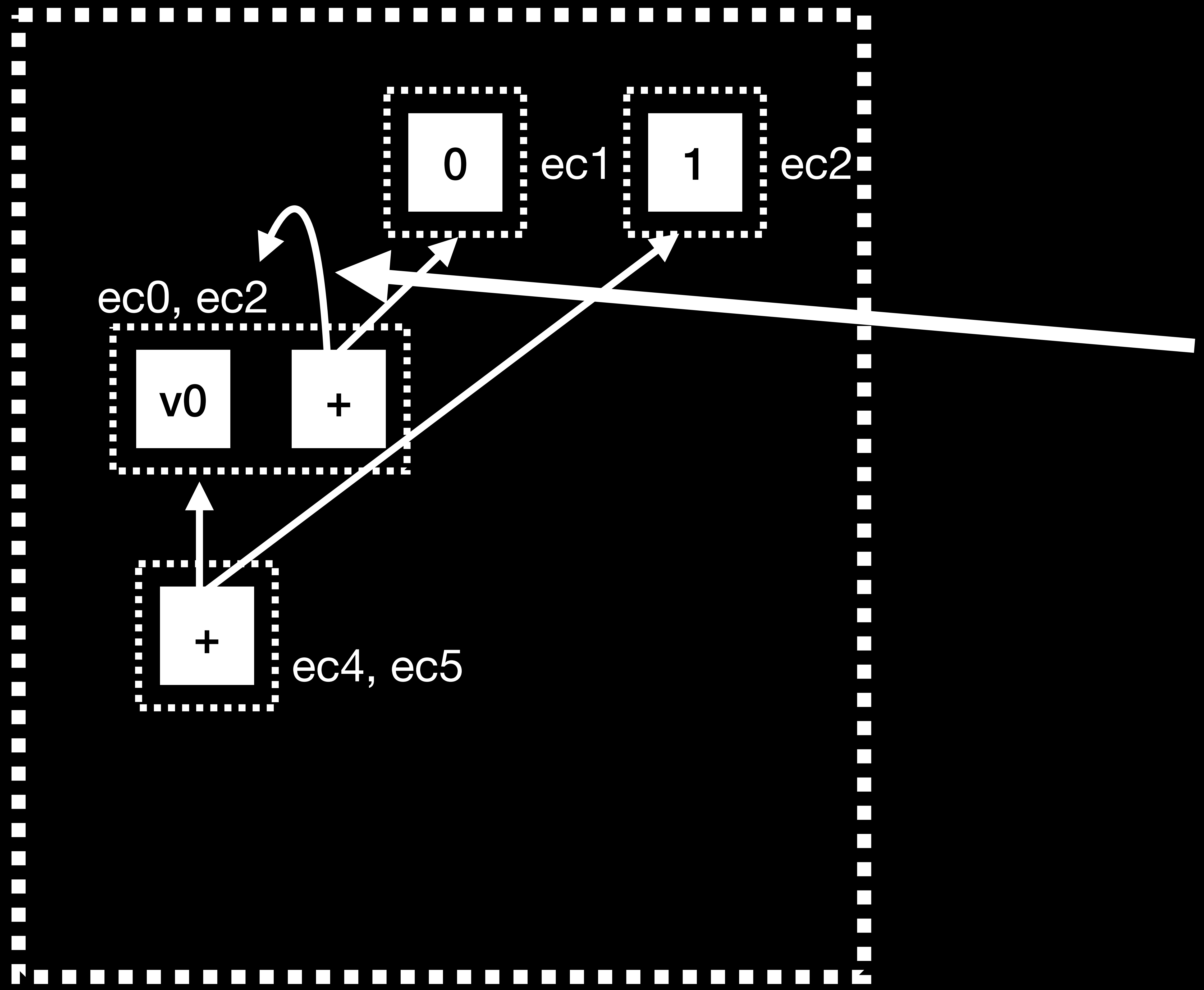
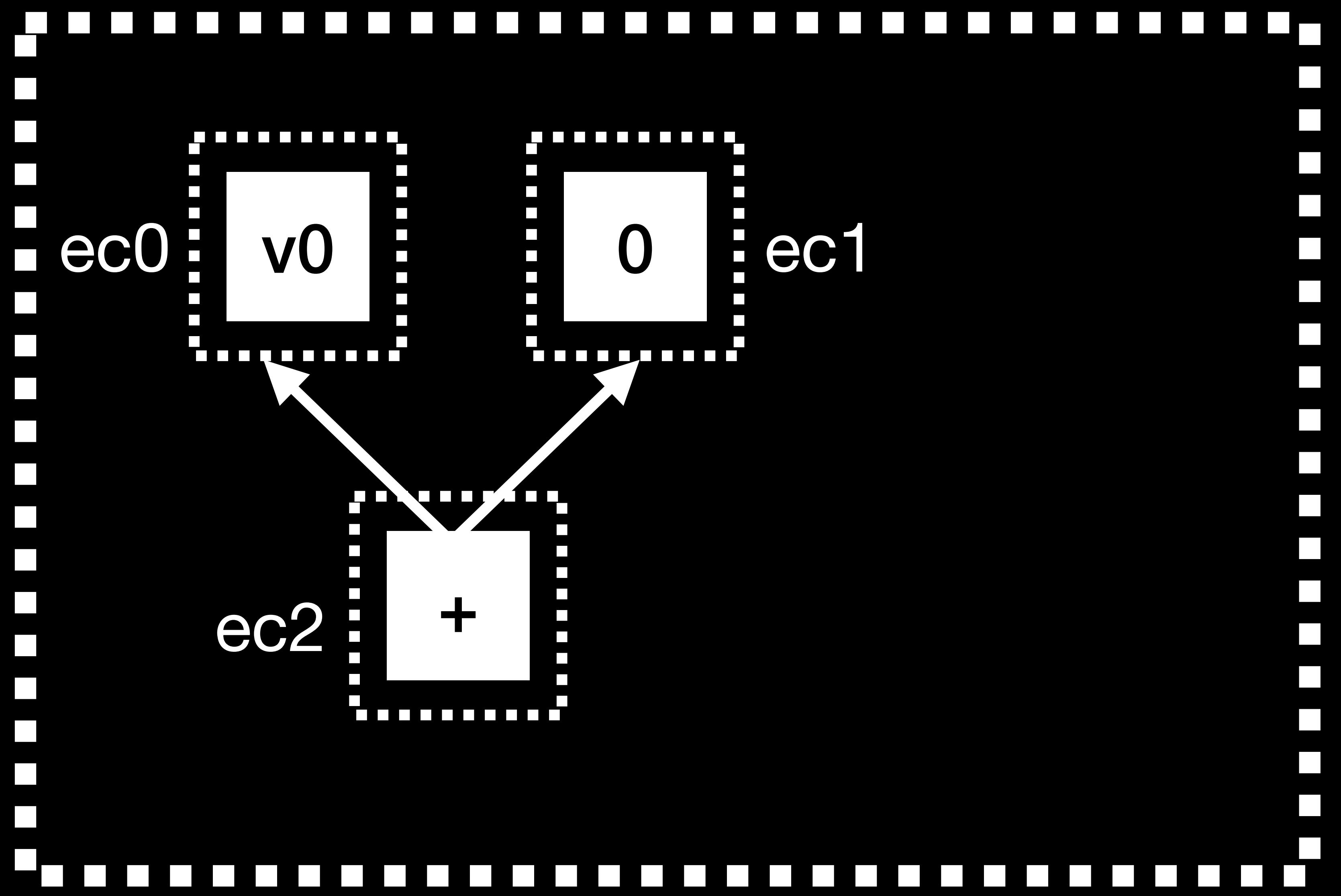


How do we handle this cycle?

- Cycles preclude single pass (imply fixpoint algorithm)
- We’re rewriting the arg after its use (no longer eager)
  —> need parent lists again

Cycles in E-graphs



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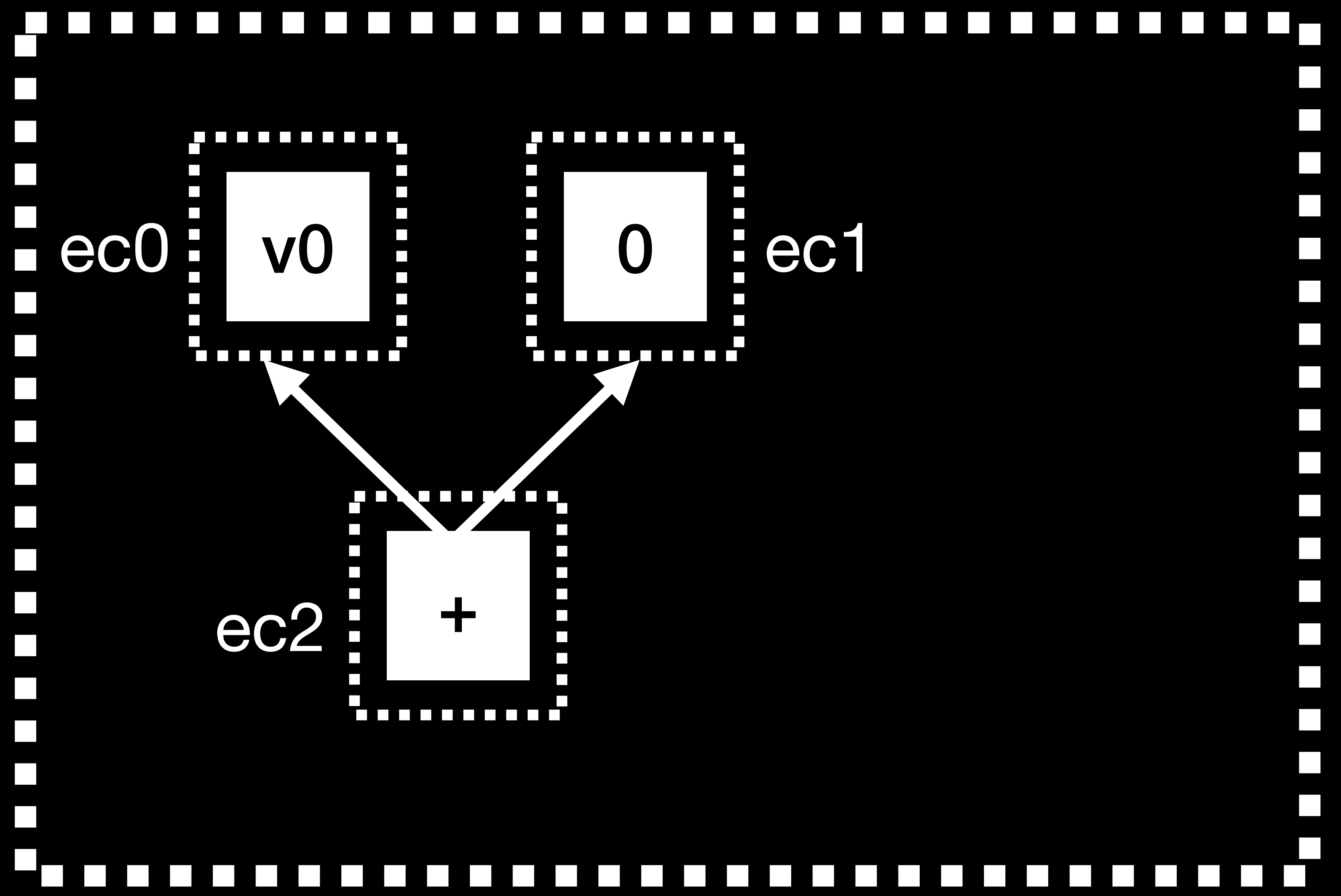

