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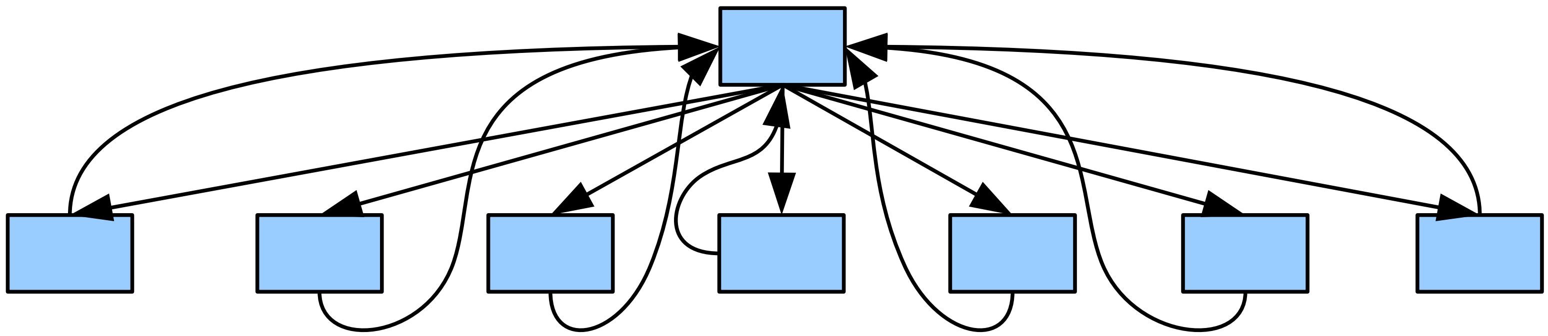
  - Tolerate errors.
  - Manage memory / resources.

e.g. Reverse Engineering

Static CFG (from e.g. Apple Fairplay):



This is the result of a control flow flattening obfuscation.

[http://tigress.cs.arizona.edu/transformPage/docs/flatten/]

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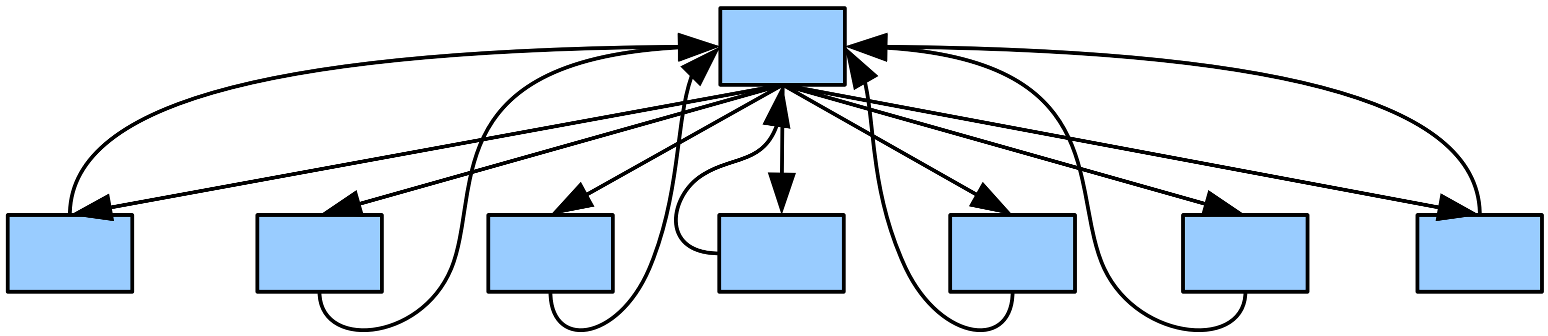
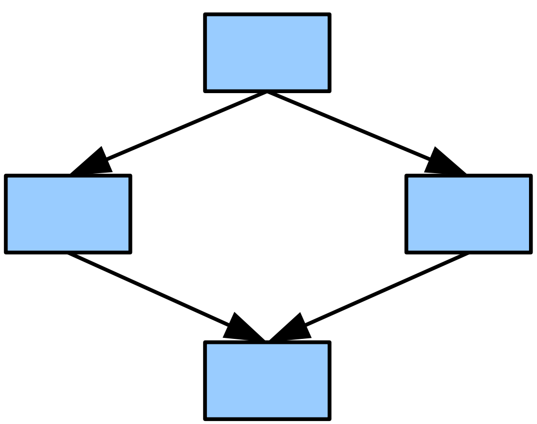


Dynamically Simplified CFG:



How?

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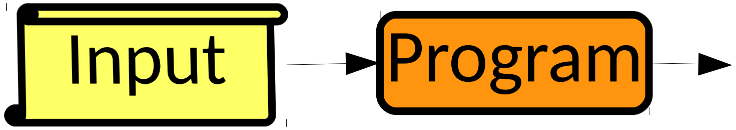

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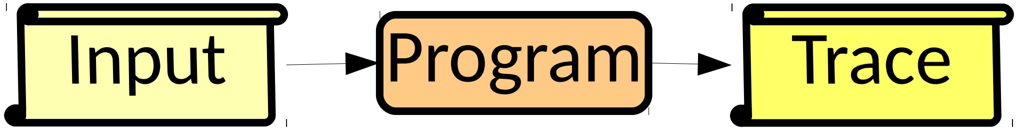

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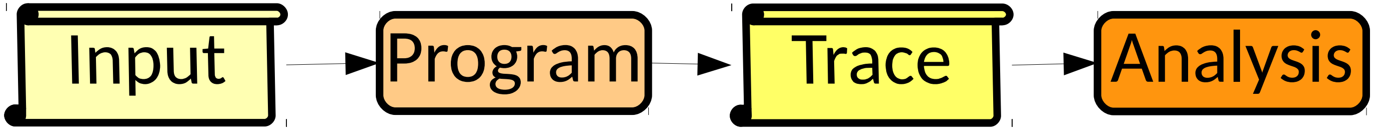

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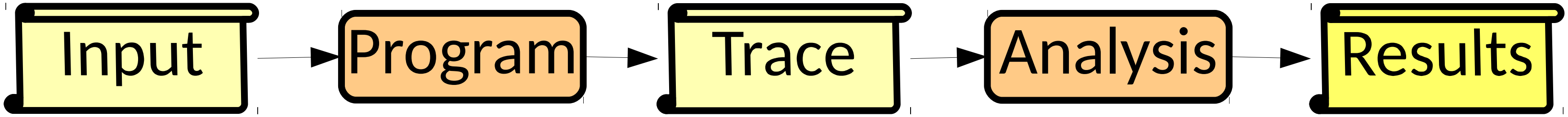

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  - Record to a trace
  - Analyze post mortem / offline
  - Scalability issues: need enough space to store it
- Can perform analysis online
  - *Instrument* the program
  - Modified program invokes code to 'analyze' itself
- Can do both
  - Lightweight recording
  - Instrument a replayed instance of the execution

Simple Idea: Basic Block Profiling

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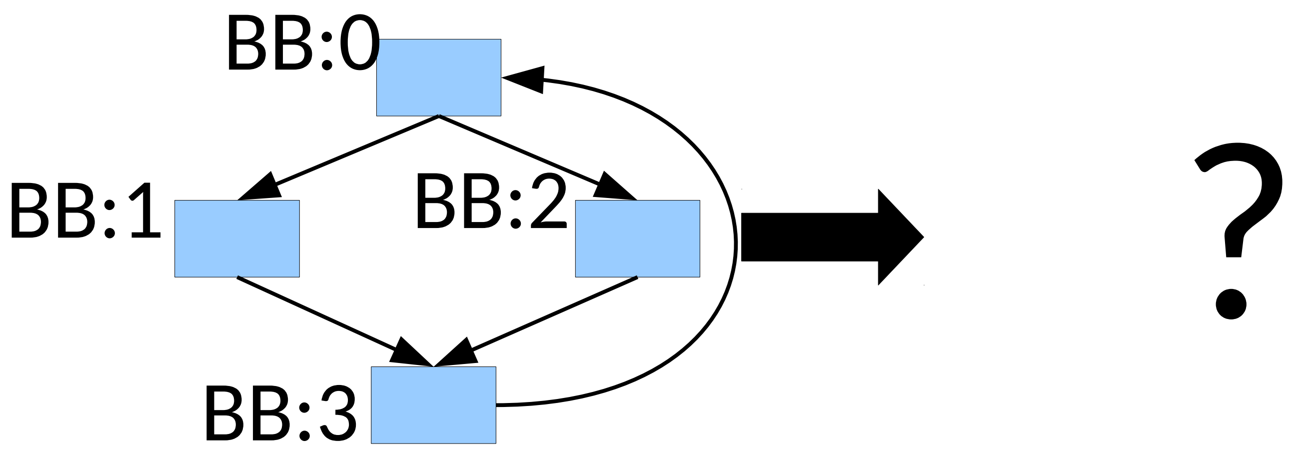

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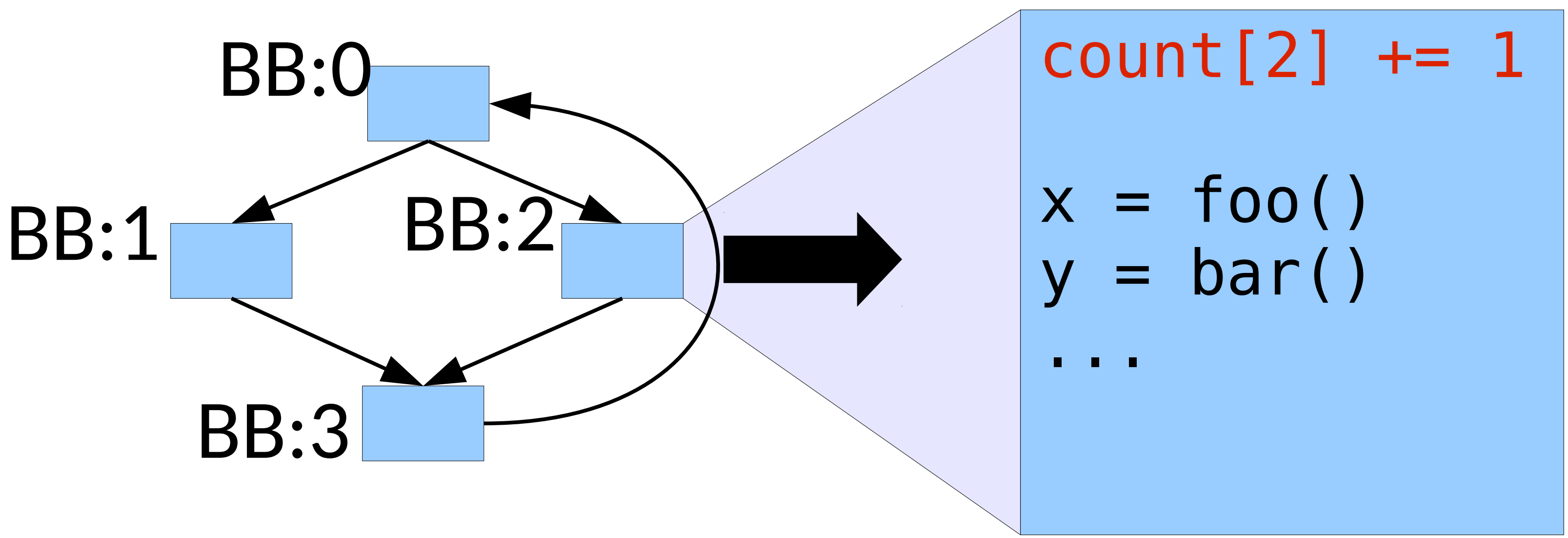

Start:

```
for i in BBs:
  count[i] = 0
```

End:

```
for i in BBs:
  print(count[i])
```

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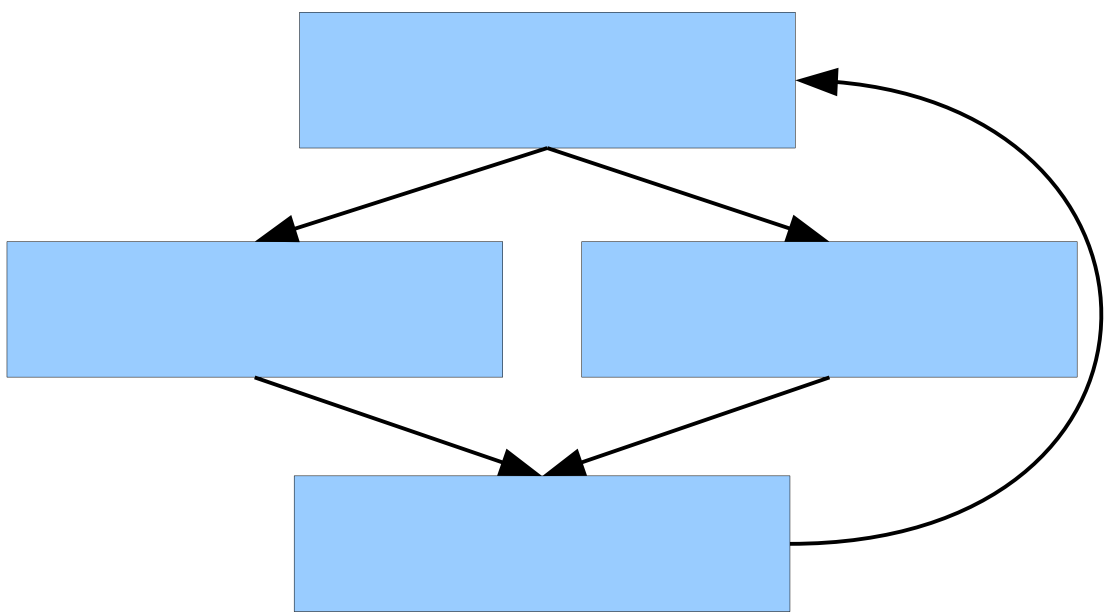

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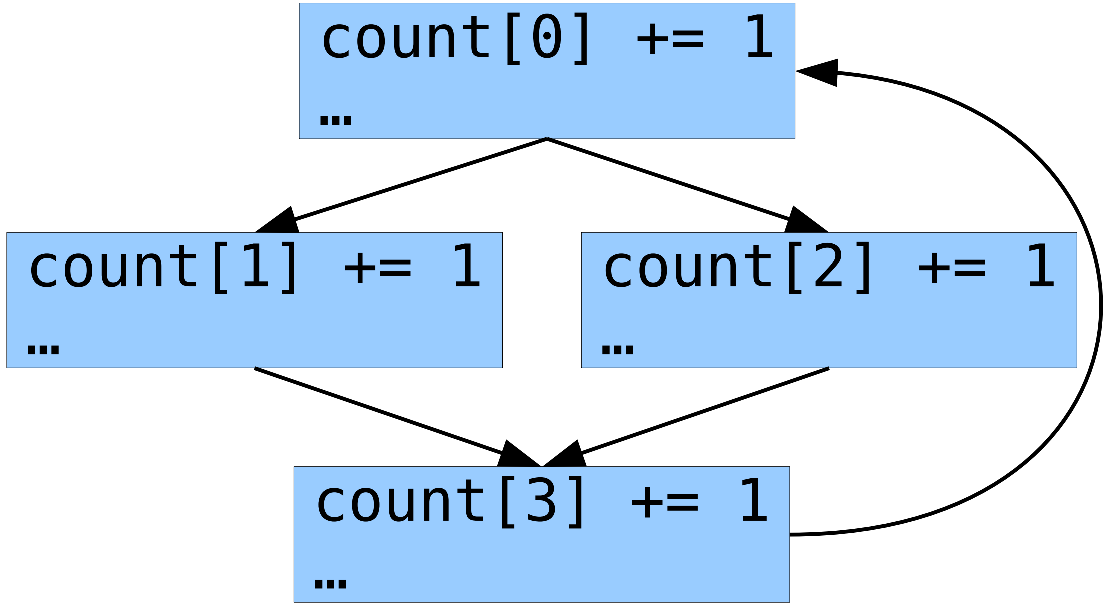

