Program Analysis

- Attackers: need to analyze our program to modify it!
- Defenders: need to analyze our program to protect it!
- Two kinds of analyses:
  1. *static analysis tools* collect information about a program by studying its code;
  2. *dynamic analysis tools* collect information from executing the program.

Static and Dynamic Analyses

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- disassembly: turn raw executables into assembly code.

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- disassembly: turn raw executables into assembly code.
- decompilation: turn raw assembly code into source code.

Outline

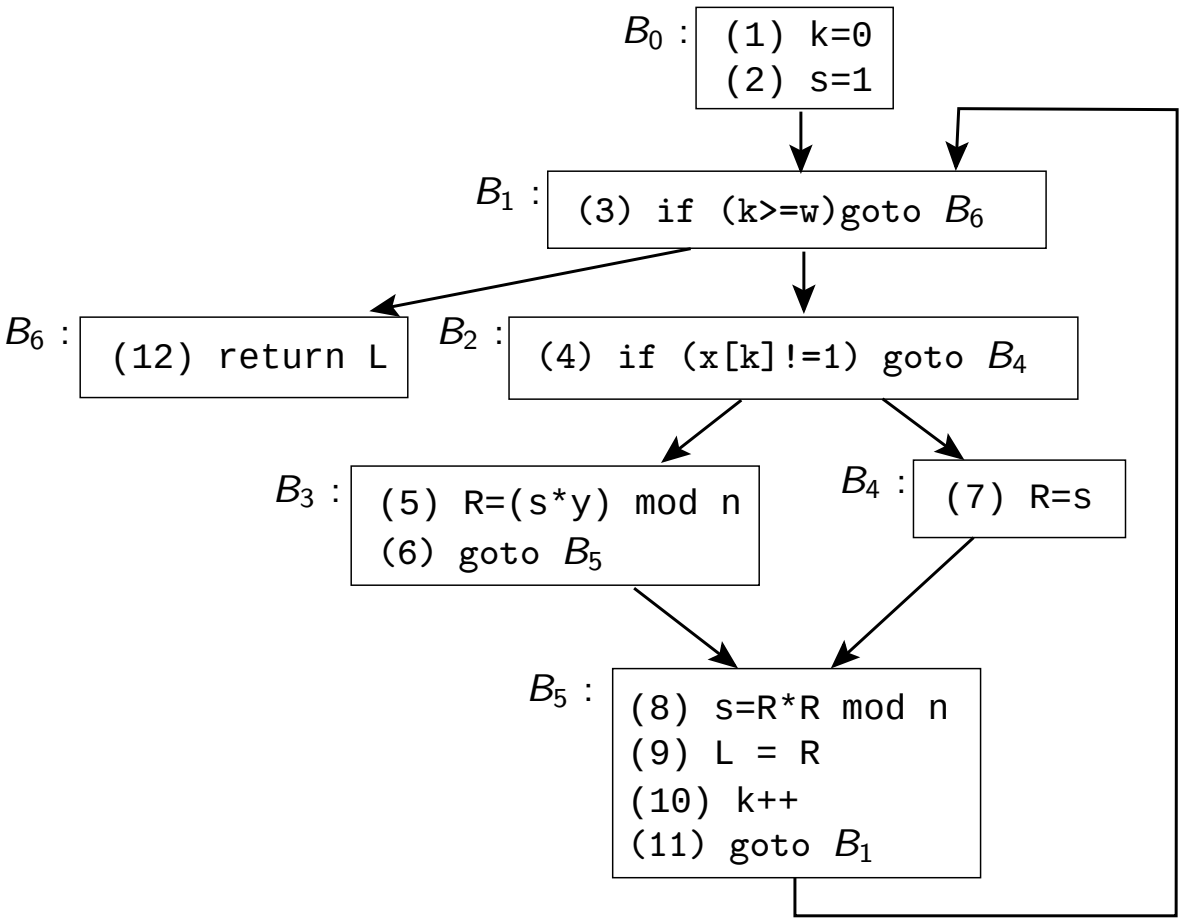
Control-flow Graphs (CFGs)