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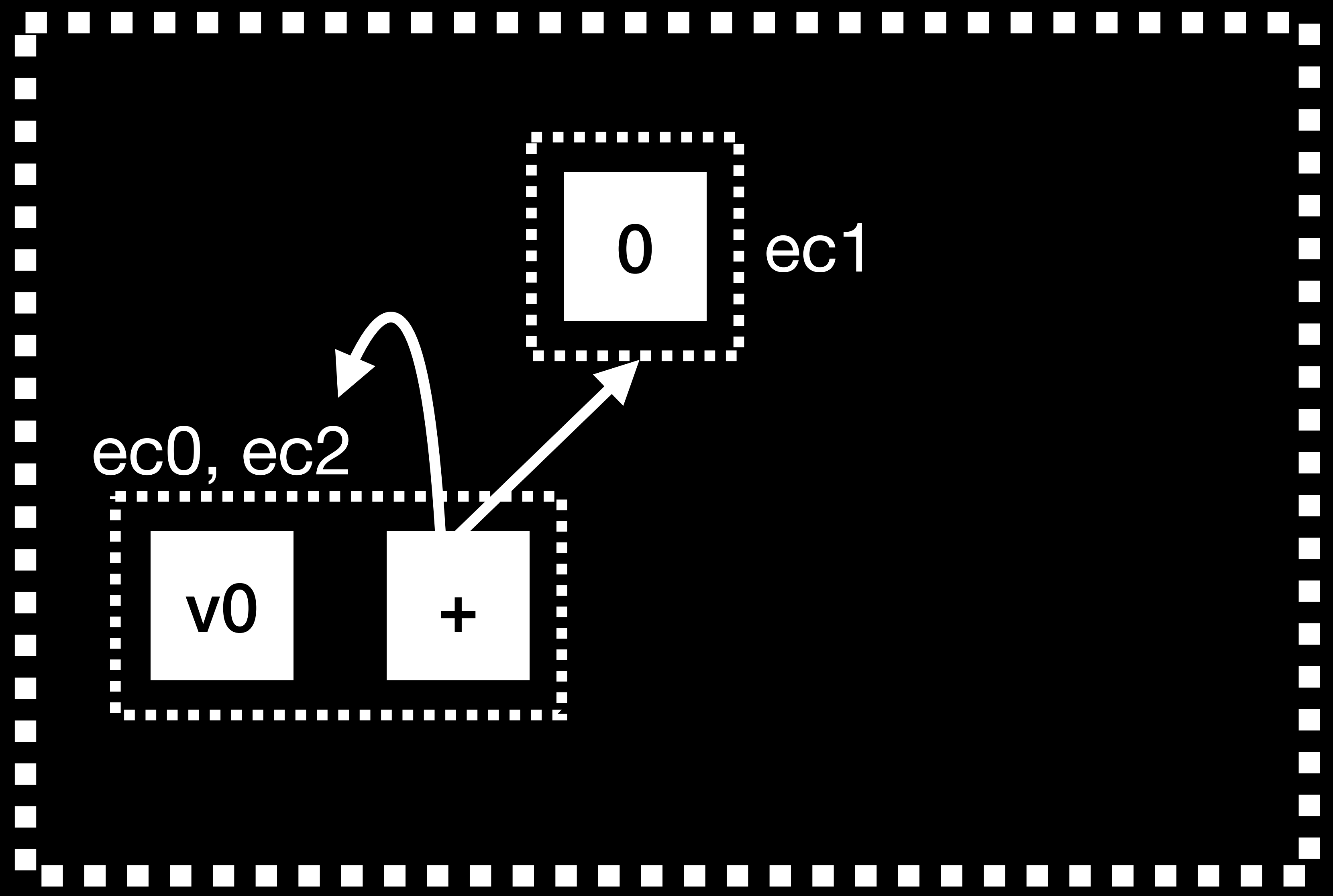

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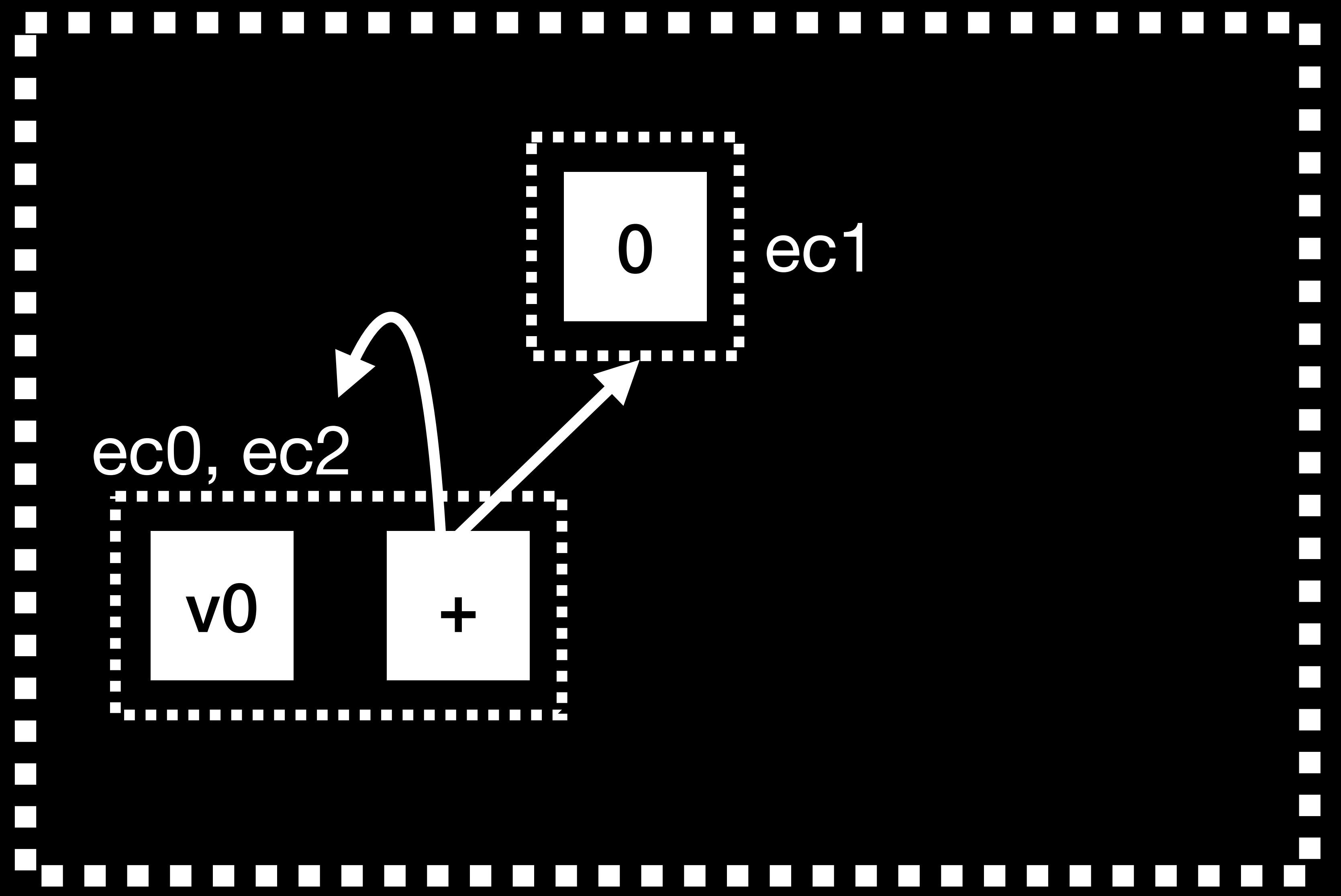

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Observation:

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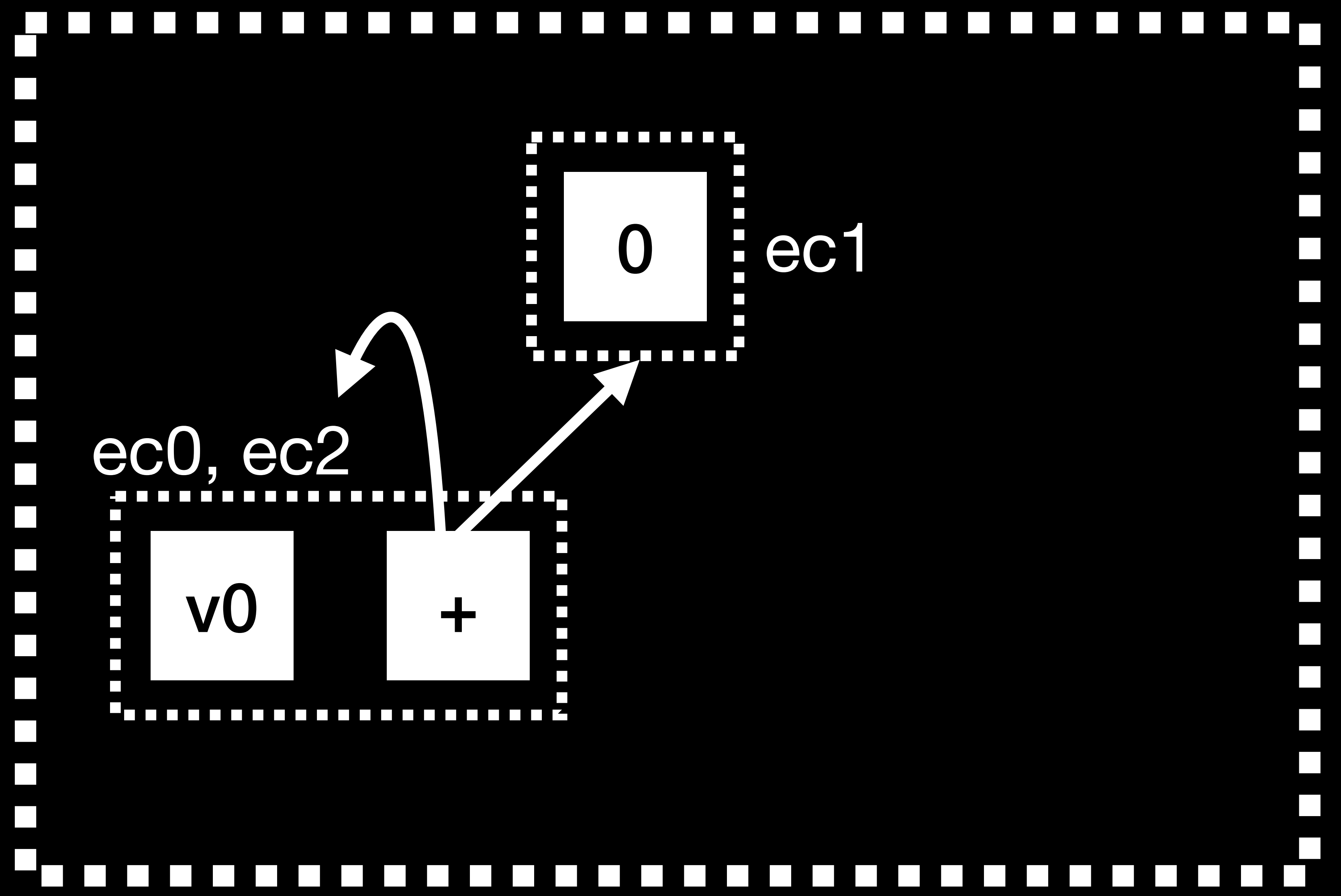