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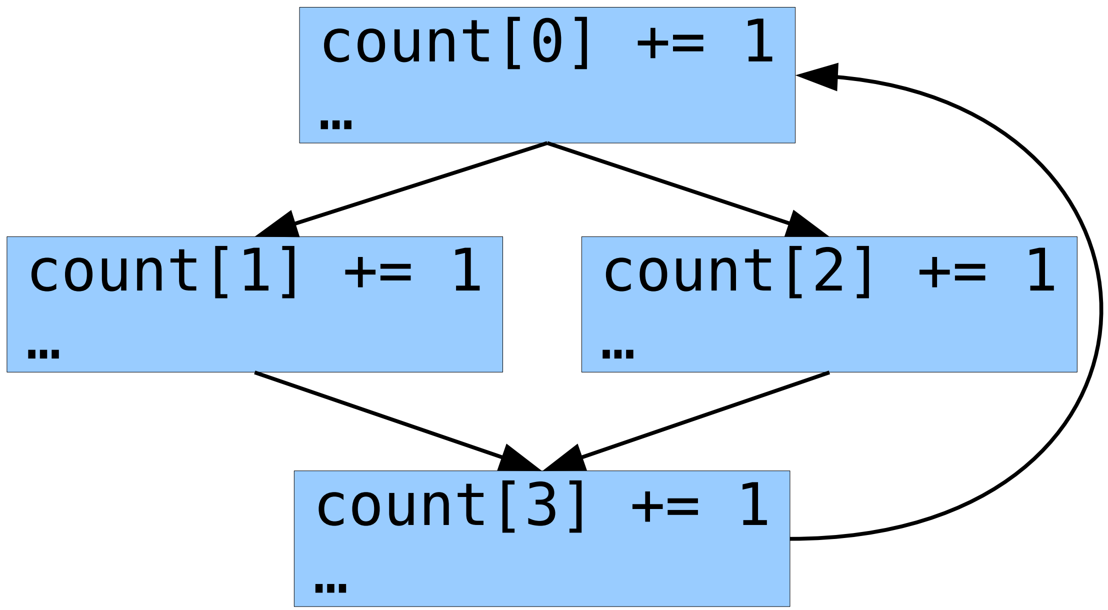

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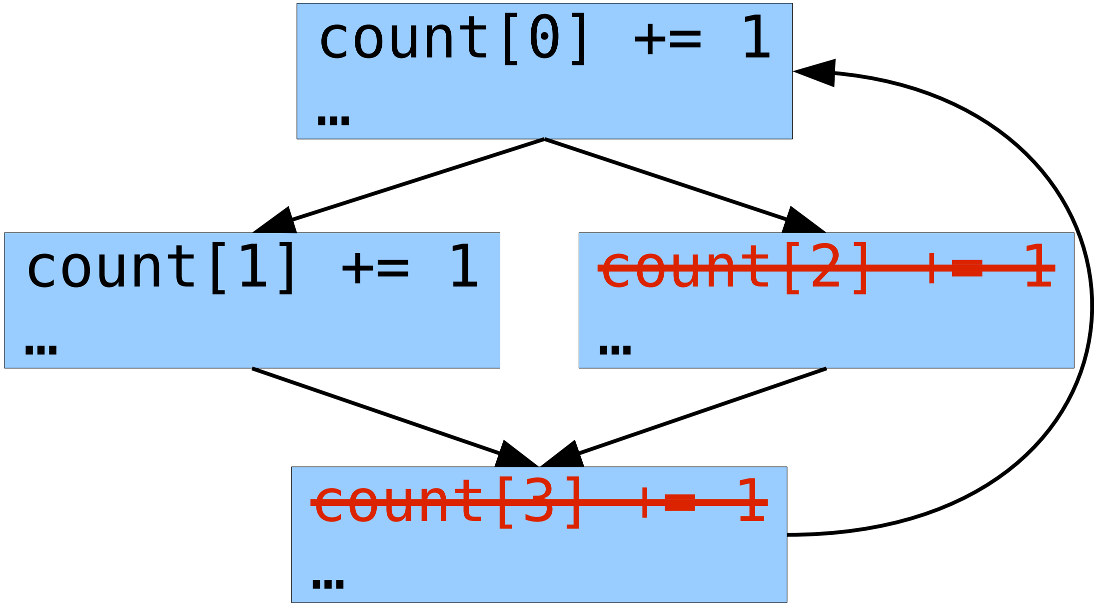

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```
count[0] = count[3]
count[2] = count[0] - count[1]
```

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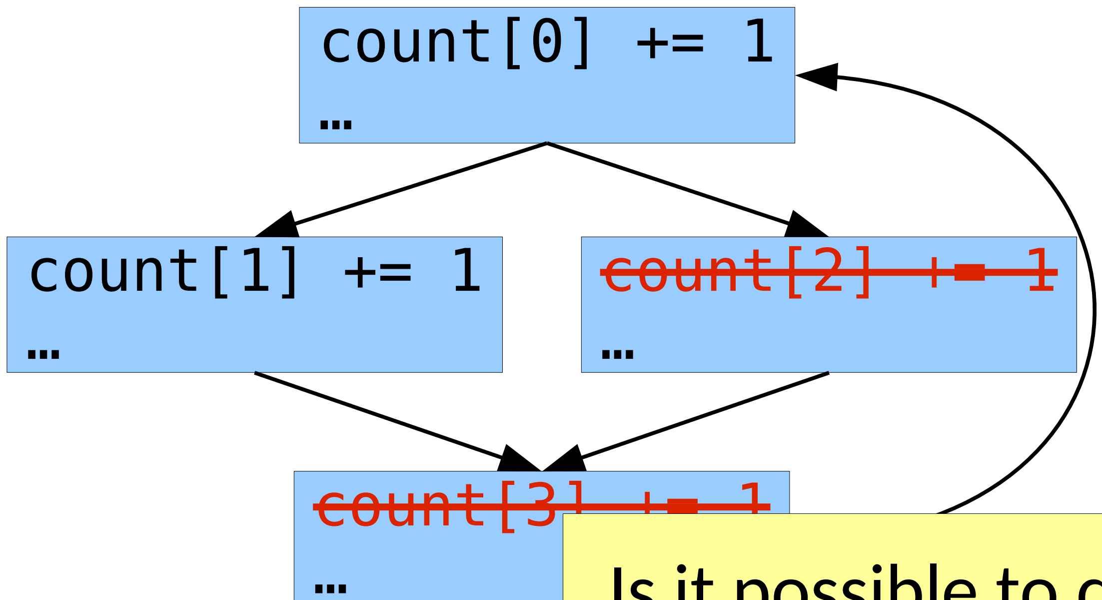

Is it possible to do even better?

  - Can we do better?

```
count[0] = count[3]
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```

Efficiency Tactics

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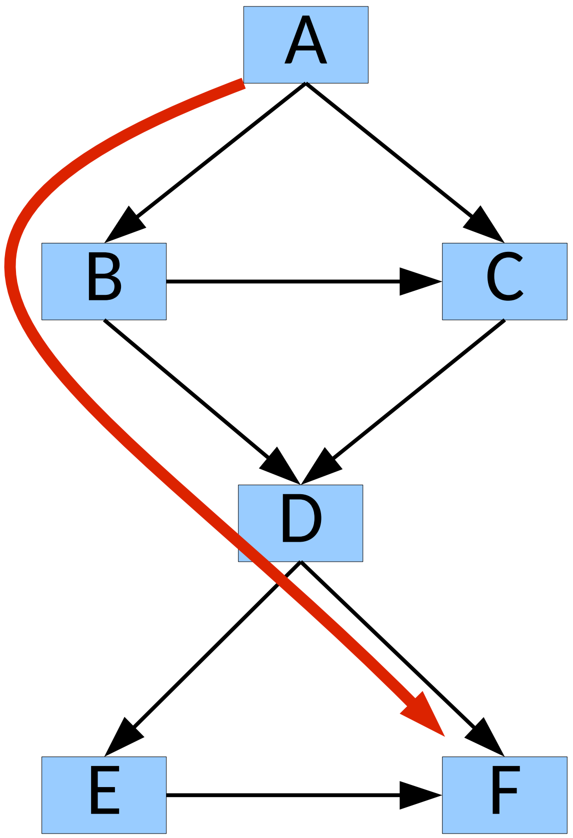
- **Goal:** How often does an acyclic path execute?



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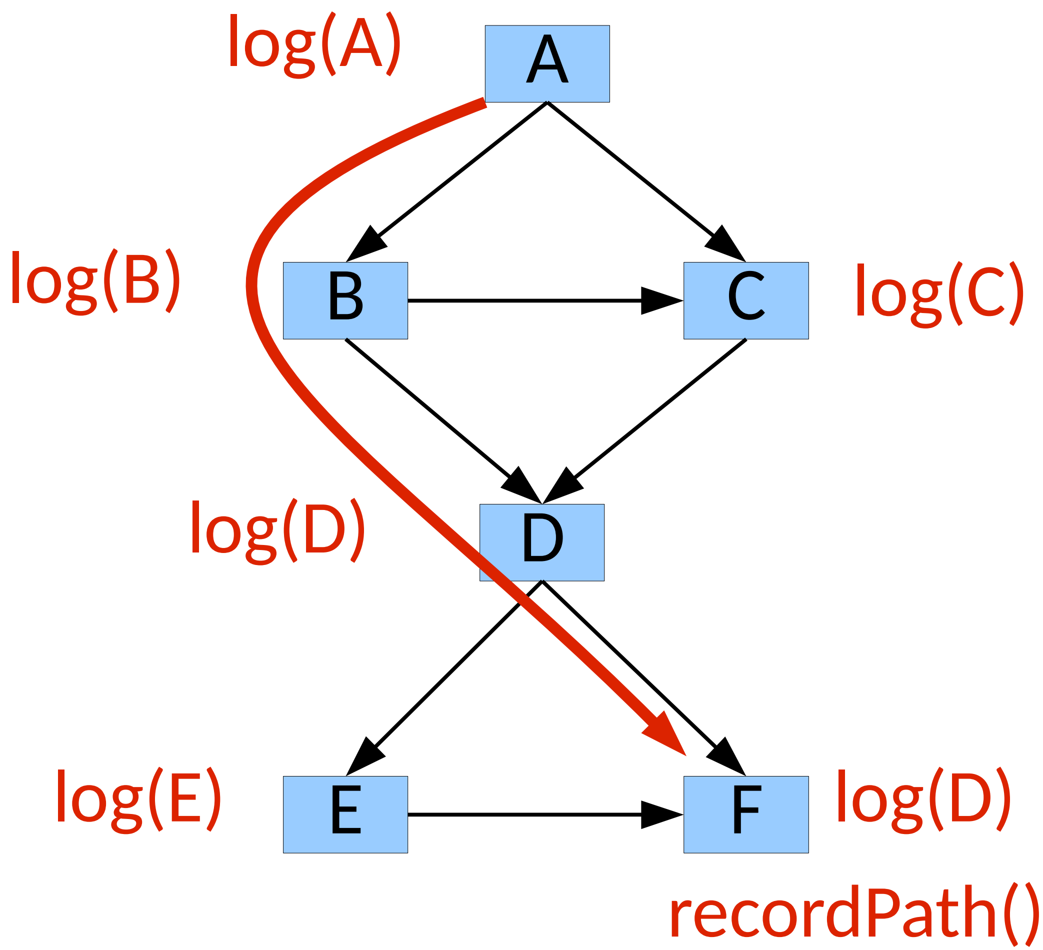
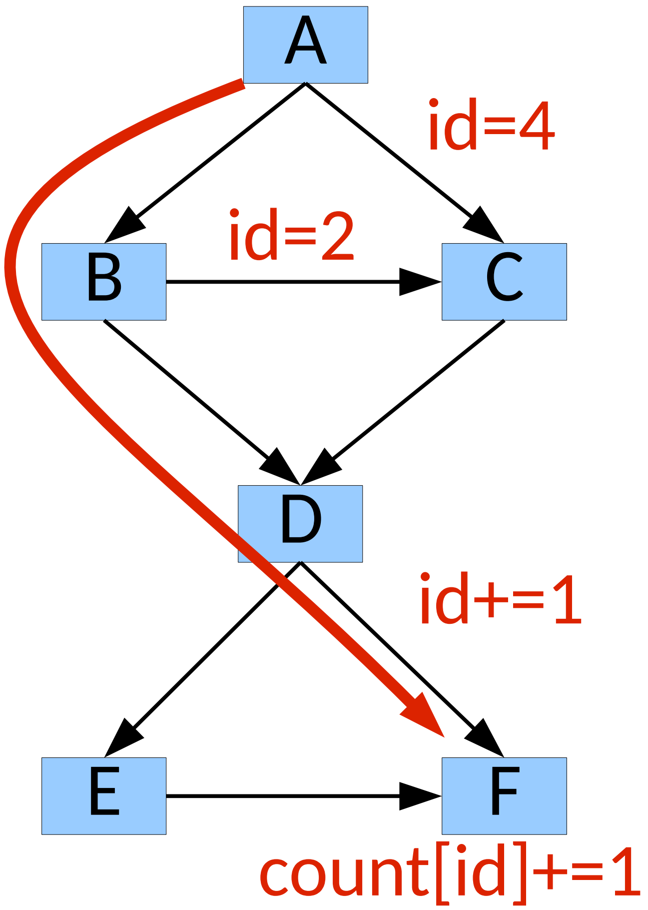


Path Profiling

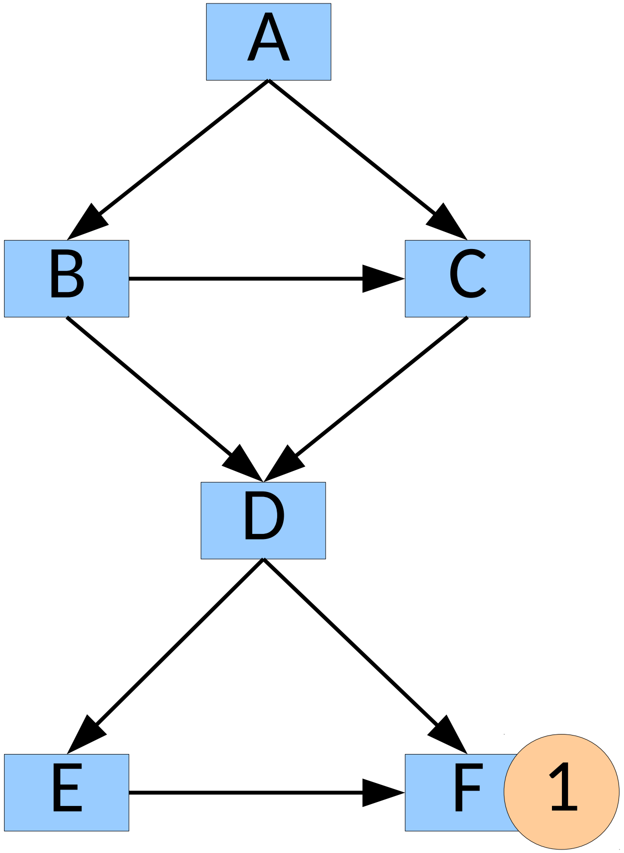
- **Goal:** How often does an acyclic path execute?
  - Could log the trace…
  - Could *encode the paths*

Path	Encoding
ABDEF	0
ABDF	1
ABCDEF	2
ABCDF	3
ACDEF	4
ACDF	5



Path Profiling

- Step 1: Count the # of paths *from* each node to the exit



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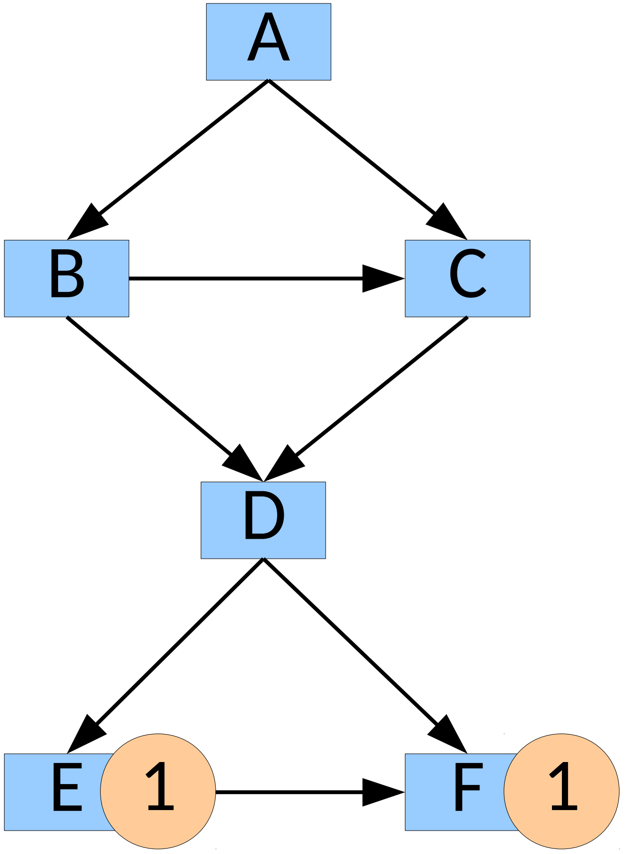