- A way to represent functions.
- Nodes are called basic blocks.
- Each block consists of straight-line code ending (possibly) in a branch.
- An edge $A \longrightarrow B$: control could flow from A to B.

```
int modexp(int y, int x[],
           int w, int n) {
    int R, L;
    int k = 0;
    int s = 1;
    while (k < w) {
        if (x[k] == 1)
            R = (s*y) % n;
        else
            R = s;
        s = R*R % n;
        L = R;
        k++;
    }
    return L;
```

```
(1)  k=0
(2)  s=1
(3)  if (k>=w) goto (12)
(4)  if (x[k]!=1) goto (7)
(5)  R=(s*y)%n
(6)  goto (8)
(7)  R=s
(8)  s=R*R%n
(9)  L=R
(10) k++
(11) goto (3)
(12) return L
```

The resulting graph



BuildCFG(F):

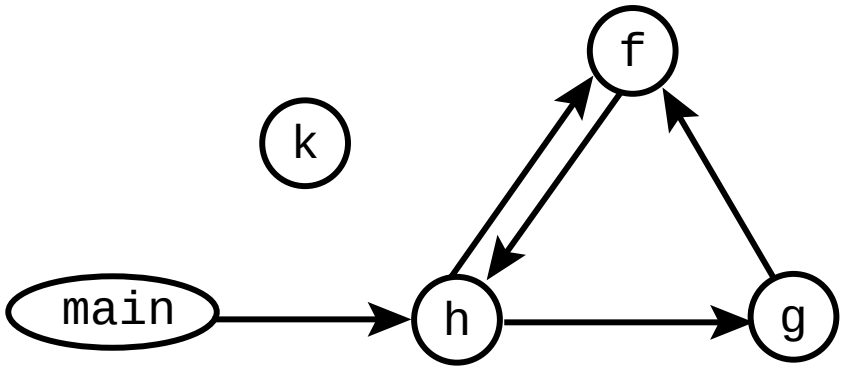
1. Mark every instruction which can start a basic block as a *leader*:
   - the first instruction is a leader;
   - any target of a branch is a leader;
   - the instruction following a conditional branch is a leader.
2. A basic block consists of the instructions from a leader up to, but not including, the next leader.
3. Add an edge $A \to B$ if A ends with a branch to B or can fall through to B. □

Interprocedural control flow

- *Interprocedural analysis* also considers flow of information between functions.
- Call graphs are a way to represent possible function calls.
- Each node represents a function.
- An edge $A \longrightarrow B$: A might call B.

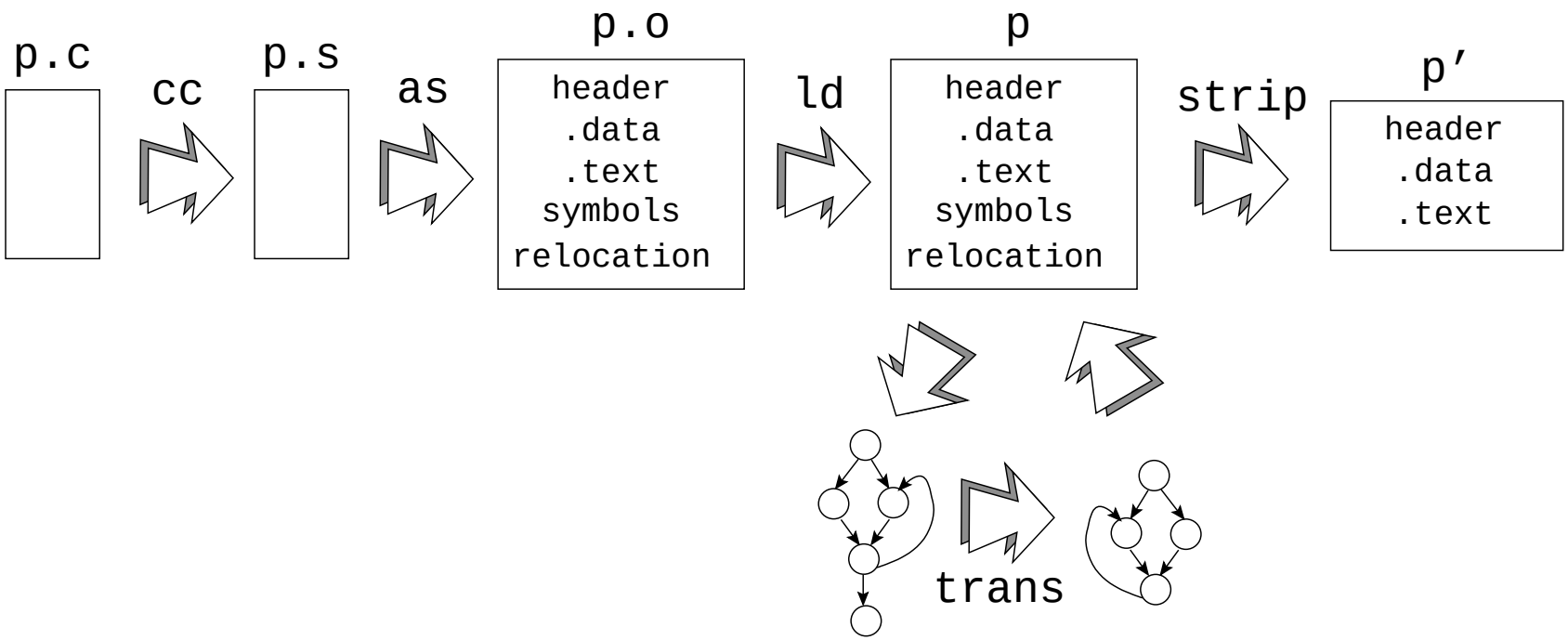
Building call-graphs

```
void h();

void f(){
    h();
}

void g(){
    f();
}

void h() {
   f();
   g();
}

void k() {}
```