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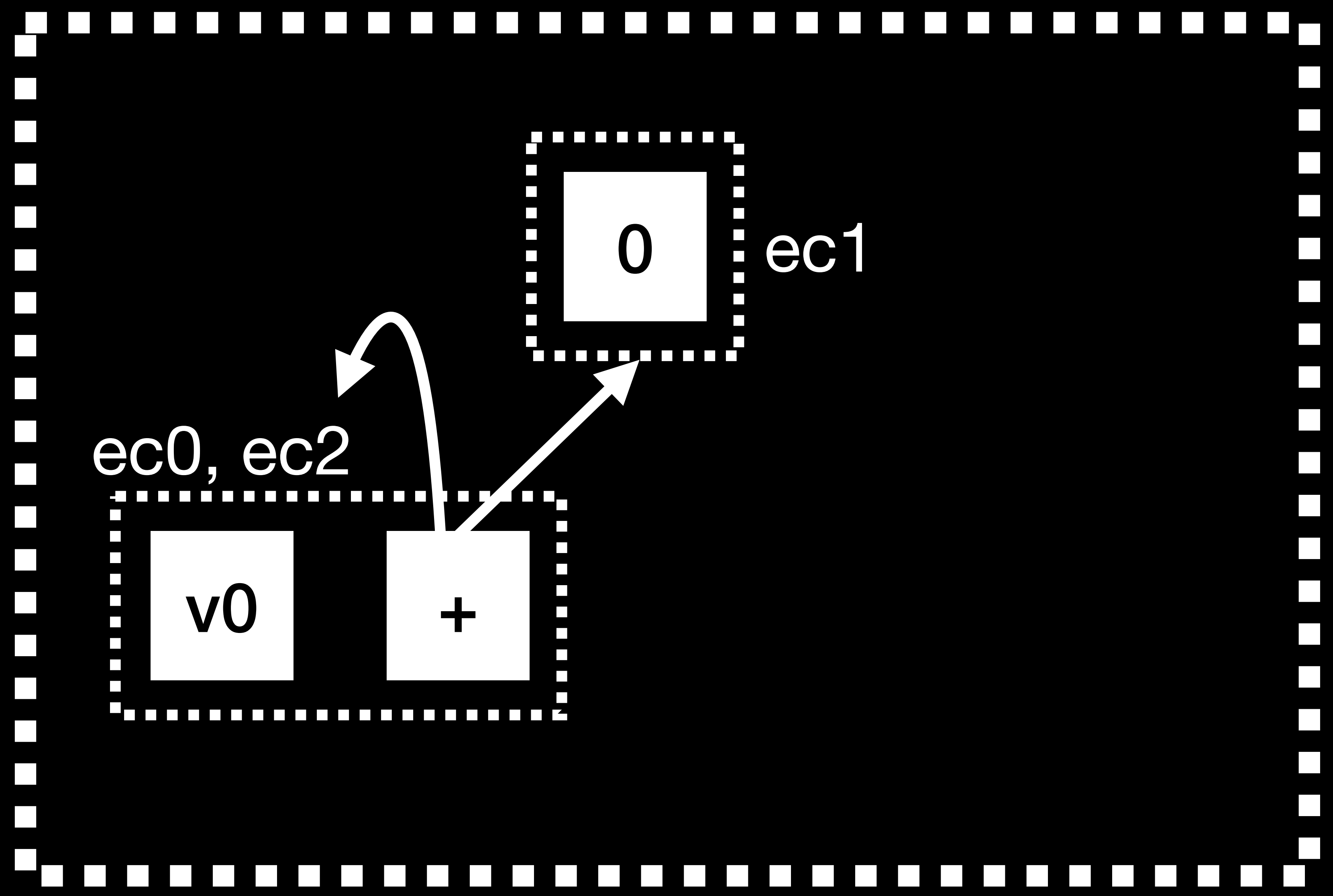

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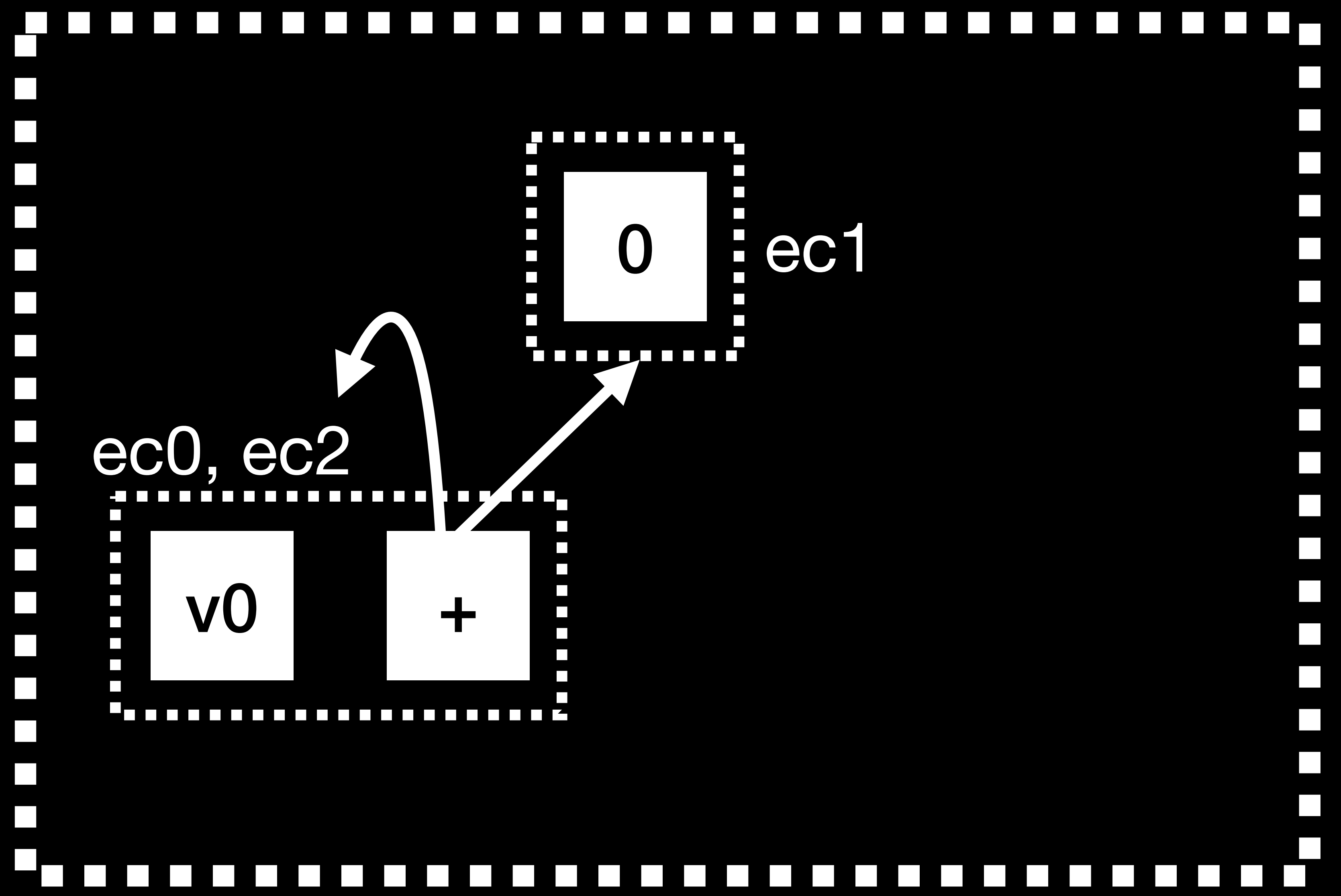

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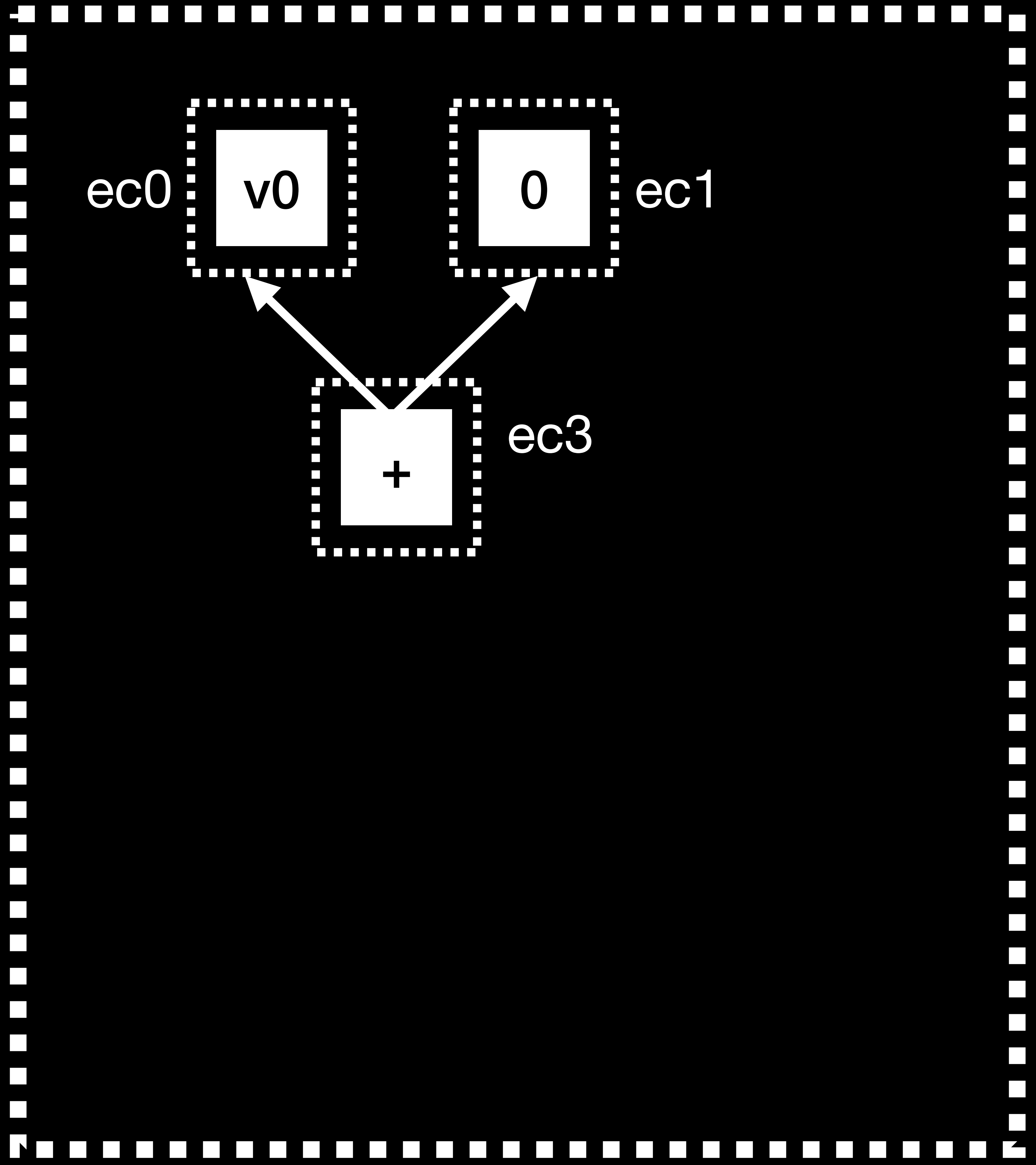
Cycles occur even if original egraph is acyclic (e.g., from SSA)