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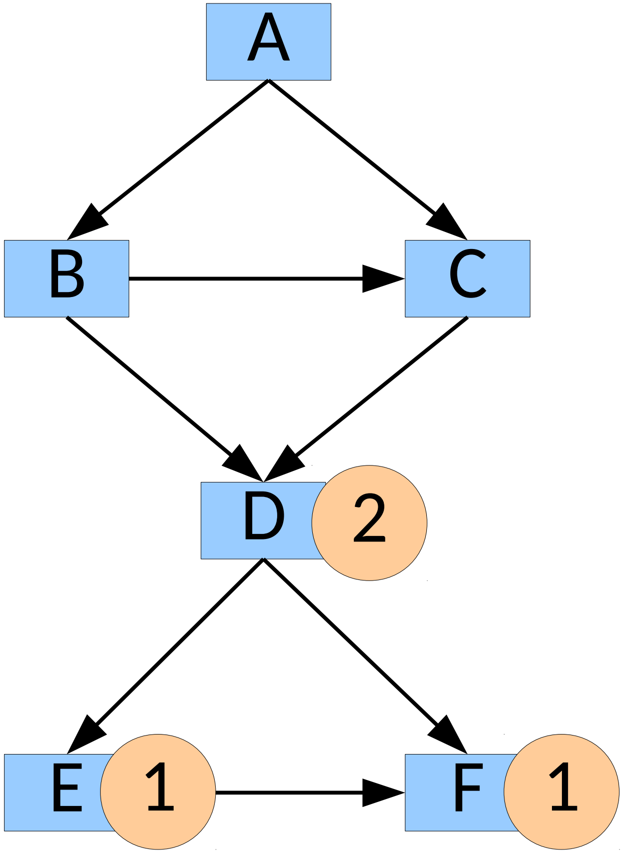

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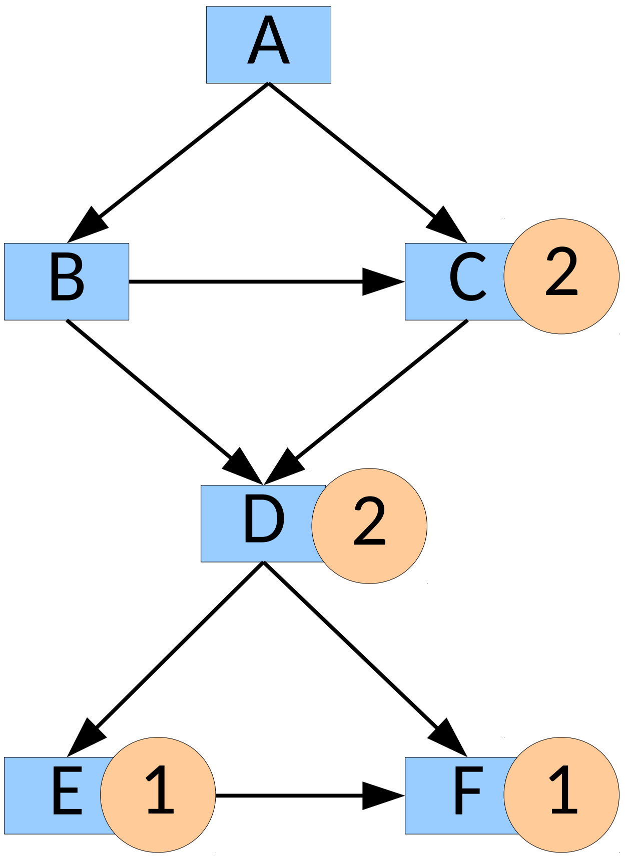

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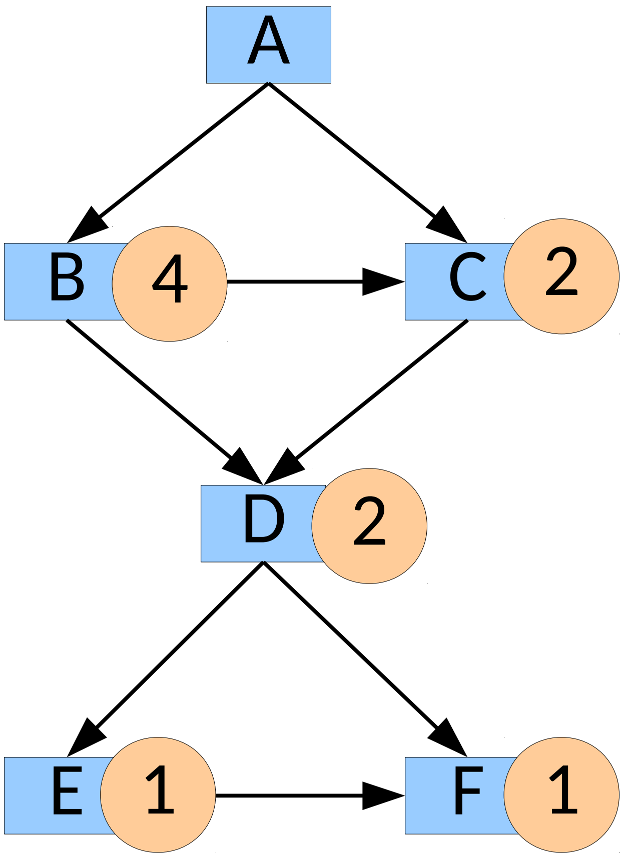

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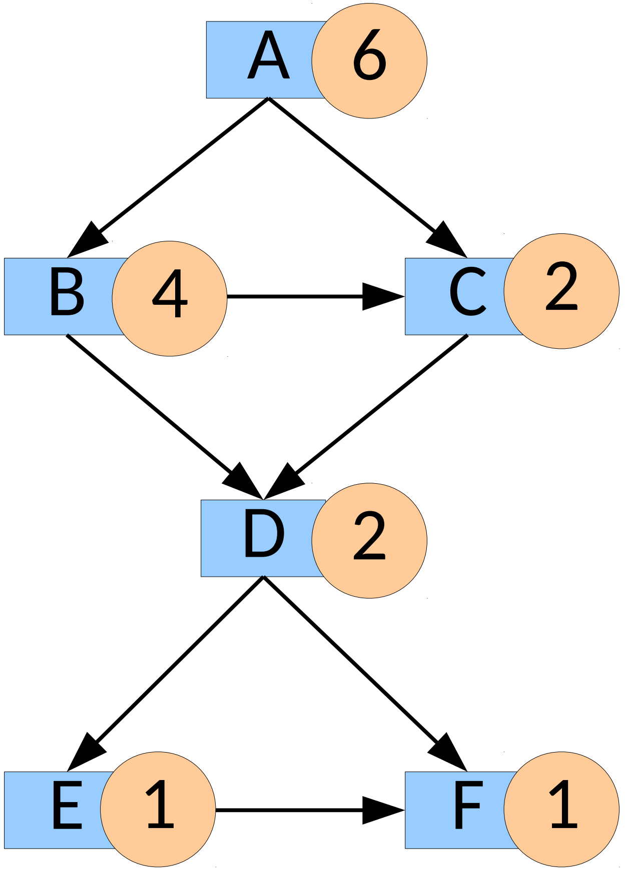

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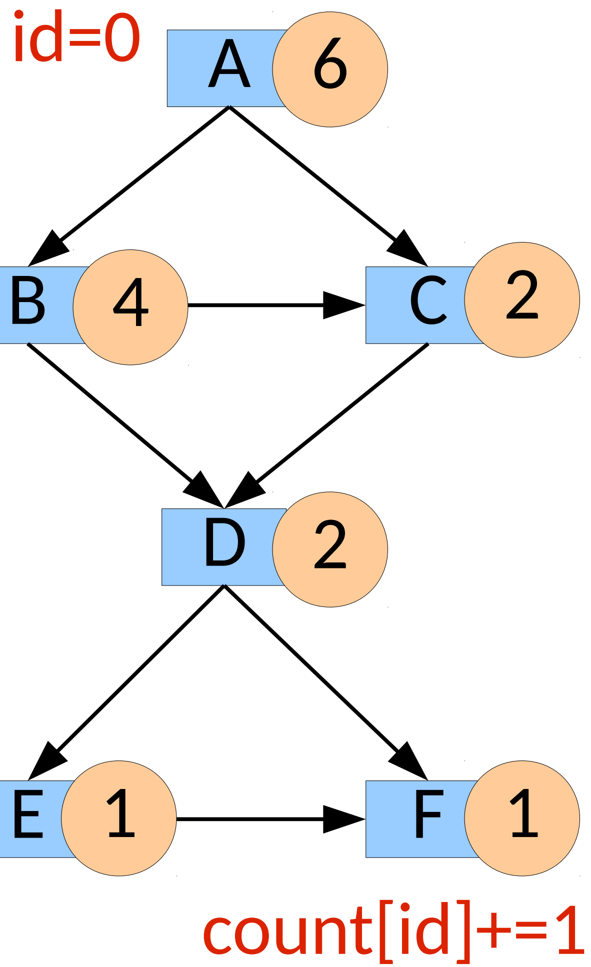

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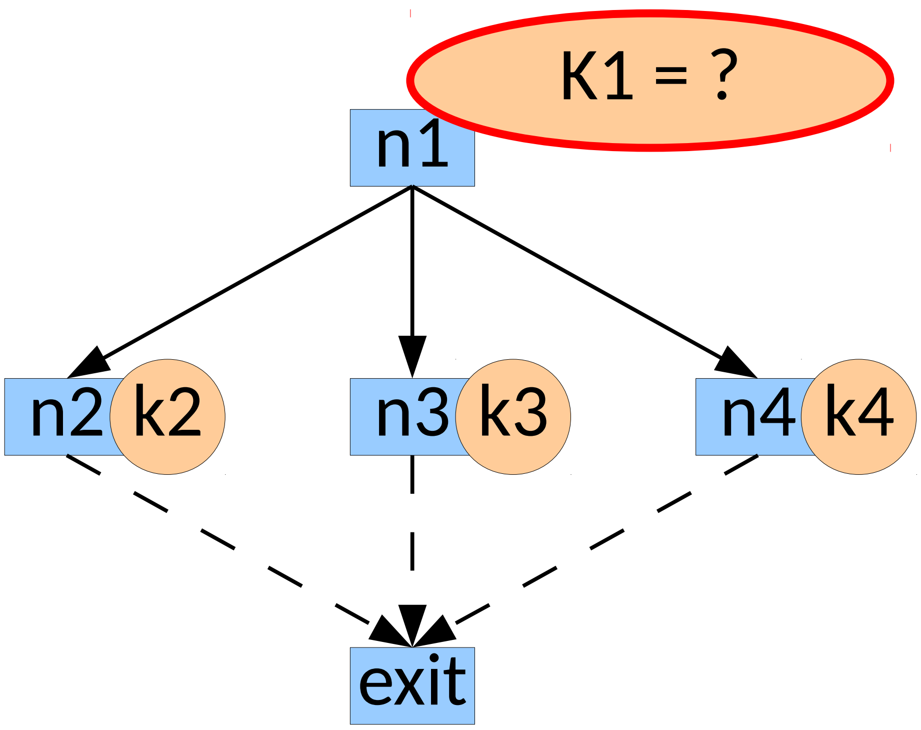

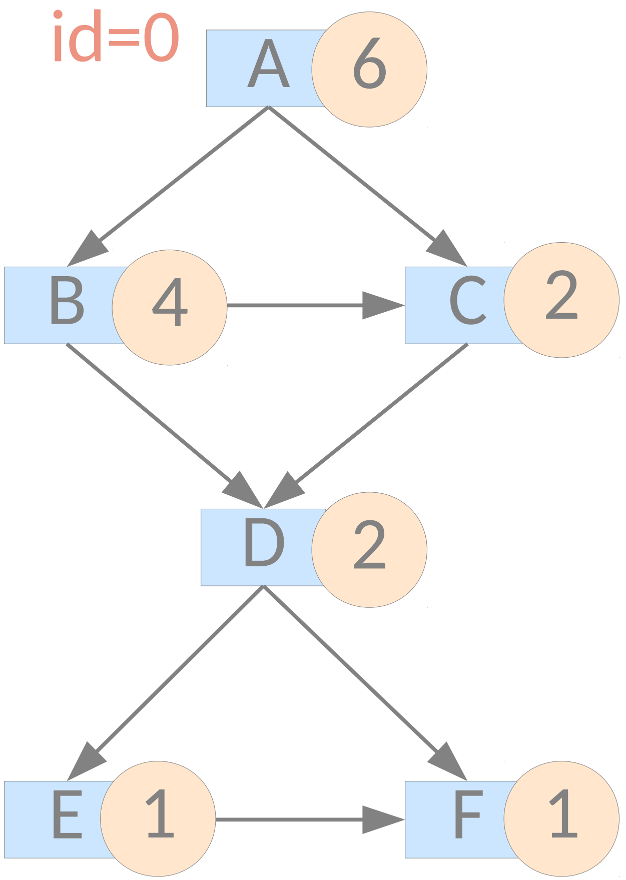

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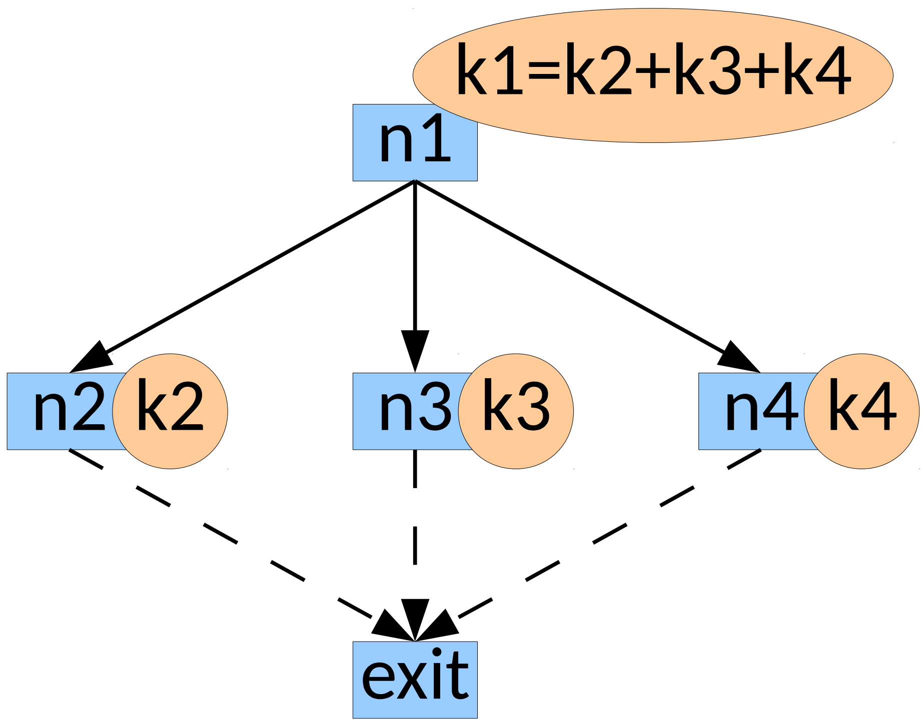