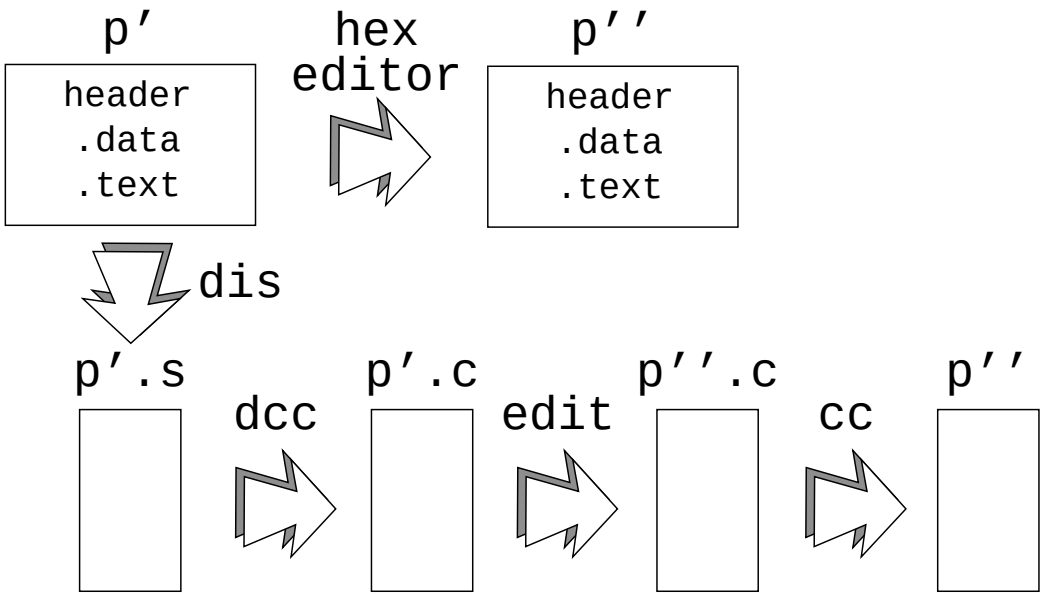


Outline

Reconstituting source



Attacking stripped binary code



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- Handwritten assembly code — won't conform to the standard calling conventions.
- code compression — the code of two functions may overlap.
- Self-modifying code.

Instruction set 1

opcode	mnemonic	operands	semantics
0	`call`	*addr*	function call to *addr*
1	`calli`	*reg*	function call to address in *reg*
2	`brg`	*offset*	branch to $\mathrm{pc} + \mathit{offset}$ if flags for $>$ are set
3	`inc`	*reg*	$\mathit{reg} \leftarrow \mathit{reg} + 1$
4	`bra`	*offset*	branch to $\mathrm{pc} + \mathit{offset}$
5	`jmpi`	*reg*	jump to address in *reg*
6	`prologue`		beginning of function
7	`ret`		return from function

- Instruction set for a small architecture.
- All operators and operands are one byte long.
- Instructions can be 1-3 bytes long.