Persistent immutable e-classes



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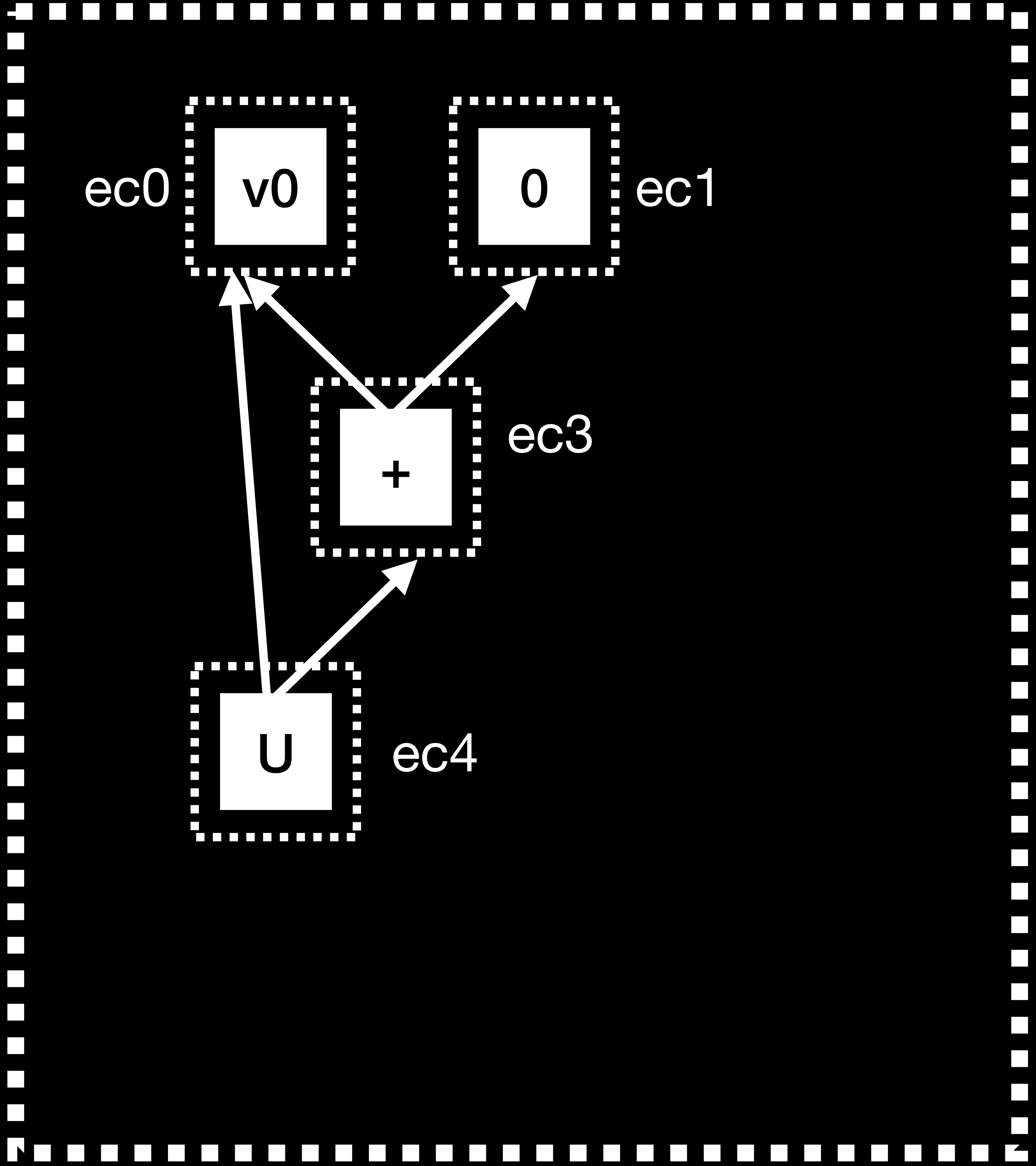

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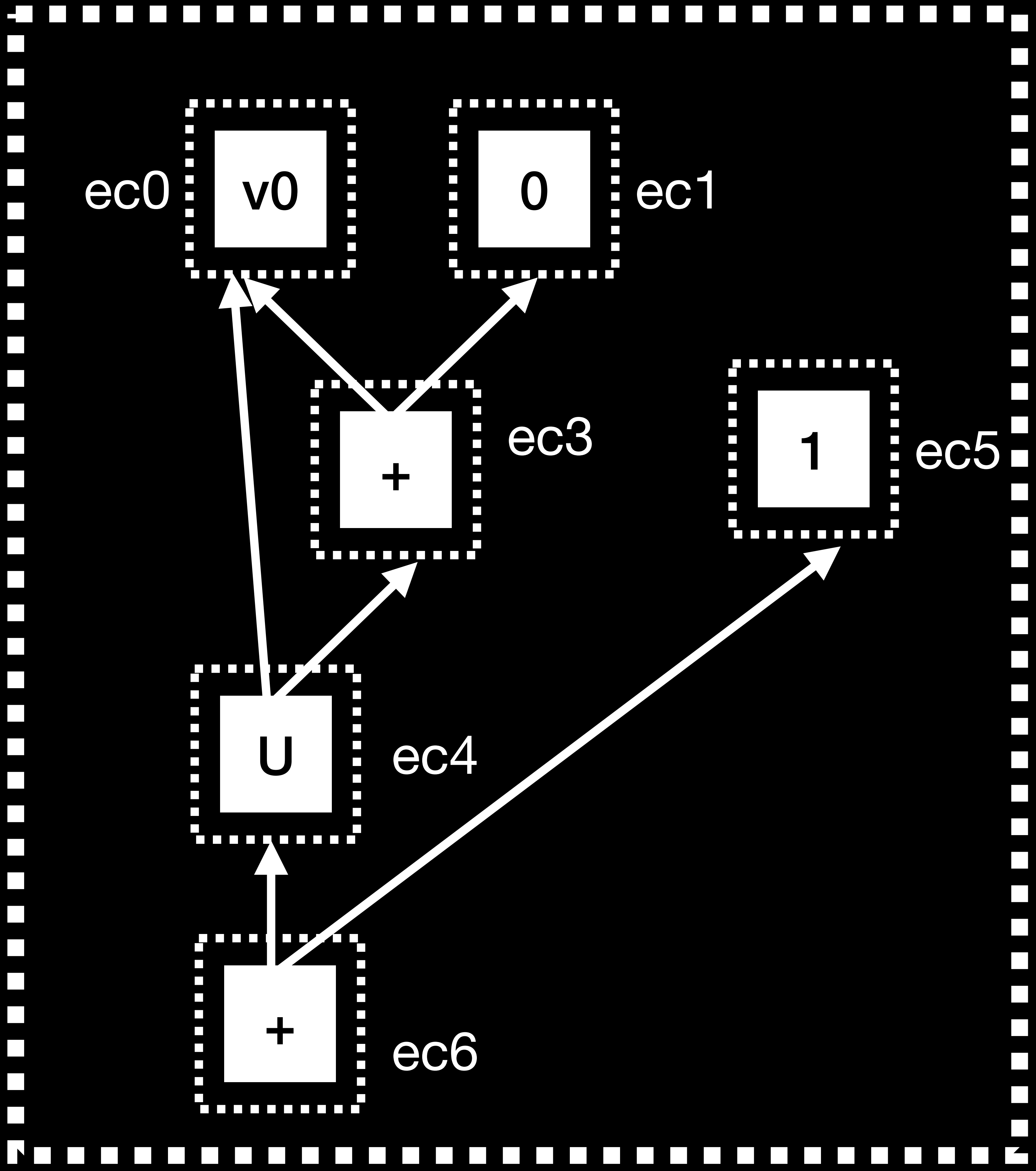

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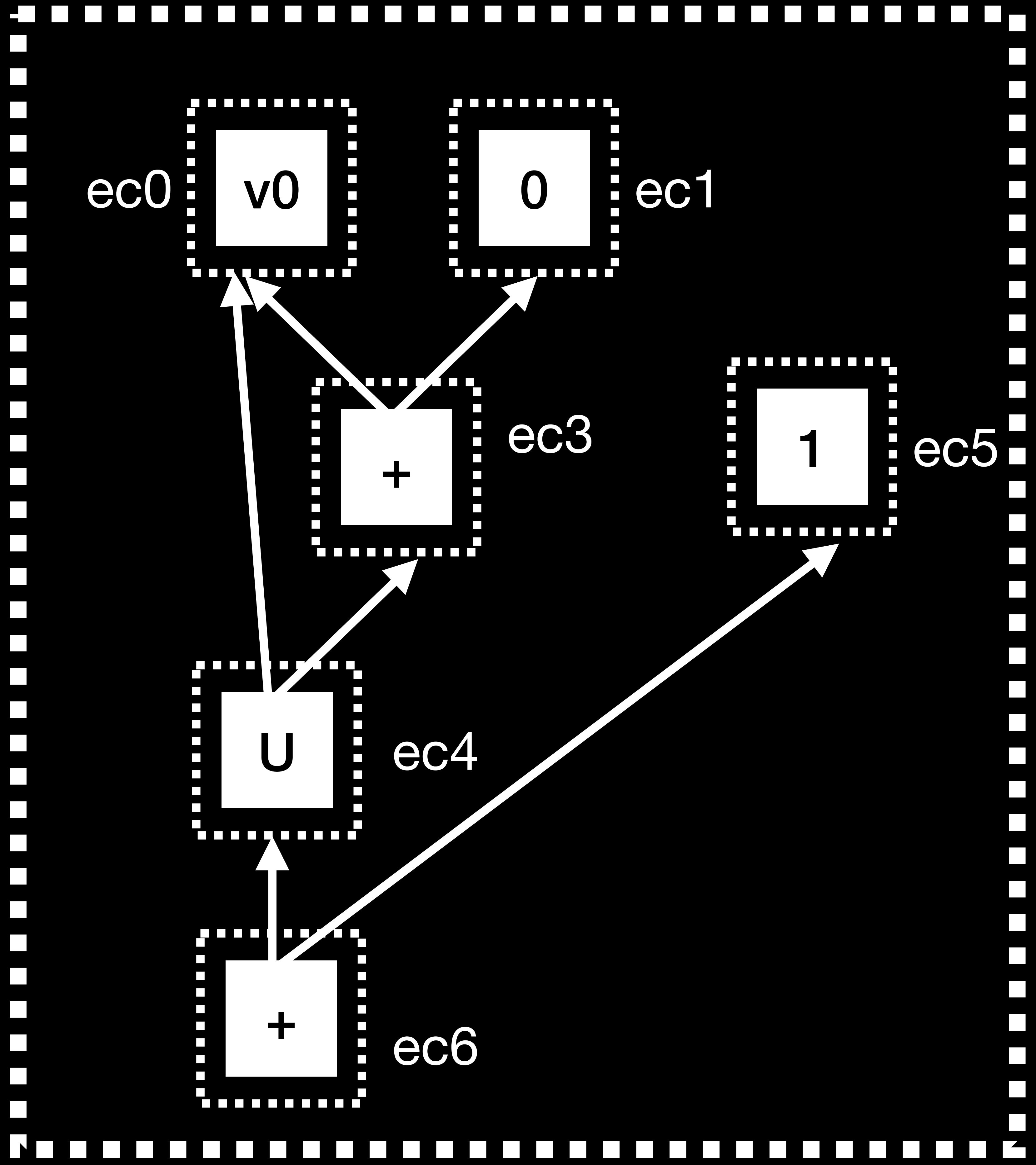