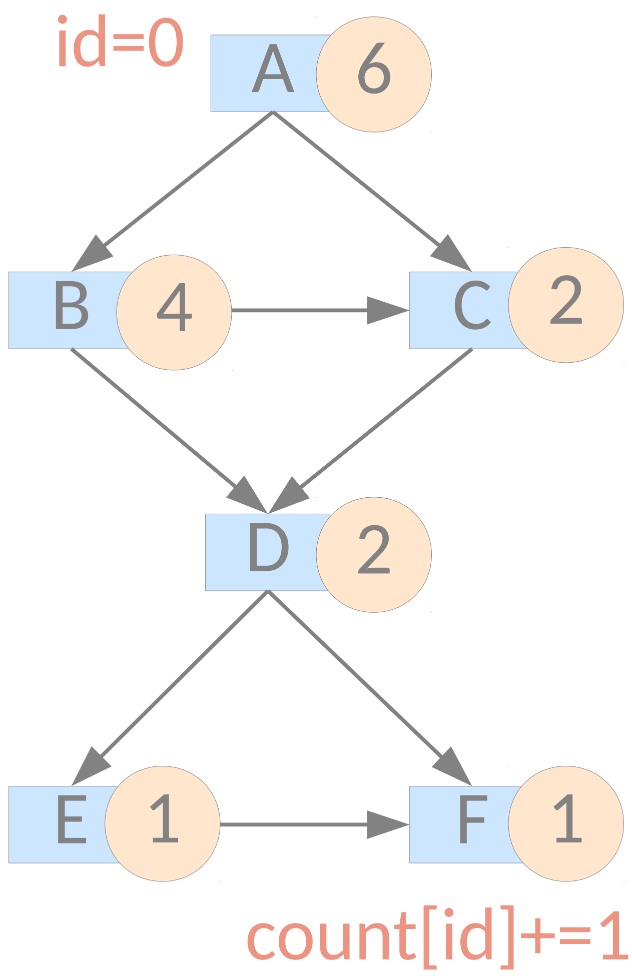

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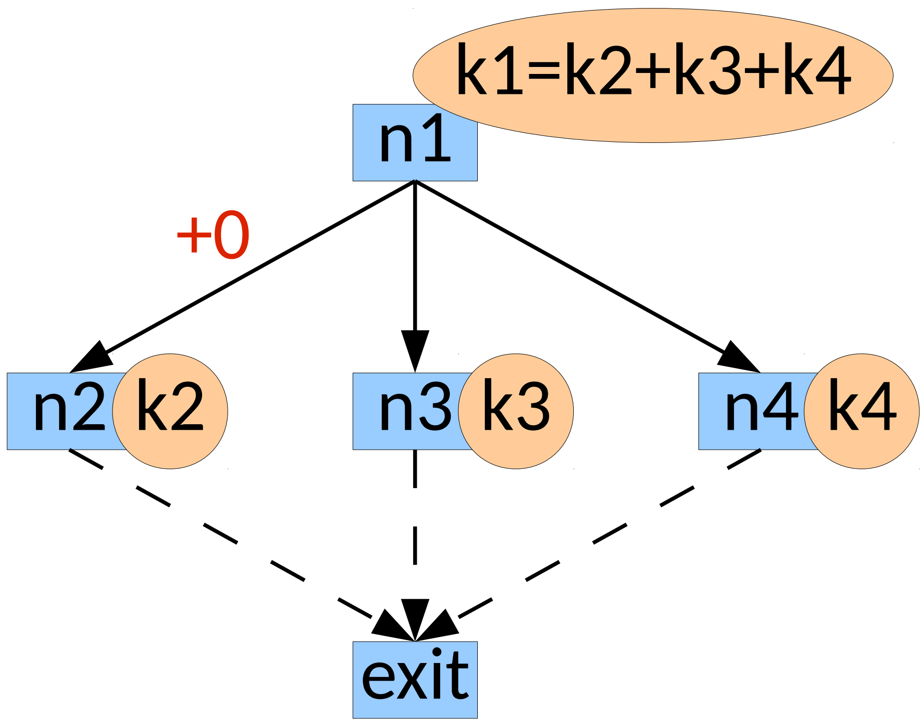

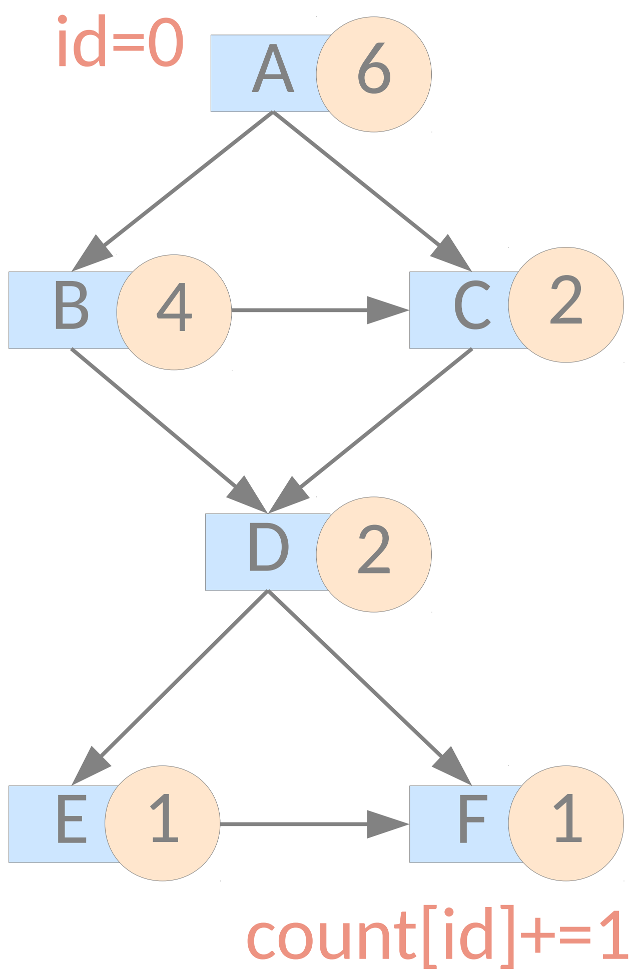

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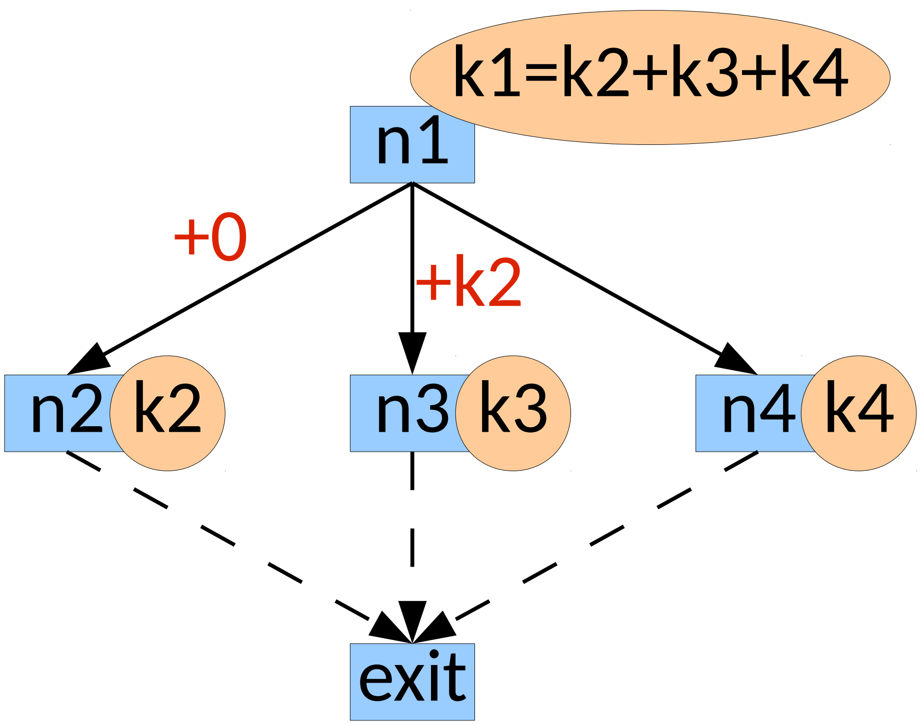

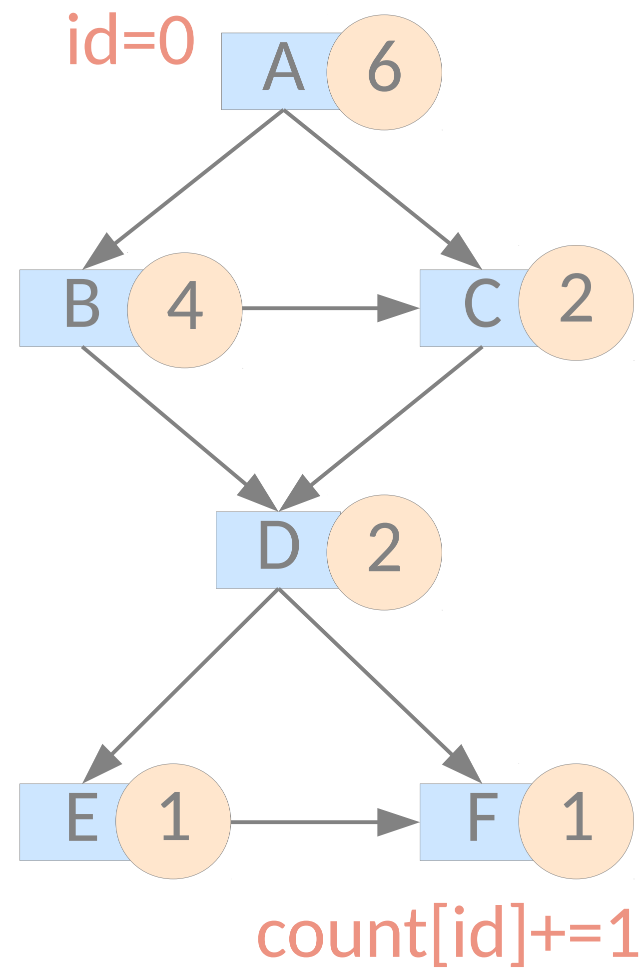

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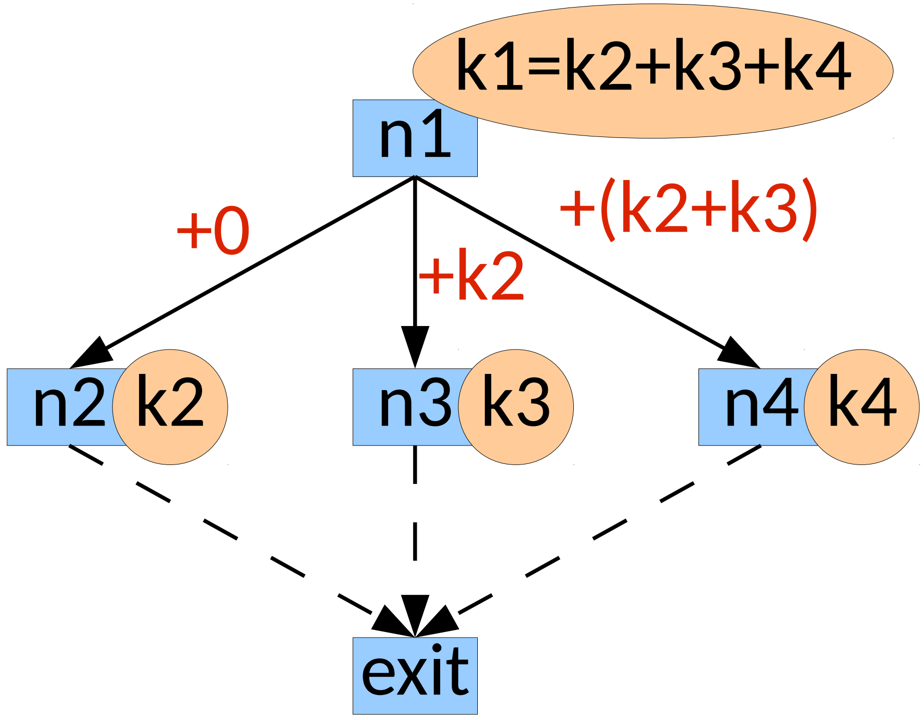

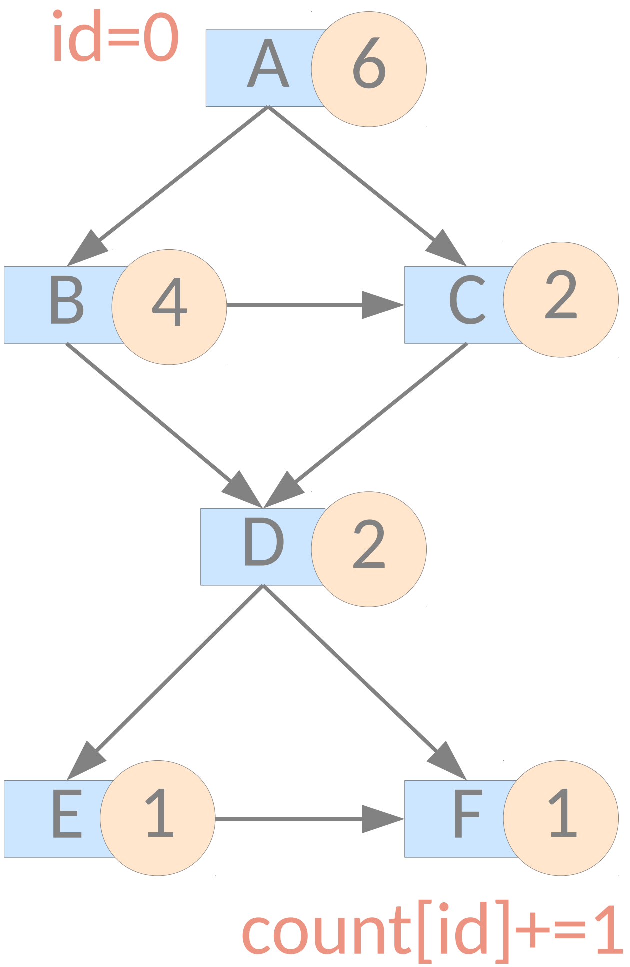

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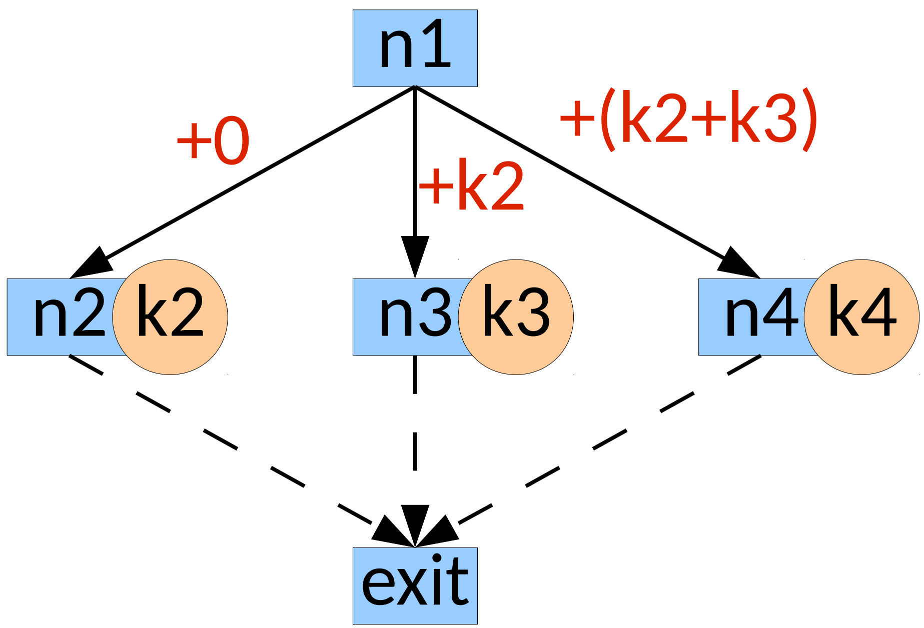