Instruction set 2

opcode	mnemonic	operands	semantics
8	`load`	$reg_1, (reg_2)$	$reg_1 \leftarrow [reg_2]$
9	`loadi`	reg, imm	$reg \leftarrow imm$
10	`cmpi`	reg, imm	compare *reg* and *imm* and set flags
11	`add`	reg_1, reg_2	$reg_1 \leftarrow reg_1 + reg_2$
12	`brge`	*offset*	branch to $\mathrm{pc} + offset$ if flags for $\geq$ are set
13	`breq`	*offset*	branch to $\mathrm{pc} + offset$ if flags for $=$ are set
14	`store`	$(reg_1), reg_2$	$[reg_1] \leftarrow reg_2$

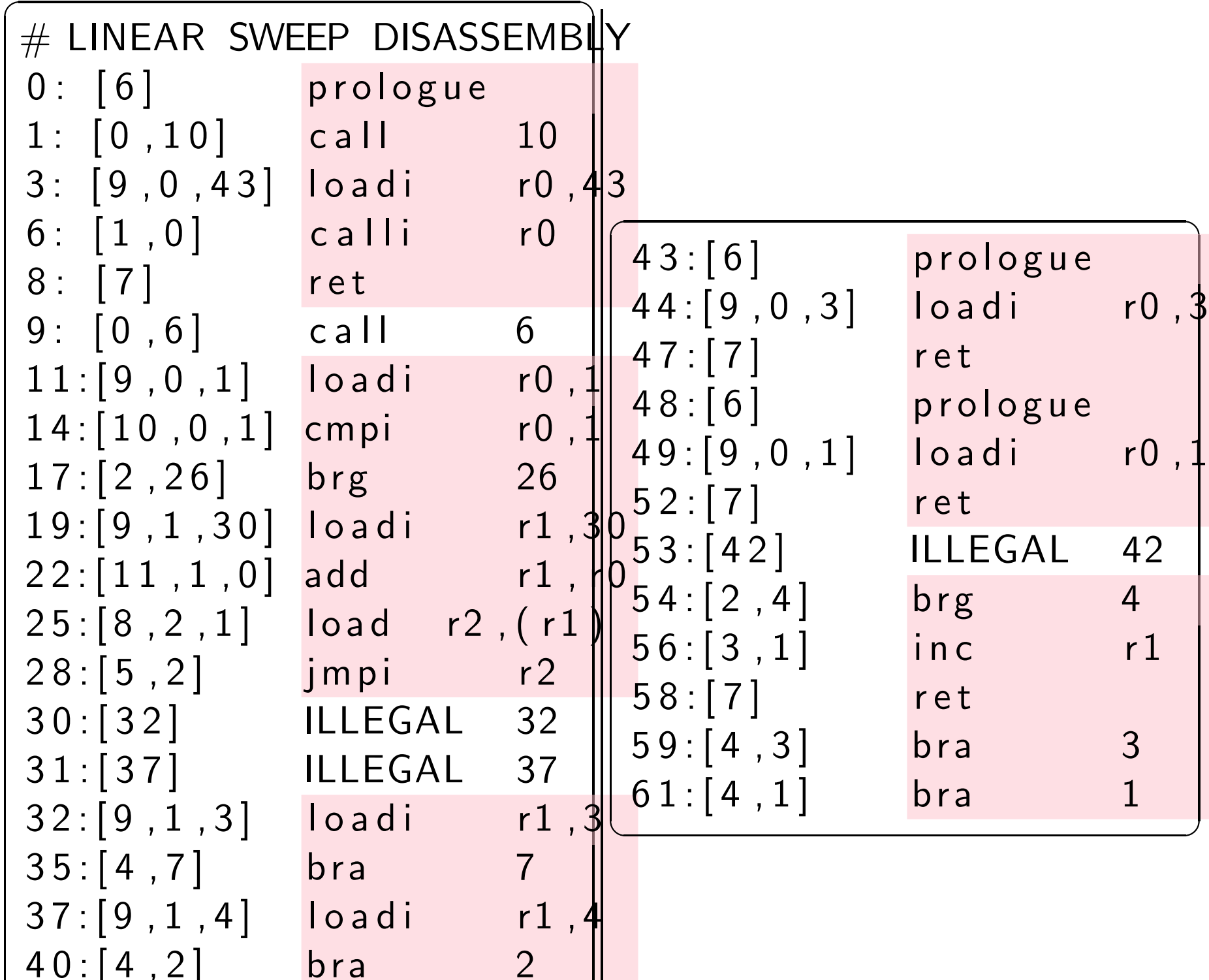
Disassembly — example

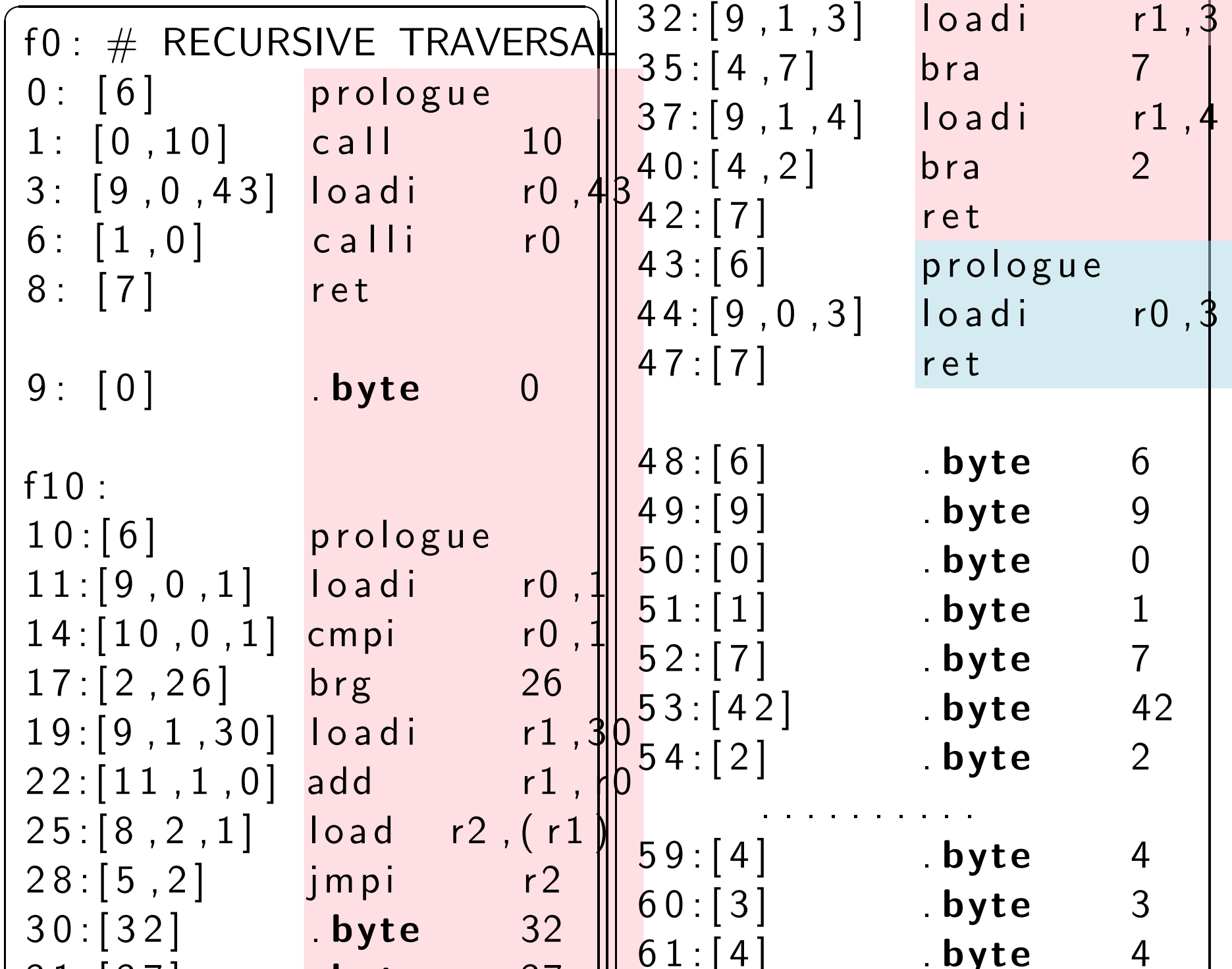
```
6 0 10 9 0 43 1 0 7 0 6 9 0 1 10 0 1 2 26 9
1 30 11 1 0 8 2 1 5 2 32 37 9 1 3 4 7 9 1 4
4 2 7 6 9 0 3 7 6 9 0 1 7 42 2 4 3 1 7 4
3 4 1
```