- Never rewrite a node
- Represent eclasses as *trees* of *union nodes*
- As we build the egraph, track *latest* id for a given value
- Invoke rewrite rules *when a node is created*
- enter into hashcons map *with final union'd ID*

Persistent immutable e-classes

Eager rewriting

Acyclicity

Persistent
immutable
data structure

Persistent immutable e-classes

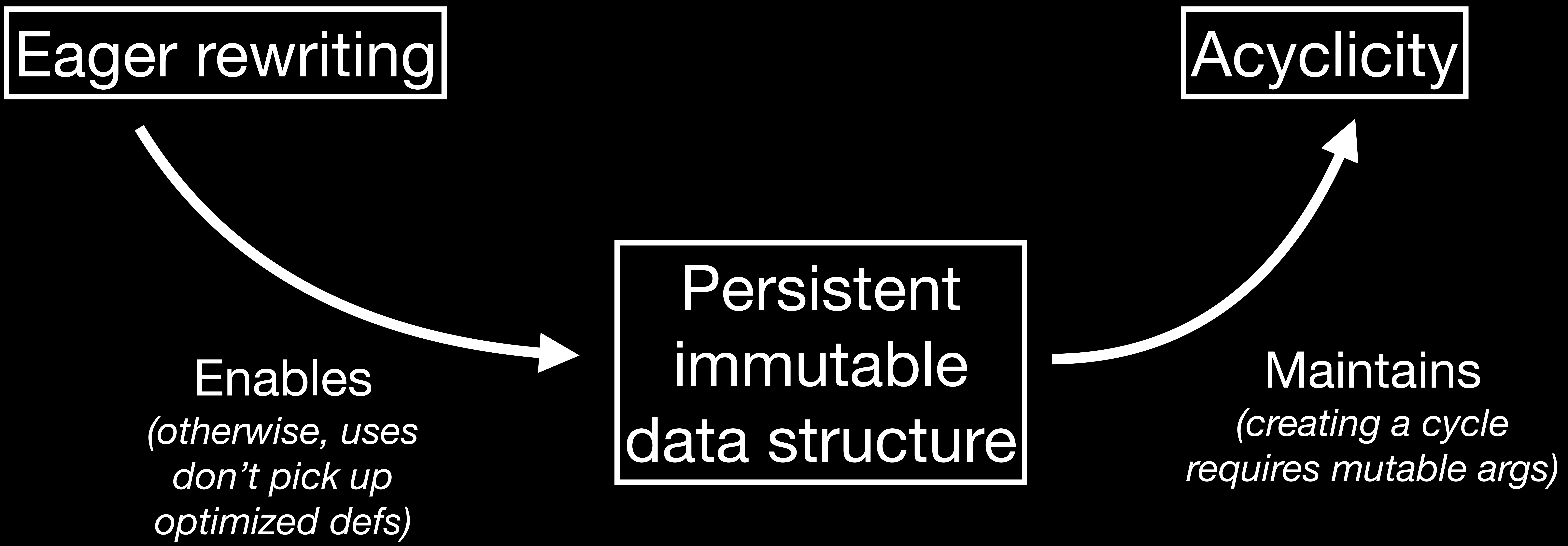
Eager rewriting

Acyclicity

Enables
(otherwise, uses don't pick up optimized defs)

Persistent immutable data structure

Persistent immutable e-classes



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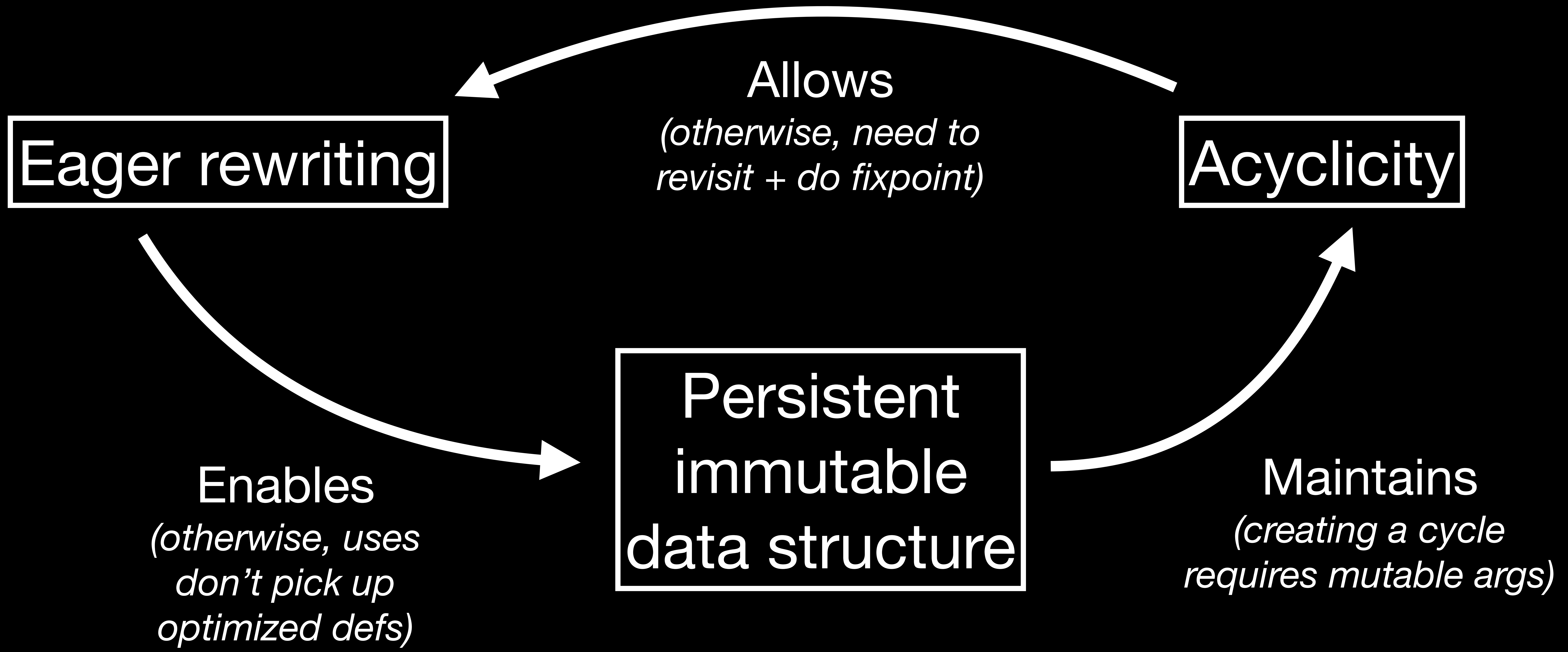

E-graph vs. ægraph

egg-style egraph:
batched rewriting + repair

+ Strongly normalizing
+ Supports arbitrarily cyclic input

- Requires parent pointers and rehashing on fixup
- Repair step is a fixpoint

ægraph:
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- Can miss rewrites
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  (e.g., seeing through phi-nodes)

+ Single-pass rewrite
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→ We can avoid batched repair because *there is no repair*

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→ OK (part of a “strategy”: push bnots downward)

→ But let’s not also have the other direction!

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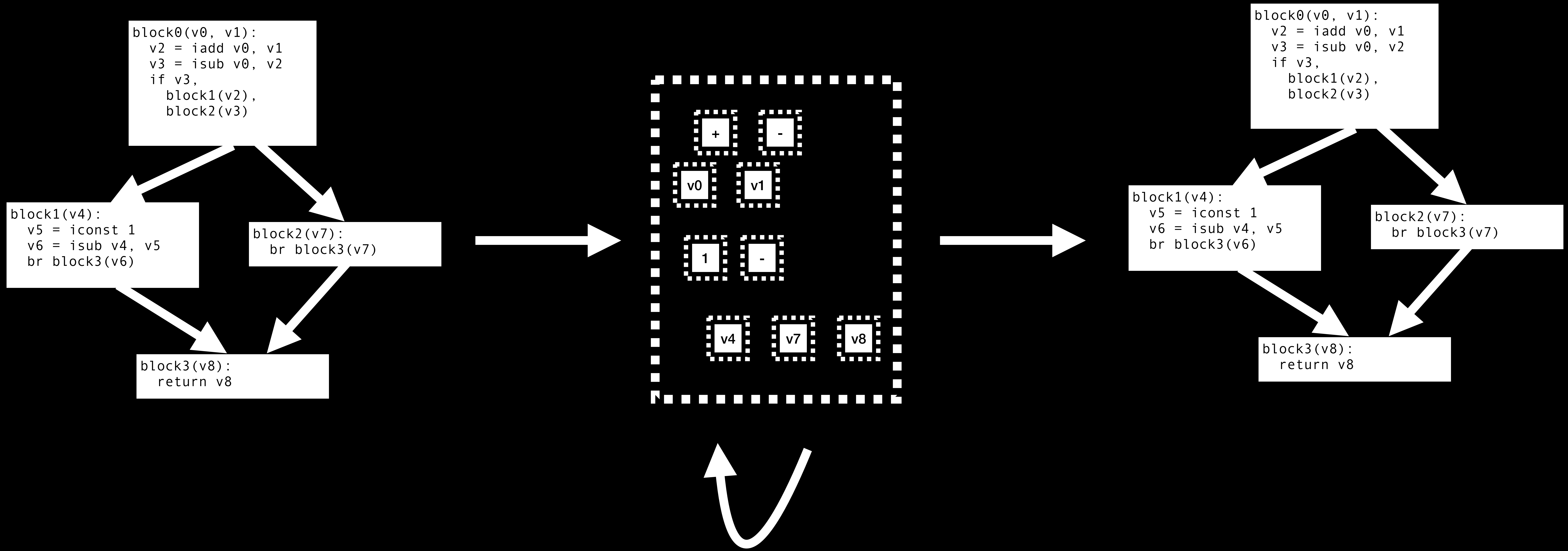
These limitations are OK!
At least as powerful as traditional rewrites;
and we’ve solved phase ordering;
and we can make use of “multi-version” + cost-based extraction.