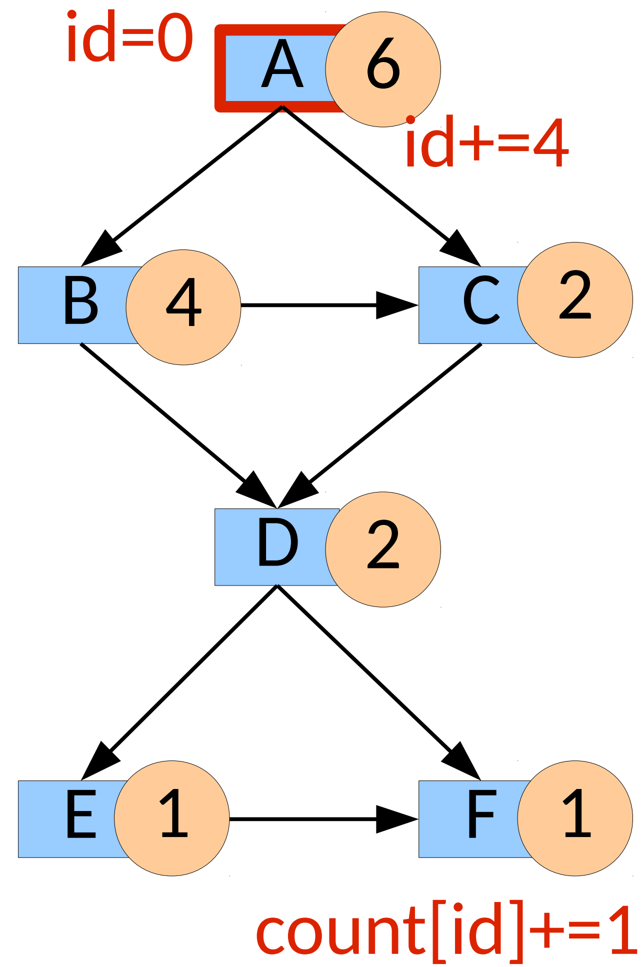

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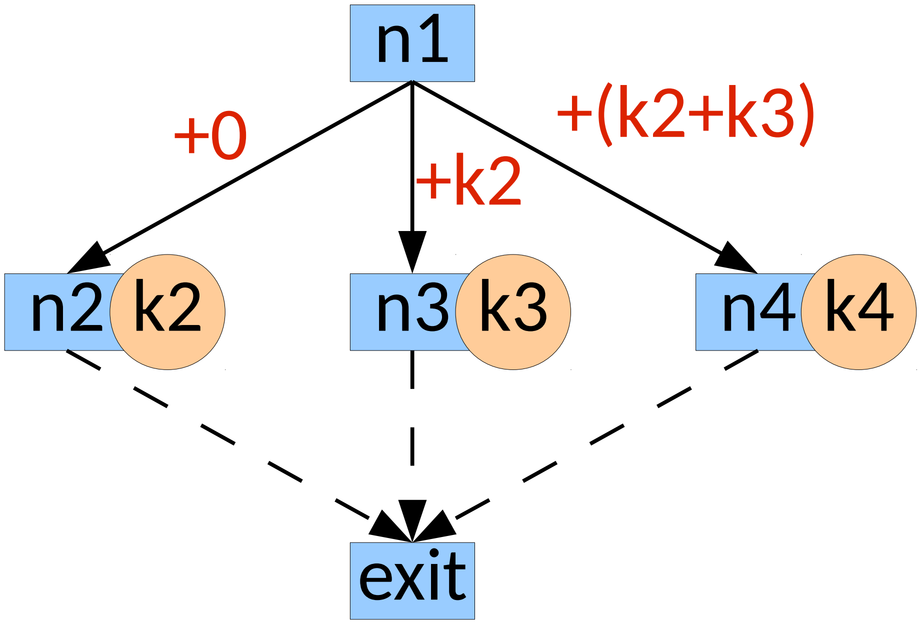

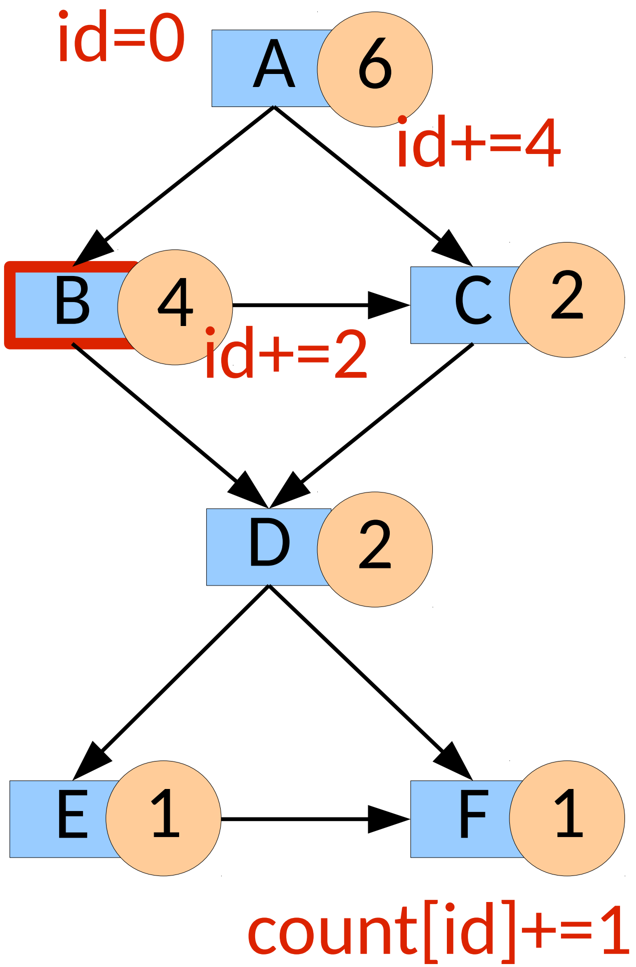

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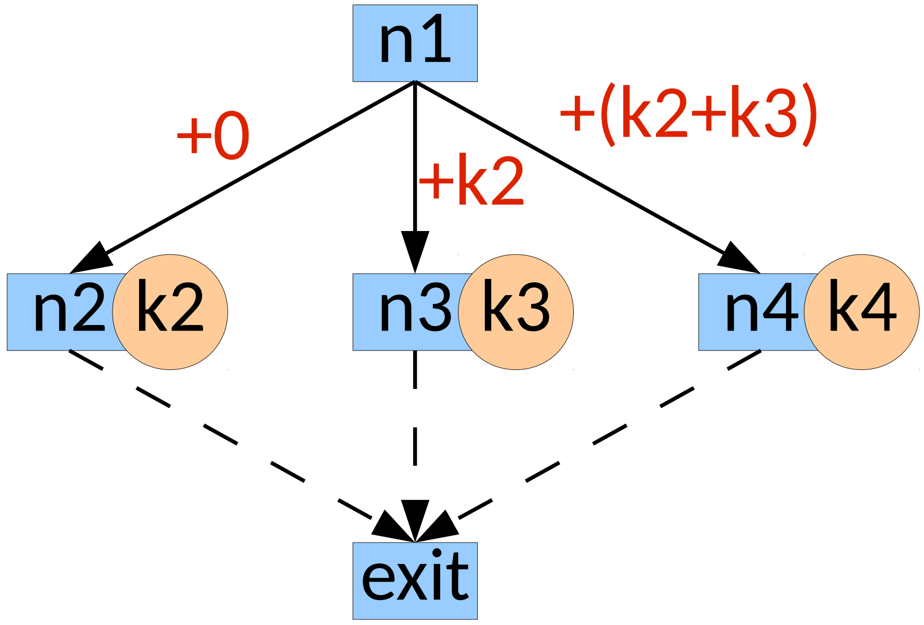

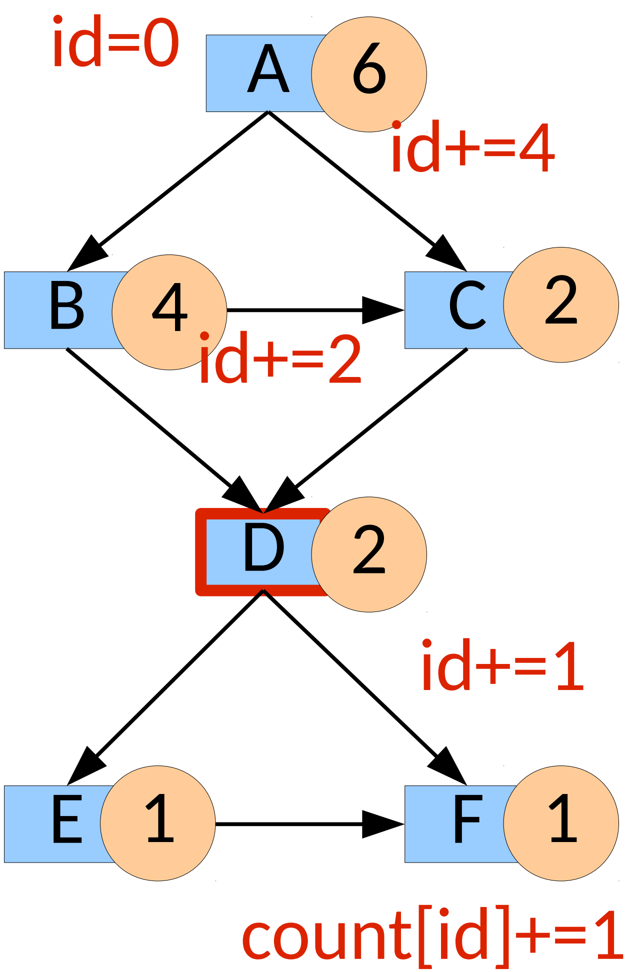

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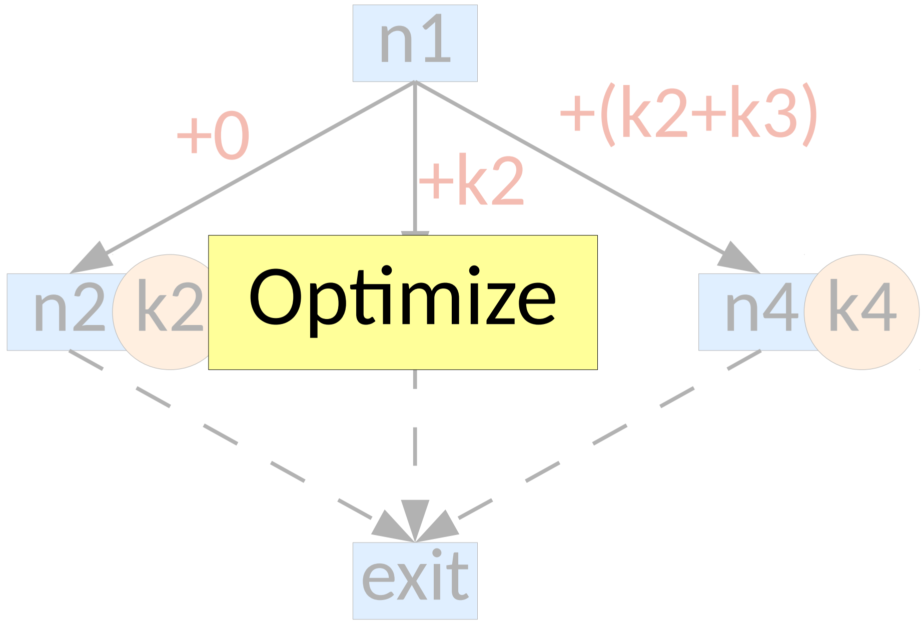
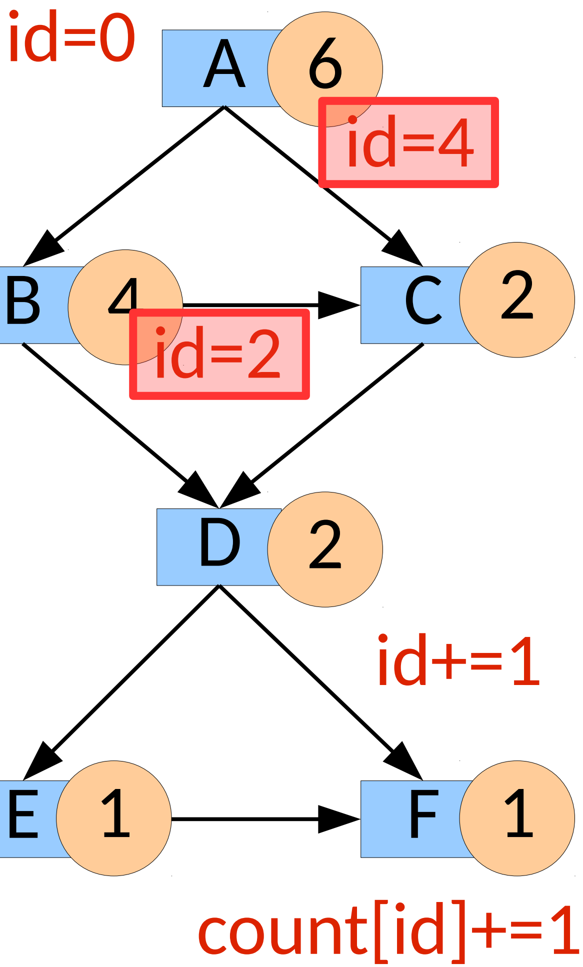
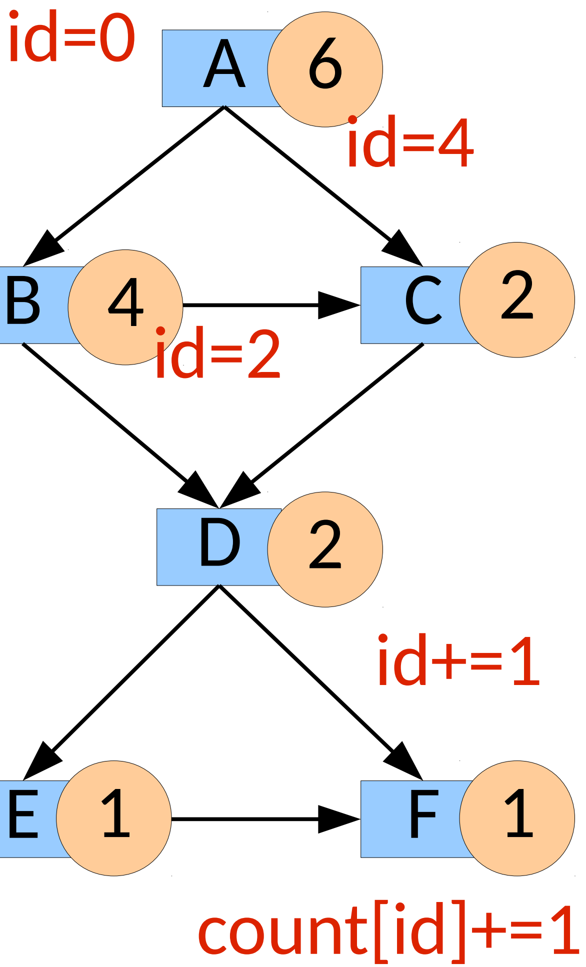




Path Profiling: Decoding

How do we know which IDs map to which paths?