- Next few slides show the results of different disassembly algorithms.
- Correctly disassembled regions are in pink.

```
main: # ORIGINAL PROGRAM
0: [6]          prologue
1: [0,10]       call       foo
3: [9,0,43]     loadi      r0,43
6: [1,0]        calli      r0
8: [7]          ret
9: [0]          .align      2
foo:
10:[6]          prologue
11:[9,0,1]      loadi      r0,1
14:[10,0,1      cmpi       r0,1
17:[2,26]       brg        26
19:[9,1,30]     loadi      r1,30
22:[11,1,0]     add        r1,r0
25:[8,2,1]      load  r2,(r1)
28:[5,2]        jmpi       r2
30:[32]         .byte      32
31:[37]         .byte      37
32:[9,1,3]      loadi      r1,3
35:[4,7]        bra        7
```

```
bar:
43:[6]          prologue
44:[9,0,3]      loadi      r0,3
47:[7]          ret
baz:
48:[6]          prologue
49:[9,0,1]      loadi      r0,1
52:[7]          ret
life:
53:[42]         .byte      42
fred:
54:[2,4]        brg        4
56:[3,1]        inc        r1
58:[7]          ret
59:[4,3]        bra        3
61:[4,1]        bra        1
```


LINEAR SWEEP DISASSEMBLY
0: [6] prologue
1: [0,10] call 10
3: [9,0,43] loadi r0,43
6: [1,0] calli r0
8: [7] ret
9: [0,6] call 6
11:[9,0,1] loadi r0,1
14:[10,0,1] cmpi r0,1
17:[2,26] brg 26
19:[9,1,30] loadi r1,30
22:[11,1,0] add r1,r0
25:[8,2,1] load r2,(r1)
28:[5,2] jmpi r2
30:[32] ILLEGAL 32
31:[37] ILLEGAL 37
32:[9,1,3] loadi r1,3
35:[4,7] bra 7
37:[9,1,4] loadi r1,4
40:[4,2] bra 2
43:[6] prologue
44:[9,0,3] loadi r0,3
47:[7] ret
48:[6] prologue
49:[9,0,1] loadi r0,1
52:[7] ret
53:[42] ILLEGAL 42
54:[2,4] brg 4
56:[3,1] inc r1
58:[7] ret
59:[4,3] bra 3
61:[4,1] bra 1


f0: # RECURSIVE TRAVERSAL
0: [6] prologue
1: [0,10] call 10
3: [9,0,43] loadi r0,43
6: [1,0] calli r0
8: [7] ret
9: [0] .byte 0
f10:
10:[6] prologue
11:[9,0,1] loadi r0,1
14:[10,0,1] cmpi r0,1
17:[2,26] brg 26
19:[9,1,30] loadi r1,30
22:[11,1,0] add r1,r0
25:[8,2,1] load r2,(r1)
28:[5,2] jmpi r2
30:[32] .byte 32
32:[9,1,3] loadi r1,3
35:[4,7] bra 7
37:[9,1,4] loadi r1,4
40:[4,2] bra 2
42:[7] ret
43:[6] prologue
44:[9,0,3] loadi r0,3
47:[7] ret
48:[6] .byte 6
49:[9] .byte 9
50:[0] .byte 0
51:[1] .byte 1
52:[7] .byte 7
53:[42] .byte 42
54:[2] .byte 2
59:[4] .byte 4
60:[3] .byte 3
61:[4] .byte 4

Algorithm reHM

- Extends the standard recursive traversal algorithm with a collection of heuristics to inrease precision.