What E-graphs Gave Us

- If not full EqSat + repair phase, what do ægraphs take from e-graphs?
  - **Rewriting:** a powerful unifying paradigm for optimizations
  - **Multiple value representations:** explores all rewrite paths; cost function makes final resolution in principled way
  - **Sea-of-nodes IR for pure values:** natural framework for code motion

The ægraph Passes



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…

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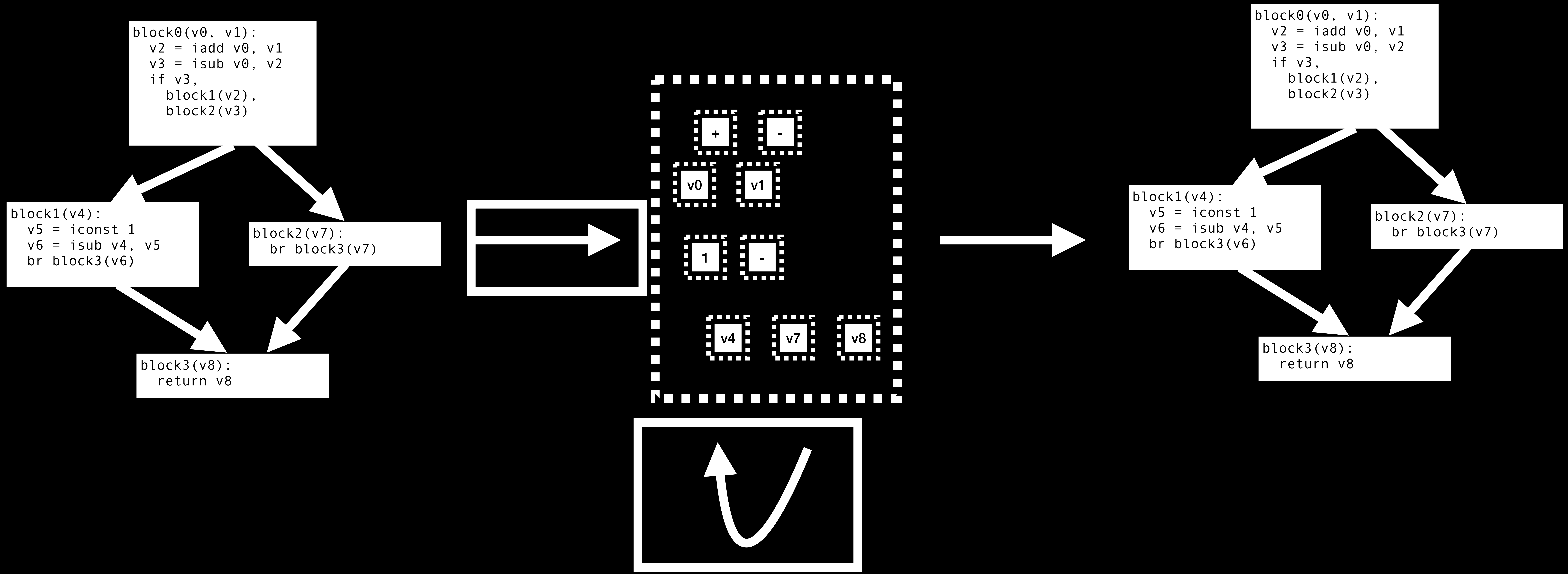
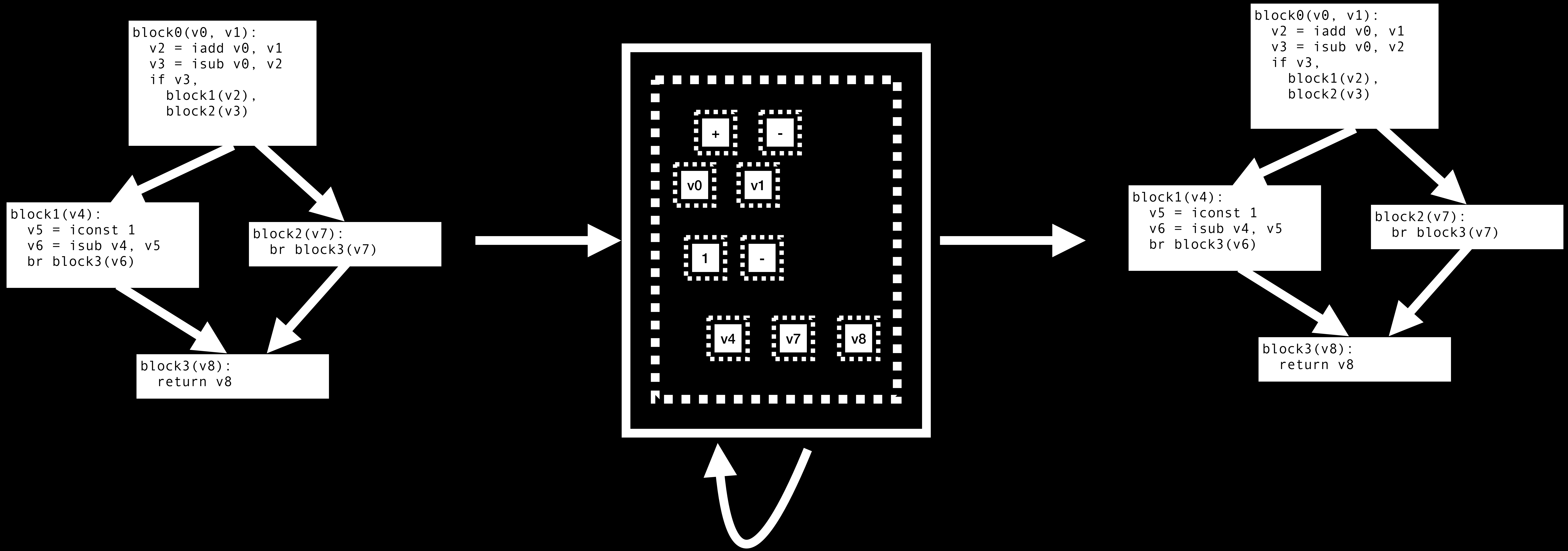


x + 0 => x

...

1. Build ægraph *and* eagerly rewrite

The ægraph Passes



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2. Perform extraction

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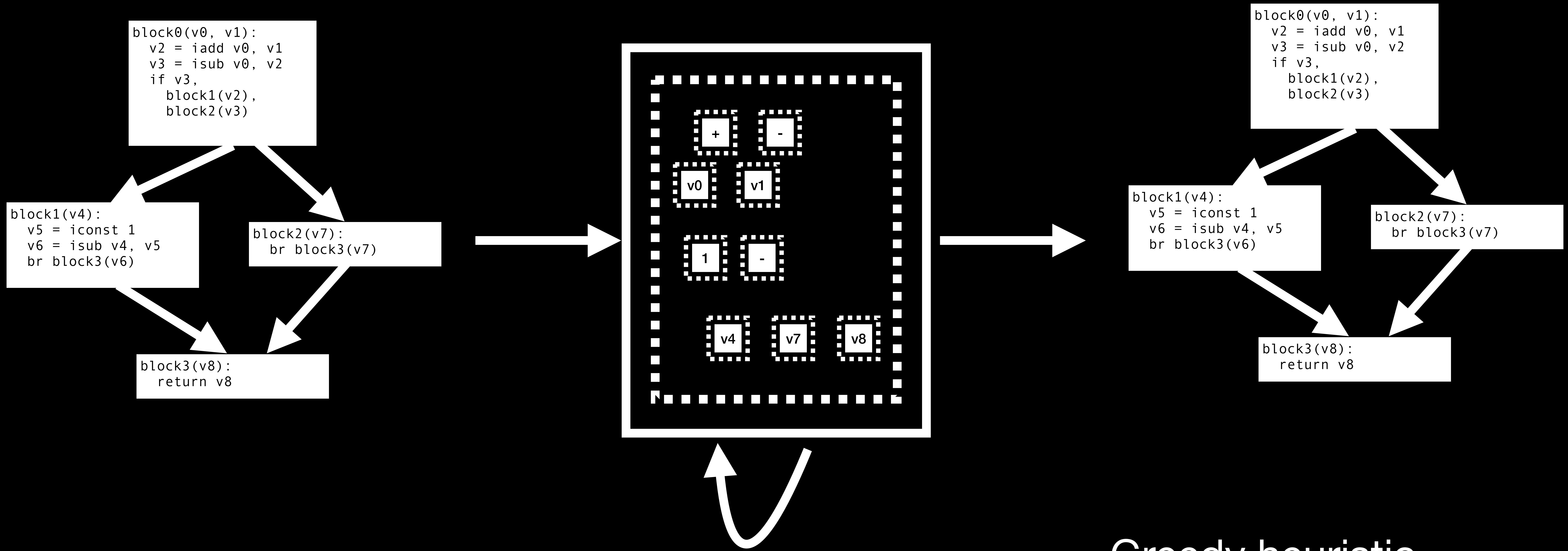


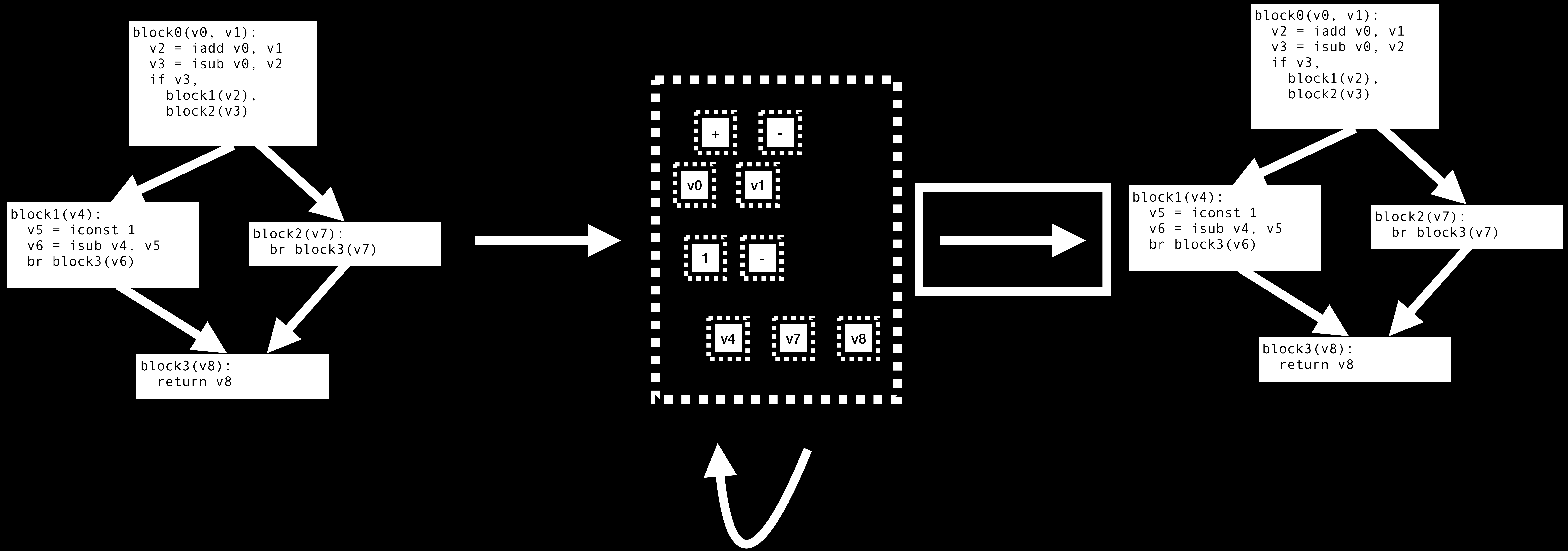
x + 0 => x

…

2. Perform extraction

- Greedy heuristic
- Dynamic programming (single pass)

The ægraph Passes



x + 0 => x

...