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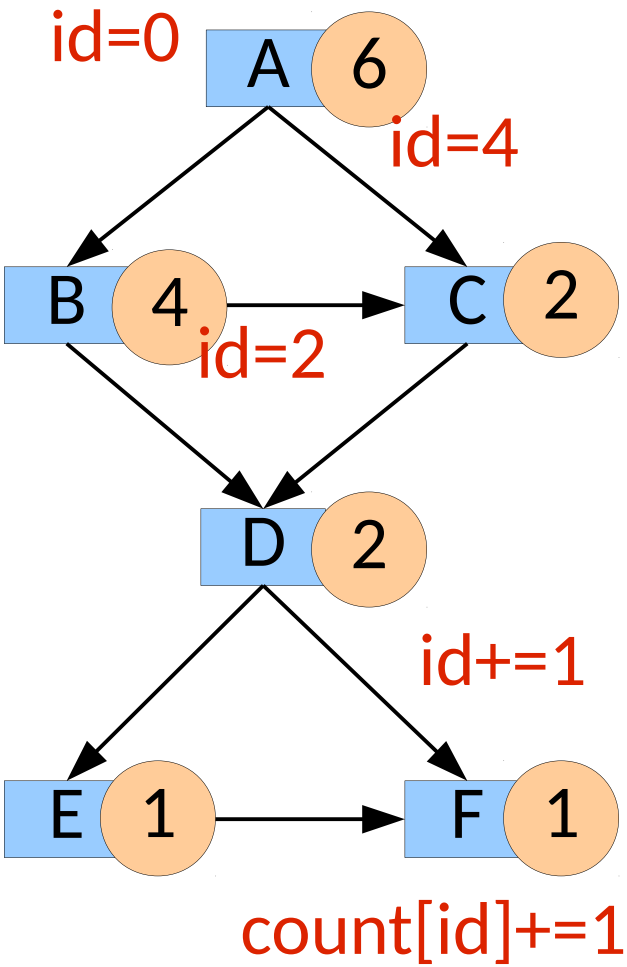

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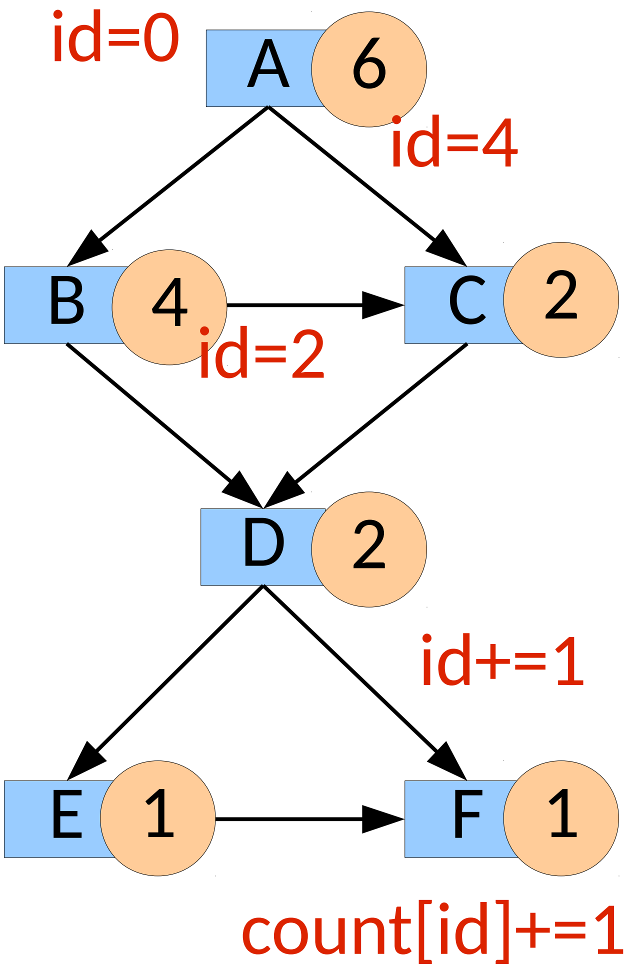

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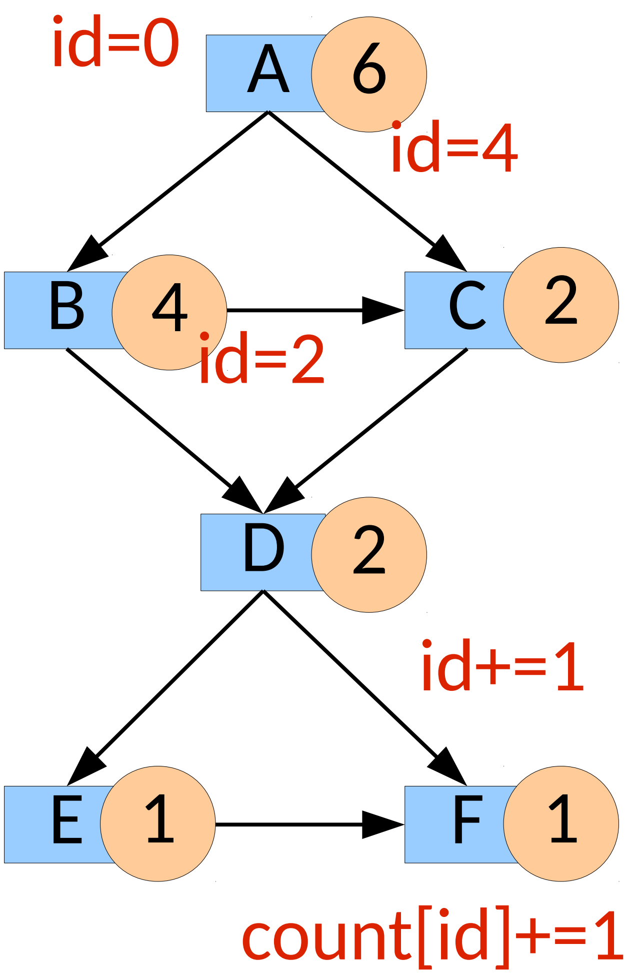

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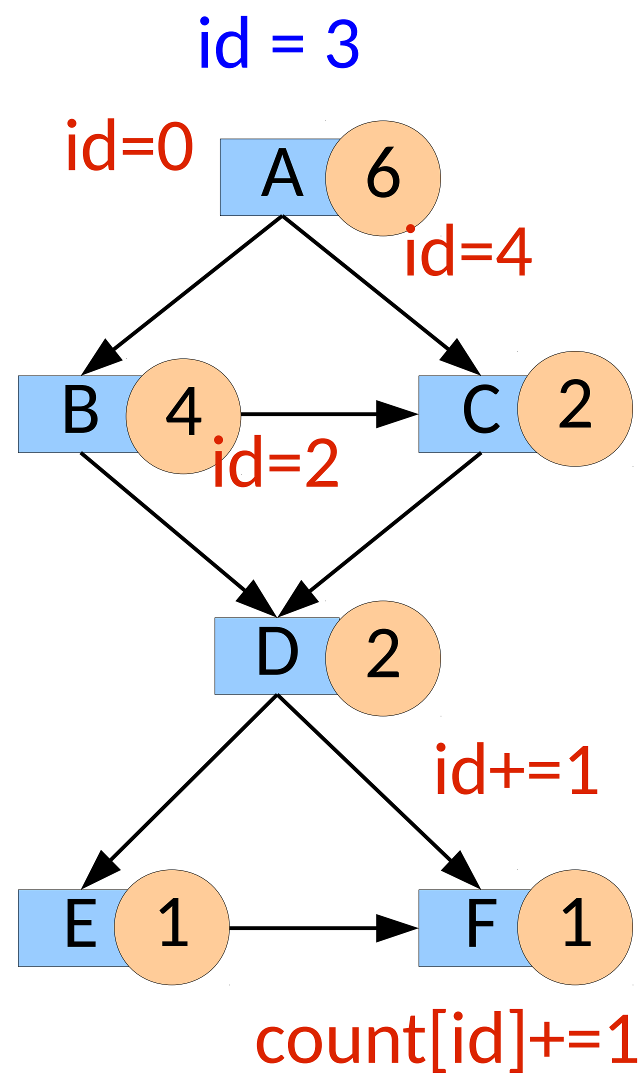

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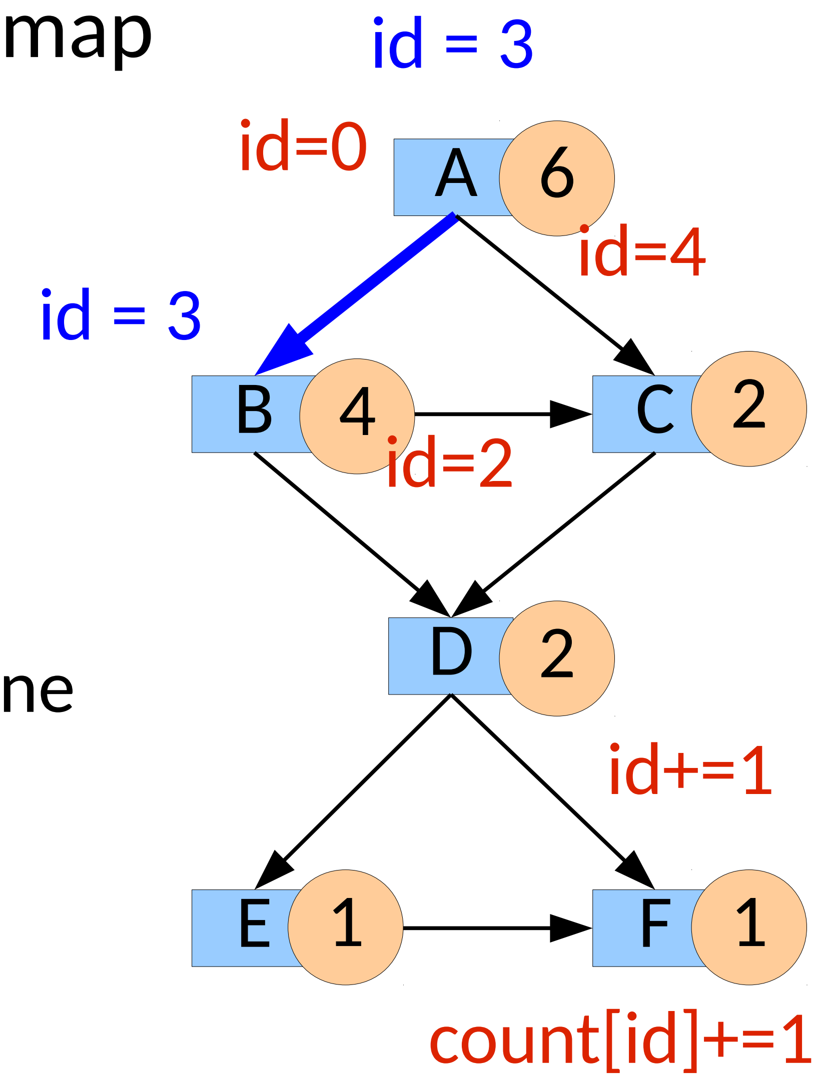

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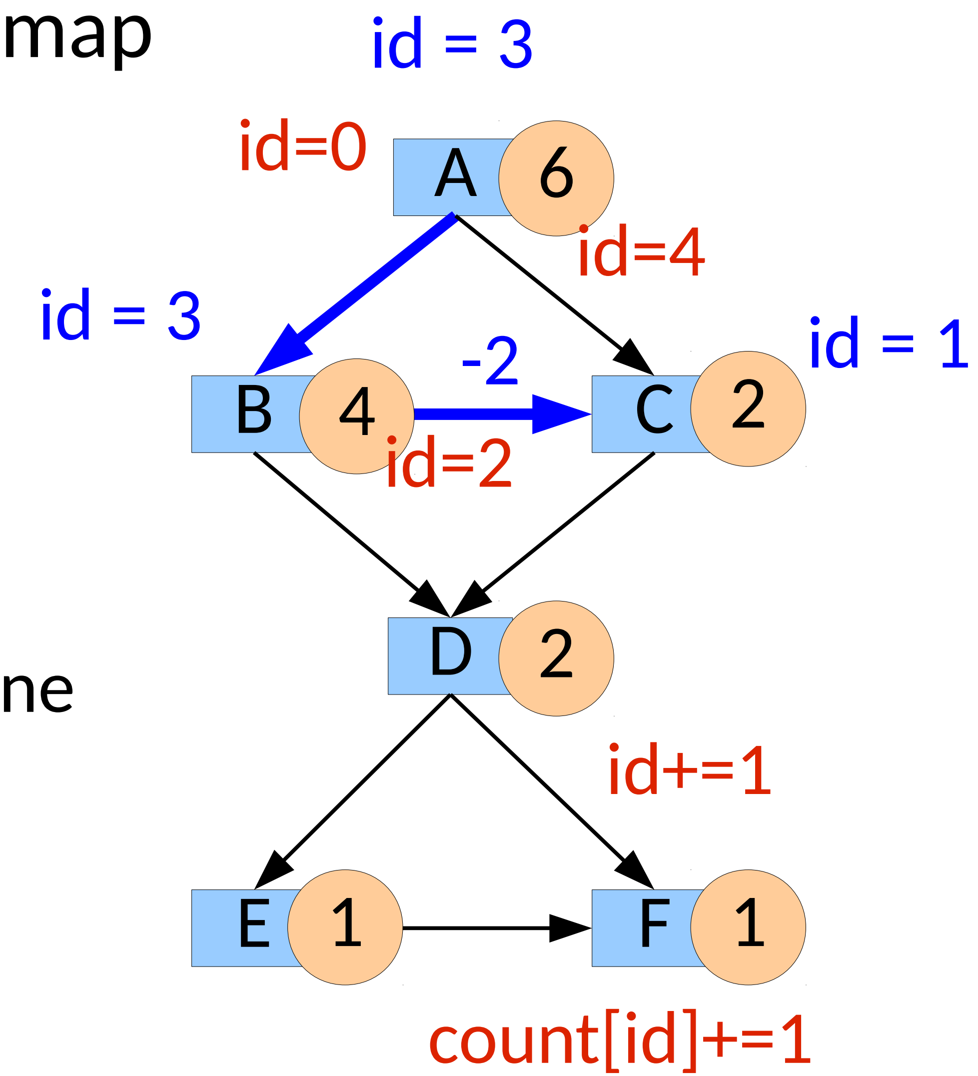

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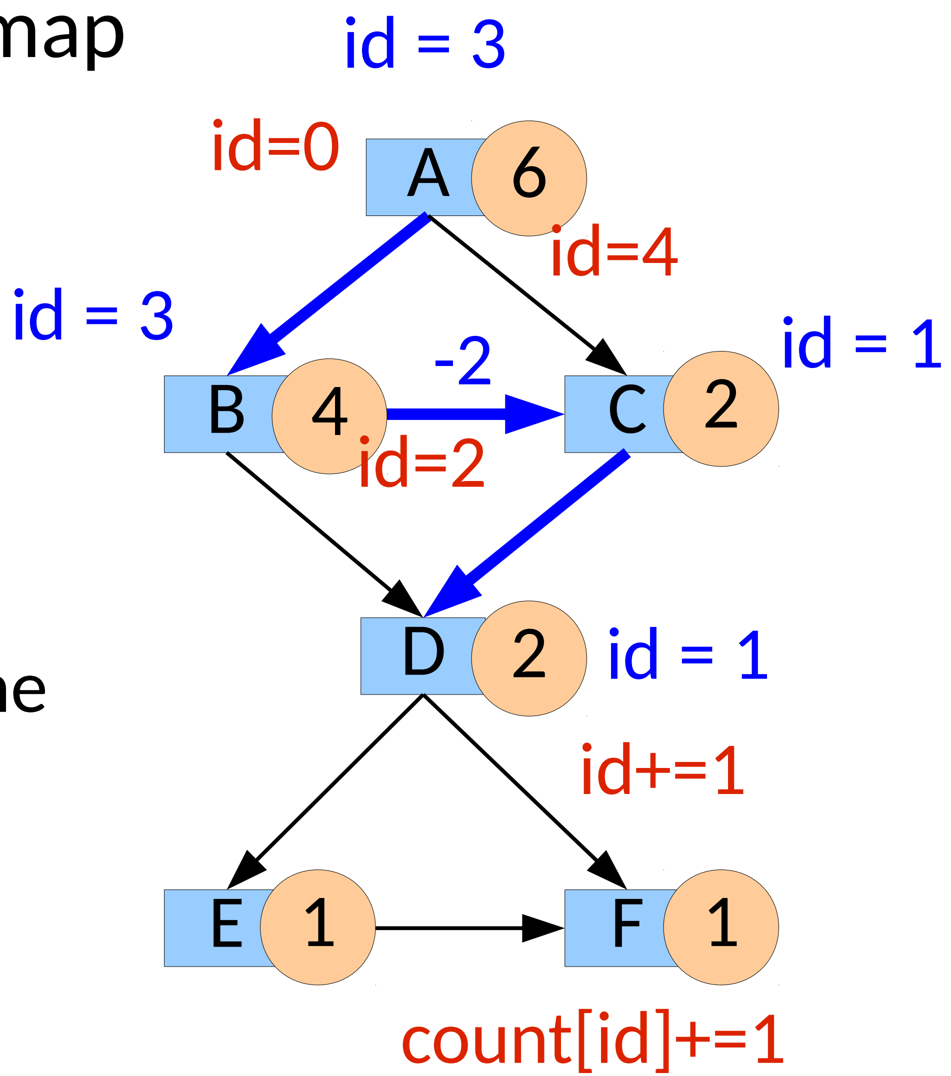