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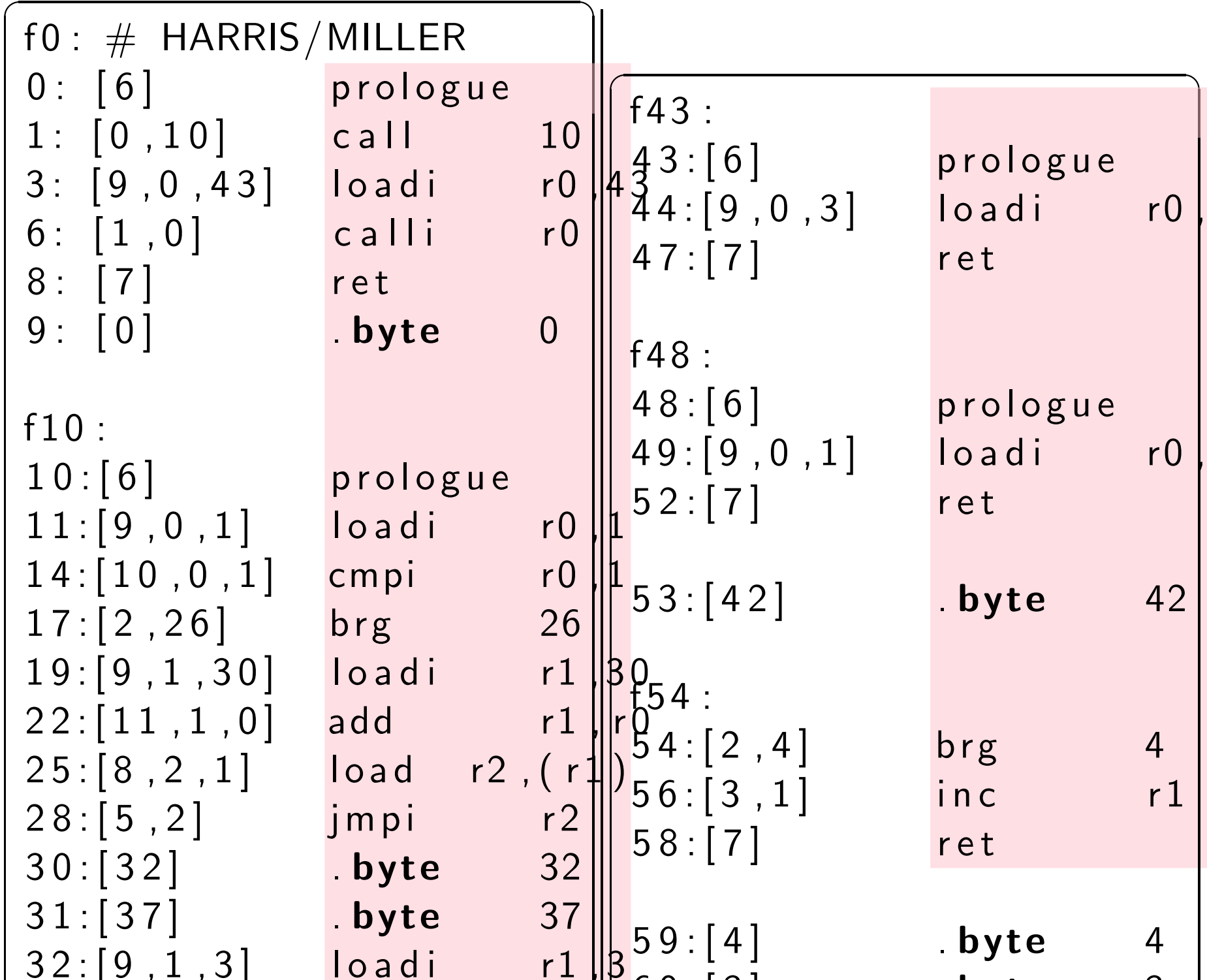
- Next, try to build a reasonable control flow graph from the remaining undecoded bytes.
- Reasonable CFG: "there are no jumps into the middle of another instruction and the resulting function contains at least two control transfer instruction."


f0: # HARRIS/MILLER
0: [6] prologue
1: [0,10] call 10
3: [9,0,43] loadi r0,43
6: [1,0] calli r0
8: [7] ret
9: [0] .byte 0
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44:[9,0,3] loadi r0,3
47:[7] ret
f48:
48:[6] prologue
49:[9,0,1] loadi r0,1
52:[7] ret
53:[42] .byte 42
f54:
54:[2,4] brg 4
56:[3,1] inc r1
58:[7] ret
59:[4] .byte 4

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Algorithm REHM

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Algorithm REHM

- Function `f43` is only called indirectly, function `f48` isn't called at all — the disassembler still finds them by searching for their `prologue` instructions.
- The disassembler next starts at location 53, realizes that 42 isn't a valid opcode, moves to location 54, builds a valid CFG.
- The algorithm recovered 95.6% of all functions over a set of Windows and Linux programs.