3. Scoped elaboration

The ægraph Passes

1. Build and rewrite
2. Extraction
3. Scoped elaboration

→ Three linear passes, no fix-point loops

1. Why *we want a rewrite-based optimizer*

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Performance

Performance

SpiderMonkey.wasm

11% faster runtime

2% longer compile-time

Performance

SpiderMonkey.wasm

11% faster runtime

2% longer compile-time

bz2

3% higher runtime

2% faster compile-time

Performance

Speedups

gimli	22%
spidermonkey	11%
minicsv	9%
ratelimit	8%
switch	3%
fib2	3%
intgemm	1%

Performance

Speedups		*Slowdowns*	
gimli	22%	random	-31%
spidermonkey	11%	hex-simd	-16%
minicsv	9%	meshoptimizer	-14%
ratelimit	8%	ed25519	-13%
switch	3%	blake3-simd	-6%
fib2	3%	keccak	-4%
intgemm	1%	bz2	-3%

Performance

- Instruction scheduling: #6260
- Missing opt rules
  - Magic div constants: #6049

Speedups

gimli	22%
spidermonkey	11%
minicsv	9%
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switch	3%
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Performance

bjorn3 commented on Dec 14, 2022

I just did some benchmarking of egraphs and the perf improvement is huge on the benchmark I tried:

```
Benchmark 1: ./raytracer_cg_clif
  Time (mean ± σ):      8.553 s ±  0.010 s    [User: 8.539 s, System: 0.014 s]
  Range (min … max):    8.543 s …  8.568 s    10 runs

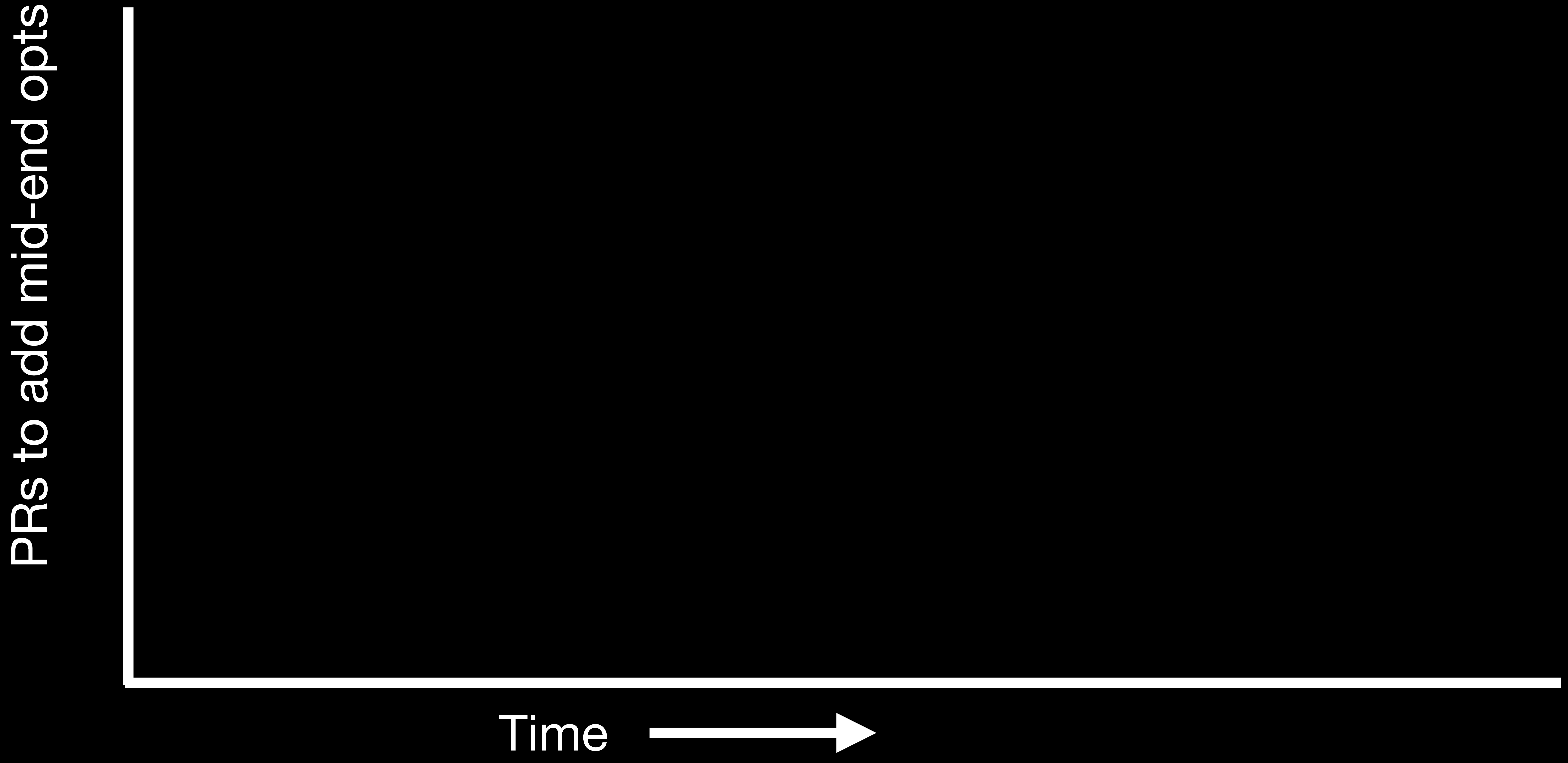
Benchmark 2: ./raytracer_cg_clif_egraph
  Time (mean ± σ):      6.068 s ±  0.017 s    [User: 6.057 s, System: 0.011 s]
  Range (min … max):    6.047 s …  6.108 s    10 runs

Benchmark 3: ./raytracer_cg_clif_release
  Time (mean ± σ):      6.450 s ±  0.021 s    [User: 6.439 s, System: 0.012 s]
  Range (min … max):    6.410 s …  6.482 s    10 runs

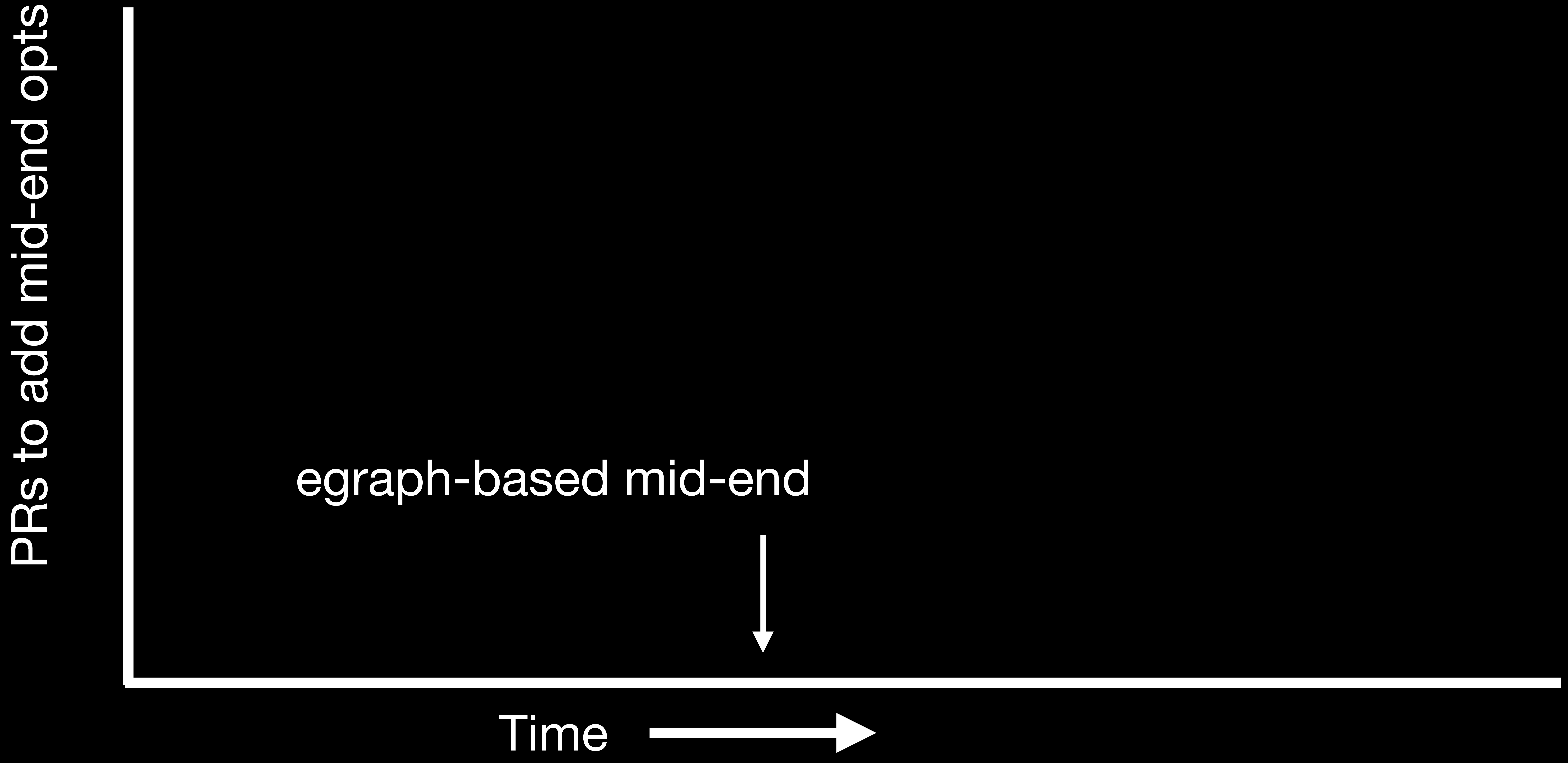
Benchmark 4: ./raytracer_cg_clif_release_egraph
  Time (mean ± σ):      5.853 s ±  0.053 s    [User: 5.841 s, System: 0.012 s]
  Range (min … max):    5.779 s …  5.908 s    10 runs

Summary
  './raytracer_cg_clif_release_egraph' ran
    1.04 ± 0.01 times faster than './raytracer_cg_clif_egraph'
    1.10 ± 0.01 times faster than './raytracer_cg_clif_release'
    1.46 ± 0.01 times faster than './raytracer_cg_clif'
```