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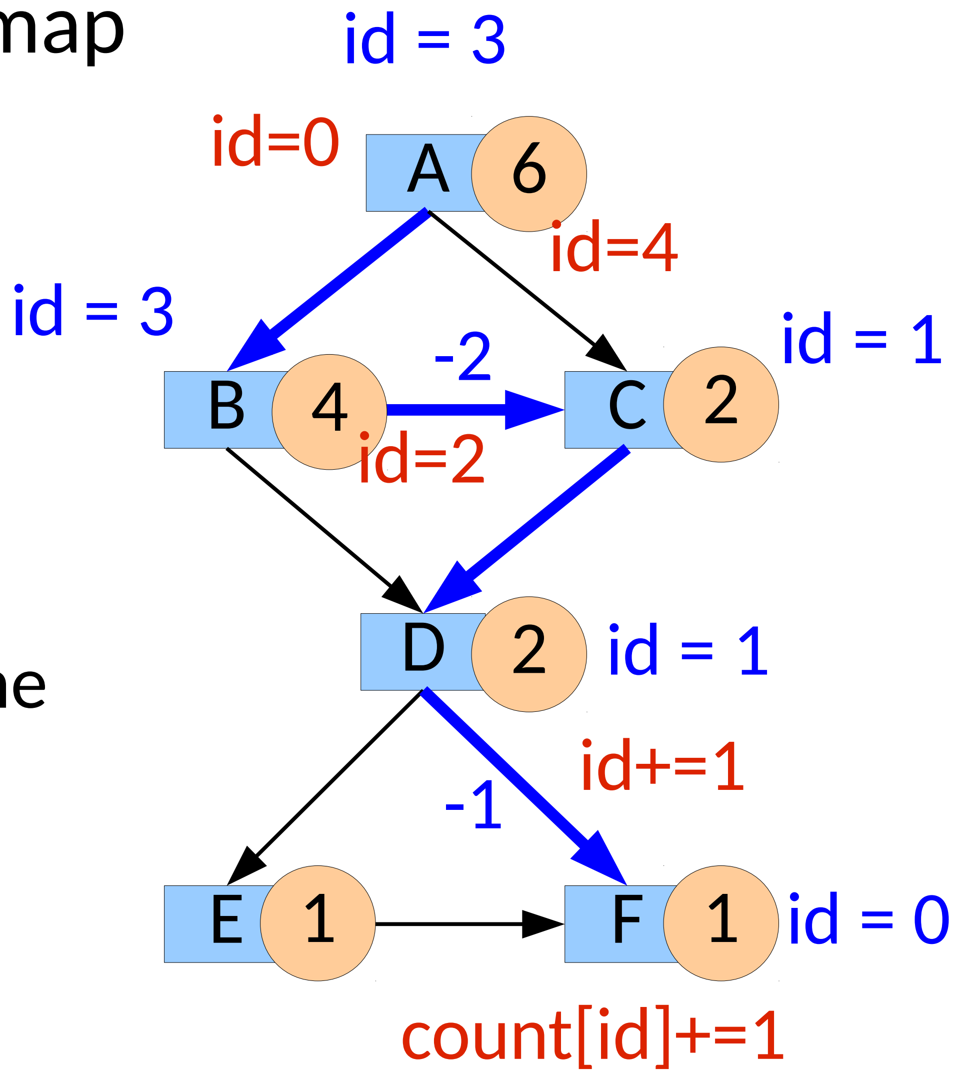

Path Profiling: Results

Benchmark	Base Time (sec)	PP Overhead %	QPT2 Overhead %	PP/ QPT	Path Inc (million)	Edge Inc (x Path)	Hashed Inc %	Inst/ Inc
099.go	885.0	53.4	24.1	2.2	1002.4	1.5	27.7	33.2
124.m88ksim	571.0	35.6	18.7	1.9	4824.9	1.2	3.9	16.2
126.gcc	322.0	96.9	52.8	1.8	9.4	1.7	16.8	15.1
129.compress	351.0	19.4	21.9	0.9	3015.7	1.5	0.0	16.6
130.li	480.0	25.4	26.7	1.0	3282.4	1.4	1.2	16.8
132.ijpeg	749.0	17.4	16.3	1.1	1164.9	1.1	1.2	31.0
134.perl	332.0	72.9	51.5	1.4	1133.0	1.9	23.4	22.2
147.vortex	684.0	37.7	34.1	1.1	3576.3	1.5	23.7	20.3
CINT95 Avg:		44.8	30.8	1.4	22251.1	1.5	12.2	21.4
101.tomcatv	503.0	19.9	2.8	7.1	574.6	1.1	95.8	93.0
102.swim	691.0	8.4	0.6	14.5	163.4	1.0	0.2	162.9
103.su2cor	465.0	10.1	5.8	1.7	558.1	1.2	21.5	92.8
104.hydro2d	811.0	37.7	5.8	6.5	1690.7	1.7	77.8	43.1
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110.applu	715.0	71.0	12.0	5.9	2111.4	1.1	99.1	44.8
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129.compress	351.0	19.4	21.9	0.9	3015.7	1.5	0.0	16.6
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132.ijpeg	749.0	17.4	16.3	1.1	1164.9	1.1	1.2	31.0
134.perl	332.0	72.9	51.5	1.4	1133.0	1.9	23.4	22.2
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What can/can't you infer from these results?

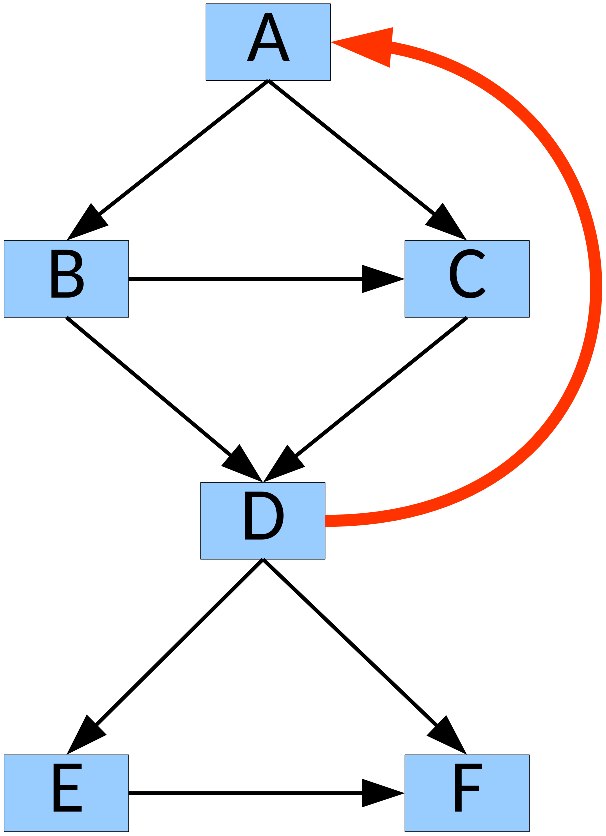
What would you add or change to the evaluation?

Path Profiling

Are there cases where this approach fails?

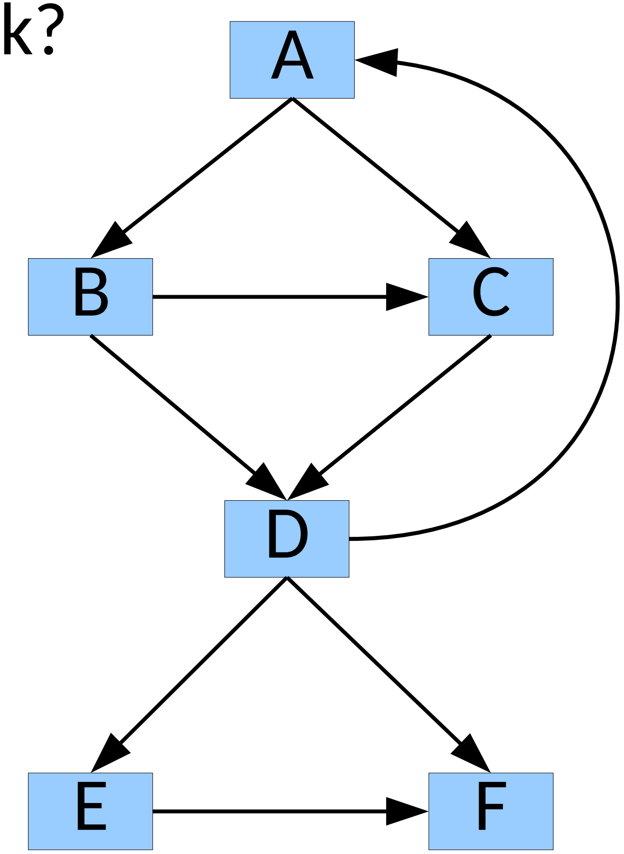
Path Profiling

- What about loops / cycles?



Path Profiling

- What about loops / cycles?
  - Does the existing approach work?



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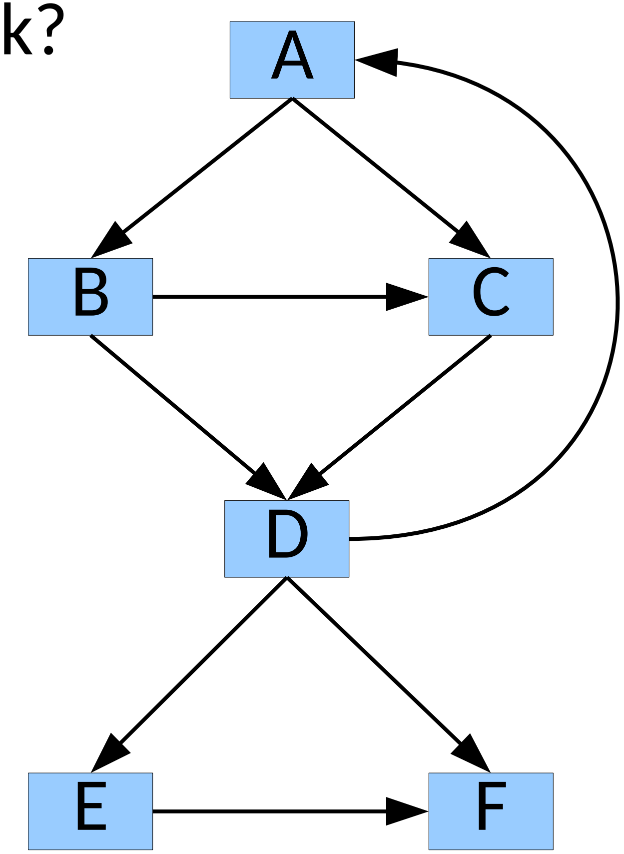

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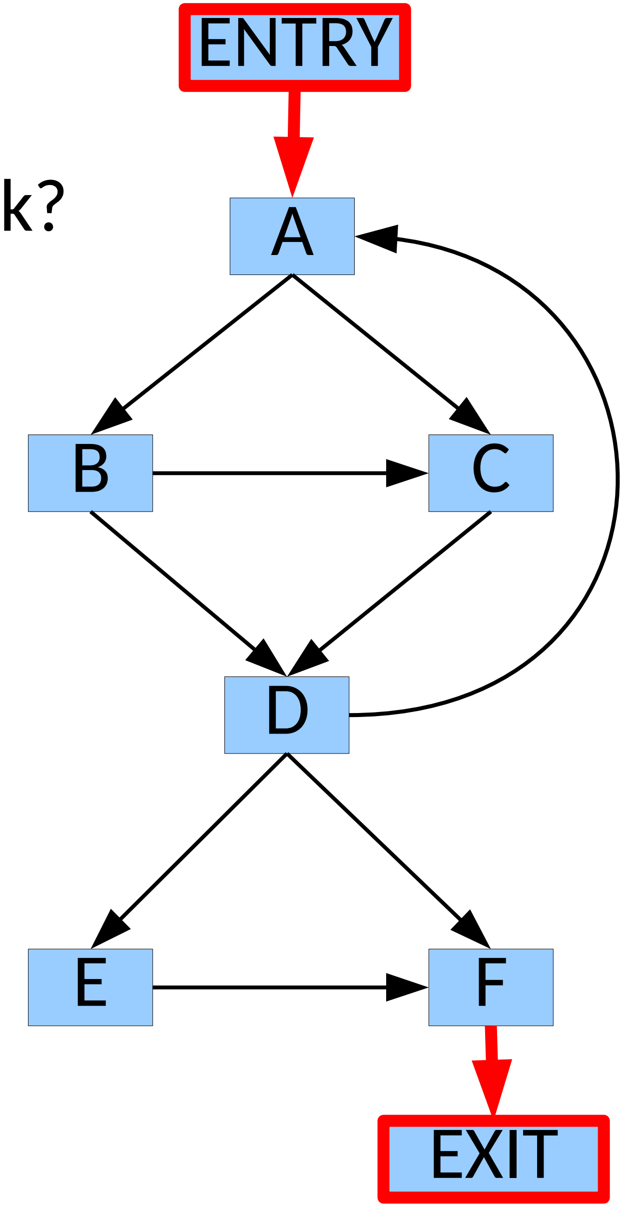

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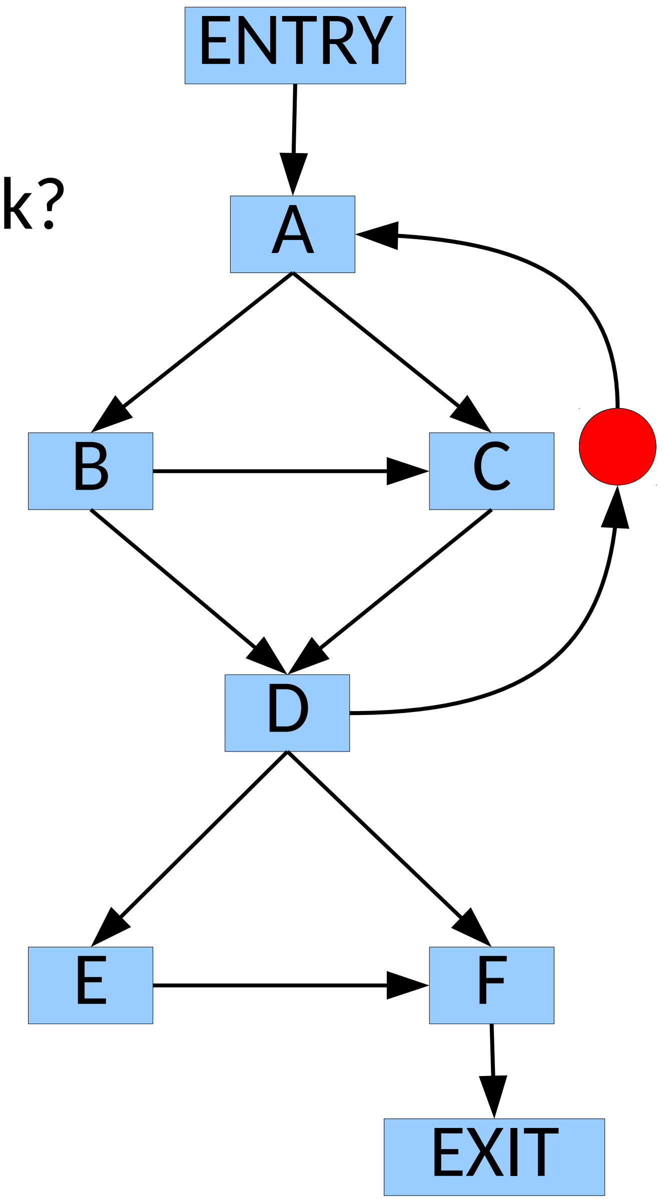

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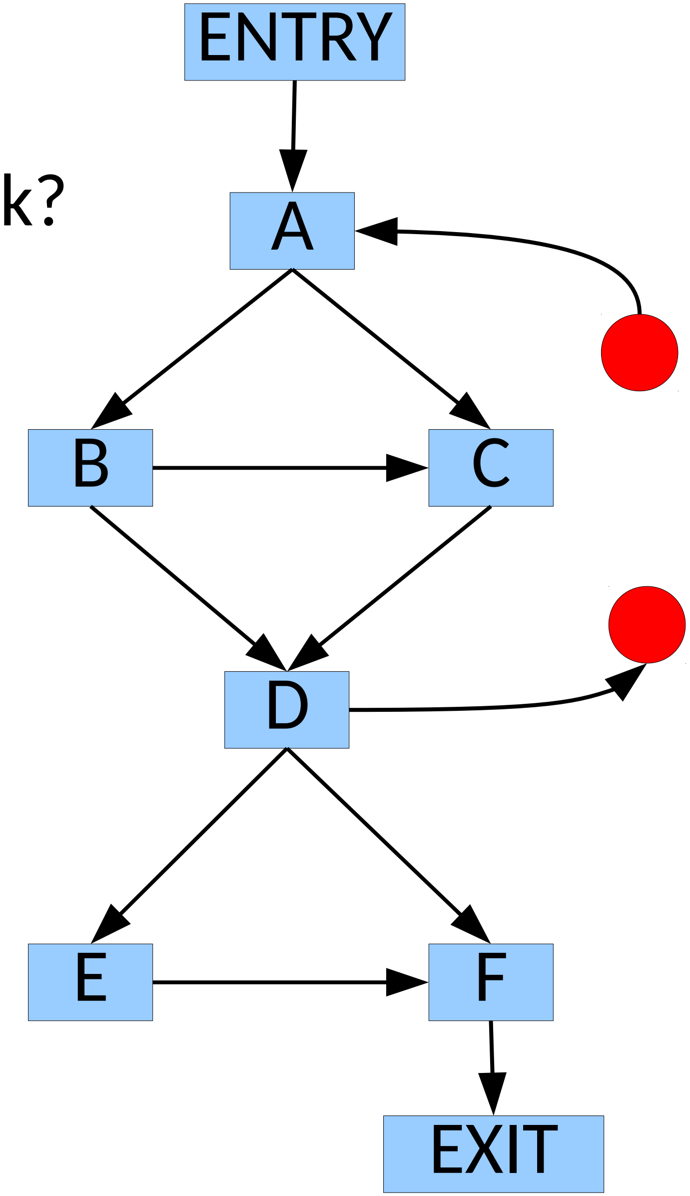