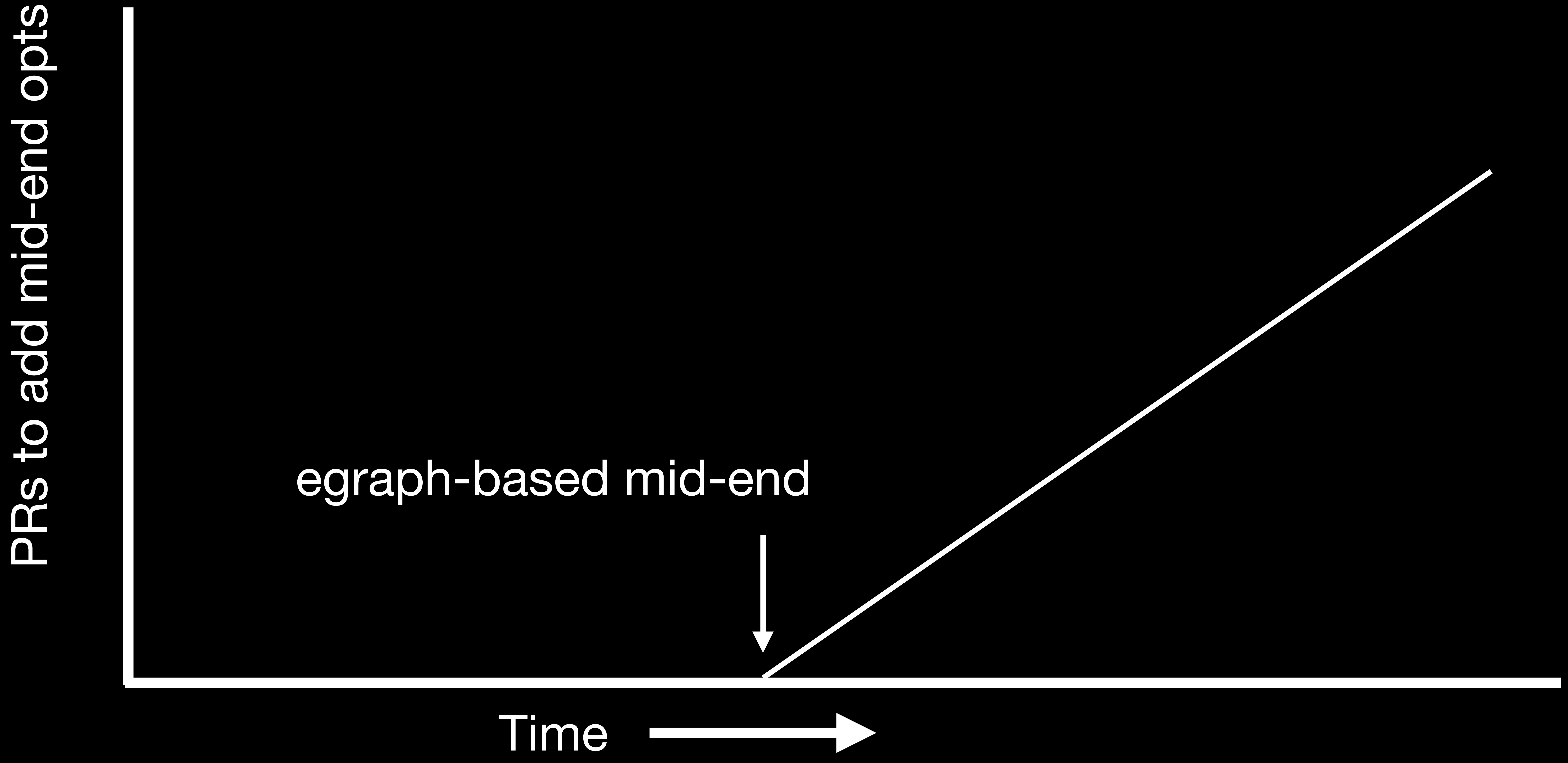
Project Health & Enablement



Project Health & Enablement



Project Health & Enablement



Project Health & Enablement

PRs to add mid-end opts

```
Optimize sign extension via shifts (#6220)
egraphs: Add `bmask` bit pattern optimization rule (#6196)
Add `multi_lane` precondition to `bitselect` => `{u,s}{min,max}` rewrite (#6201)
ISLE: simplify select/bitselect when both choices are the same (#6141)
Add egraph cprop optimizations for `splat` (#6148)
ISLE: rewrite loose inequalities to strict inequalities and strict inequalities to equalities (#6130)
ISLE: rewrite `and`/`or` of `icmp` (#6095)
ISLE: add synonyms for all variations of `icmp` (#6081)
cranelift: rewrite `iabs(ineg(x))` and `iabs(iabs(x))` (#6072)
cranelift: rewrite `x*-1` to `ineg(x)` (#6052)
craneleft: cancel `ineg` when args to `imul` (#6053)
cranelift: simplify `icmp` against UMAX/SMIN/SMAX (#6037)
cranelift: simplify `x-x` to `0` (#6032)
cranelift: simplify `fneg(fneg(x))` to `x` (#6034)
cranelift: simplify `ineg(ineg(x))` to `x` (#6033)
Add egraph optimization for fneg's cancelling out (#5910)
Cranelift: Generalize `(x << k) >> k` optimization (#5746)
cranelift: Optimize `select+icmp` into `{s,u}{min,max}` (#5546)
Cranelift: Collapse double extends into a single extend (#5772)
Generalize and/or/xor optimizations (#5744)
Algebraic opts: Reuse `iconst 0` from LHS (#5724)
Add some minor souper-harvested optimizations (#5735)
Cranelift: Only build iconst for ints <= 64 bits (#5723)
Legalize `b{and,or,xor}_not` into component instructions (#5709)
egraphs/cprop: Don't extend constants to `i128` (#5717)
Generalize u/sextend constant folding to all types (#5706)
Cranelift: Correctly wrap shifts in constant propagation (#5695)
Constant-fold icmp instructions (#5666)
Cranelift: Rewrite `or(and(x, y), not(y)) => or(x, not(y))` (#5676)
Cranelift: Rewrite `(x>>k)<<k` into masking off the bottom `k` bits (#5673)
Cranelift: constant propagate shifts (#5671)
Cranelift: Add egraph rule to rewrite `x * C ==> x << log2(C)` when `C` is a power of two (#5647)
egraph opt rules: do `(icmp cc x x) == {0,1}` only for integer types. (#5438)
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33 PRs in 5 months

… from 8 authors!

Project Health & Enablement

```
+
+ ;; A reduction-of-an-extend back to the same original type is the same as not
+ ;; actually doing the extend in the first place.
+ (rule (simplify (ireduce ty (sextend _ x @ (value_type ty)))) x)
+ (rule (simplify (ireduce ty (uextend _ x @ (value_type ty)))) x)
```

Nobody would take the time to write a manual pass to do that!

Performance: Qualitative Discussion

Q: How did we achieve near-parity?

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A: By doing nearly the same amount of work!

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A: By doing nearly the same amount of work!

- E-graph interning ≈ GVN
- E-nodes are stored as instructions (same data structure)
- Initially, rewrites in egraph are equivalent to old pipeline

Performance: Qualitative Discussion

Q: How did we achieve near-parity?

A: By doing nearly the same amount of work!

- Differences: code placement (reconstruct all vs. incremental)
multi-version (selection, rewrite multiple paths)

Performance: Qualitative Discussion

Q: How did we achieve near-parity?

A: By doing nearly the same amount of work!

“Pay as you go” is *crucial* for incremental adoption!

Possible Future Plans

- Instruction selector as extraction pass
  - We have left-hand-side patterns for what the ISA can do efficiently
  - Why not lower directly from eclasses?
  - Somewhat complex interactions with scoped elaboration + pass direction

Possible Future Plans

- Optimization through block parameters (phi-nodes)
  - Sparse conditional constant propagation! Unify branch-folding + const-prop
  - Challenge: deal with cycles
  - Are there limited forms that operate in a single pass? (skip if backedge?)

Possible Future Plans

- Non-greedy instruction selection
    - We do extraction before elaboration
    - Optimal extraction depends on elaboration:
        - multiple uses of a value can “share” its cost
        - if another inst *needs* a value that is expensive, it becomes sunk cost

Possible Future Plans

- Fused / unrolled rewrites
  - We have efficient rule dispatch (decision tree), but only one step at a time
  - Can we statically unroll a path of rewrites?
  - … and even elide insertion of intermediates if we know they're "bad" (more expensive, always subsumed)?

Possible Future Plans

- Instruction scheduling
  - The ægraph throws away location information
  - Scoped elaboration recomputes it
  - The “as late as possible” schedule that results is often quite bad
  - Heuristics from (i) register pressure, (ii) original code order, (iii) other?

1. **Why** *we want a rewrite-based optimizer*

2. **How** *to turn a CFG into an egraph and back again*

3. **Cycles** *why they occur, and what to do about them*

4. **Results** *how well does it work?* ←

5. **Lessons** *in translating research to production*

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- Robustness/predictability is important (and distinct from “fast on average”)
- We (practicing software engineers) need to do a better job of documenting “all the usual tricks”!

Limits Induce Creativity

- This work in Cranelift started with “standard” e-graphs and `egg`
  - When it wasn’t fast enough, I could have stopped and moved on!
  - Requires the “correct” amount of unjustified optimism

Limits Induce Creativity

- “Bottom-up” vs. “top-down” thinking
  - “I want to do eqsat” —> optimize all the computation needed for this, vs…
    - I tried this first!
  - … “I have N linear passes” —> which ideas can I keep?

Tradeoffs… and Incrementalism

- It’s OK to not solve the entire problem!
  - The only real requirement is that we run the program correctly*
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Tradeoffs… and Incrementalism

- It’s OK to not solve the entire problem!
  - The only real requirement is that we run the program correctly*
- Sometimes “this is the best point on the effort Pareto curve” and we’re done
- Sometimes, we can come up with better ideas later
  - And this happens all the time in Cranelift
  - View the codebase as a living, evolving understanding of problem domain

Tradeoffs… and Incrementalism

- *Design for incrementalism* by:
  - Building frameworks (rewrite language/infra, …)
  - Building guardrails (good testing, typesafe abstractions, well-documented invariants)

Tradeoffs… and Incrementalism

- *Design for incrementalism* by:
  - Building frameworks (rewrite language/infra, …)
  - Building guardrails (good testing, typesafe abstractions, well-documented invariants)
- Accept limits and ship, then fulfill last 20% of needs while plane is flying

Community Leverage Multipliers

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Community Leverage Multipliers

- Let’s talk about “design for ___” a bit more
  - Design for *community*: find abstractions that allow modular, typesafe work and enable many uses (verification!)
  - We picked up the e-graph idea because
    - It’s a clean abstraction
    - It allows modular, easy contributions of mid-end optimizations
    - It bridges the gap with academia a bit and pulls in new ideas

E-graphs… in Industry?

- Isn't this bona-fide research? Am I not a software engineer in… industry?

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  - Secret: software engineering is full of research problems
    - *Caveat: pick a domain like compilers*
  - Different *kinds* of problems with different considerations

E-graphs… in Industry?

- Isn’t this bona-fide research? Am I not a software engineer in… industry?
  - Secret: software engineering is full of research problems
    - *Caveat: pick a domain like compilers*
  - Different *kinds* of problems with different considerations
  - Different approach to risk; later in pipeline, less speculative
    - (thank you for exploring e-graphs first!)

E-graphs… in Industry?

- Research is *totally* relevant to industry if it addresses industry’s needs: robust, reliable, simple, reliable, fast, reliable

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  - But good reasons exist (security, simplicity, agility, …)!

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- Industry sometimes presents opportunities to rethink key infra (e.g. compiler)
    - It can be hard to convincingly make a case for this in a vacuum in academia
    - But good reasons exist (security, simplicity, agility, …)!
    - Academia is idea-rich and searches for problems/motivations;
      Industry is problem-rich and searches for ideas/solutions
    - Bridging the two is incredibly fruitful and rewarding!

Work with Cranelift!

- We love mentoring students and collaborating with researchers
  - Verification (VeriISLE, Veriwasm, …); chaos-mode randomized testing; exceptions; typed func-refs; e-graph-based fuzzing mutators; extensions of custom DSLs; …
  - There are many open problems and the need to solve them is immediate and directly motivated
  - It’s how we can work “smarter not harder” and keep in the game, as an underdog — we all win!

Thanks!

- Links
  - https://cranelift.dev/
  - https://bytecodealliance.zulipchat.com/
  - https://cfallin.org/