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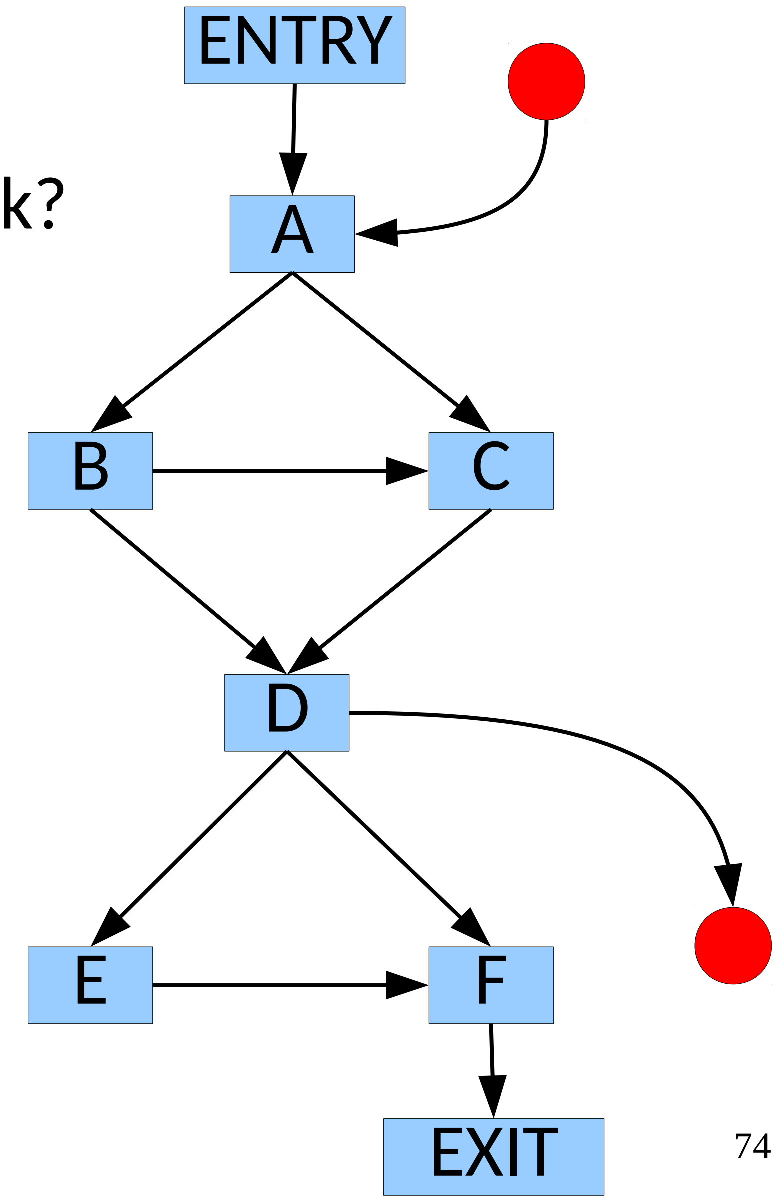

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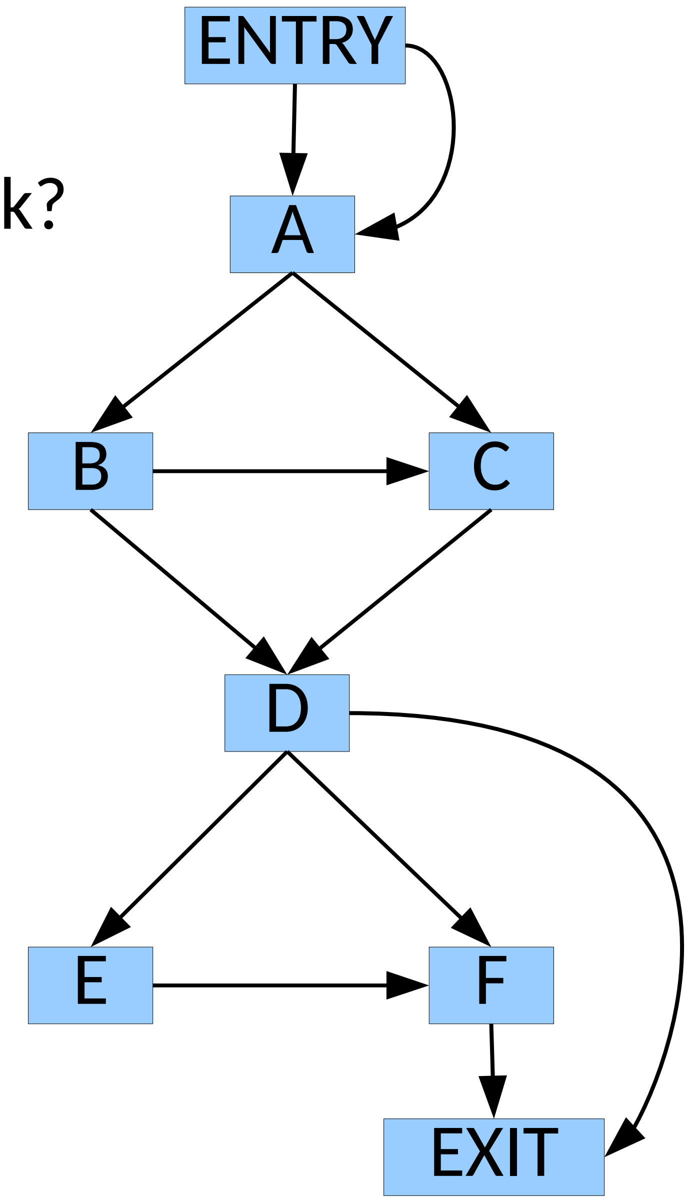

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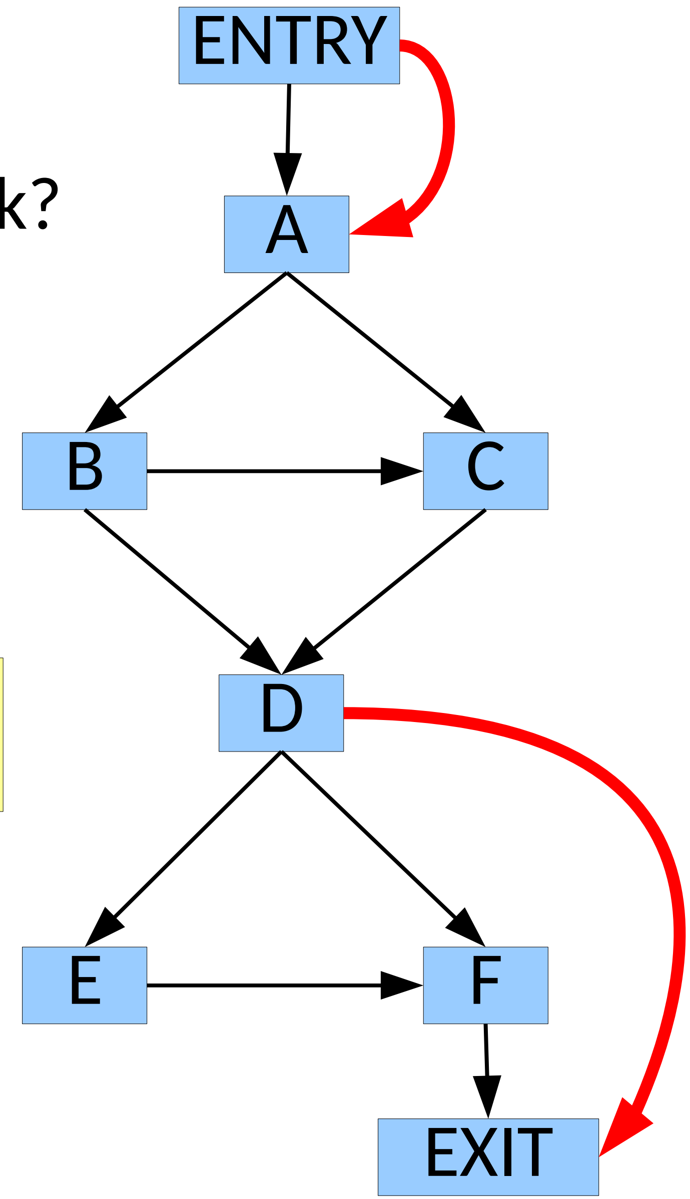
What do these edges encode?



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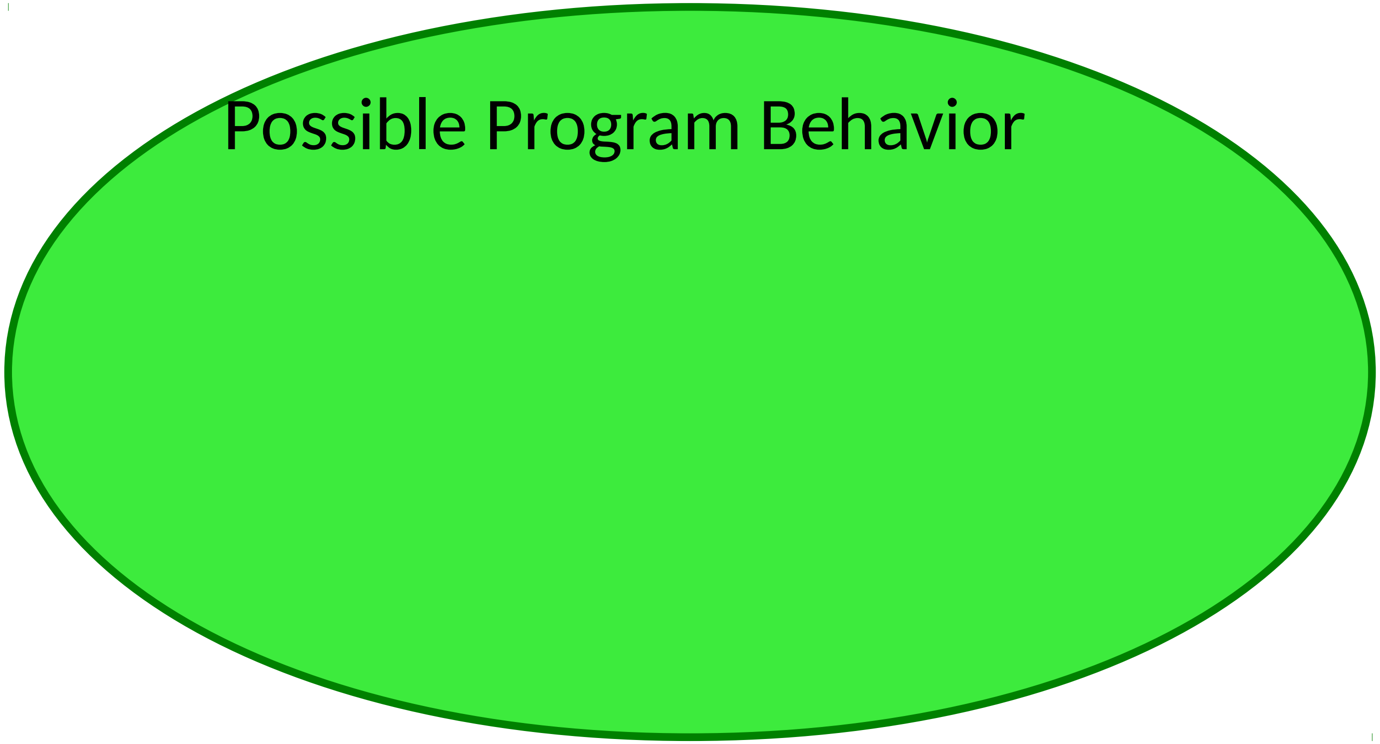
  - "What were frequent paths for this set of inputs"
- What if you don't have an input for the behavior you want to analyze?

Approximation

Modeled program behaviors



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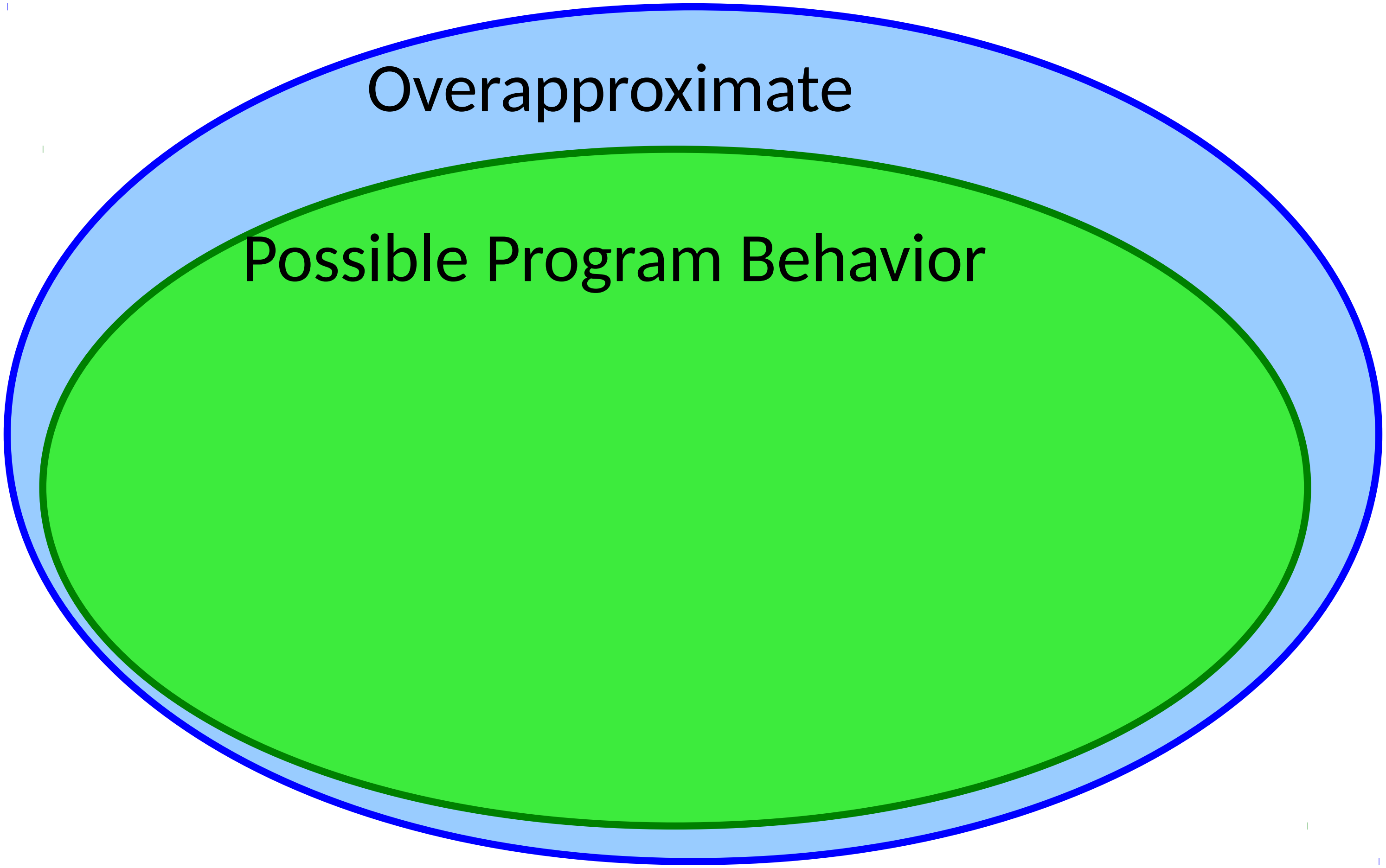

Consider some behaviors possible when they are not.

Approximation

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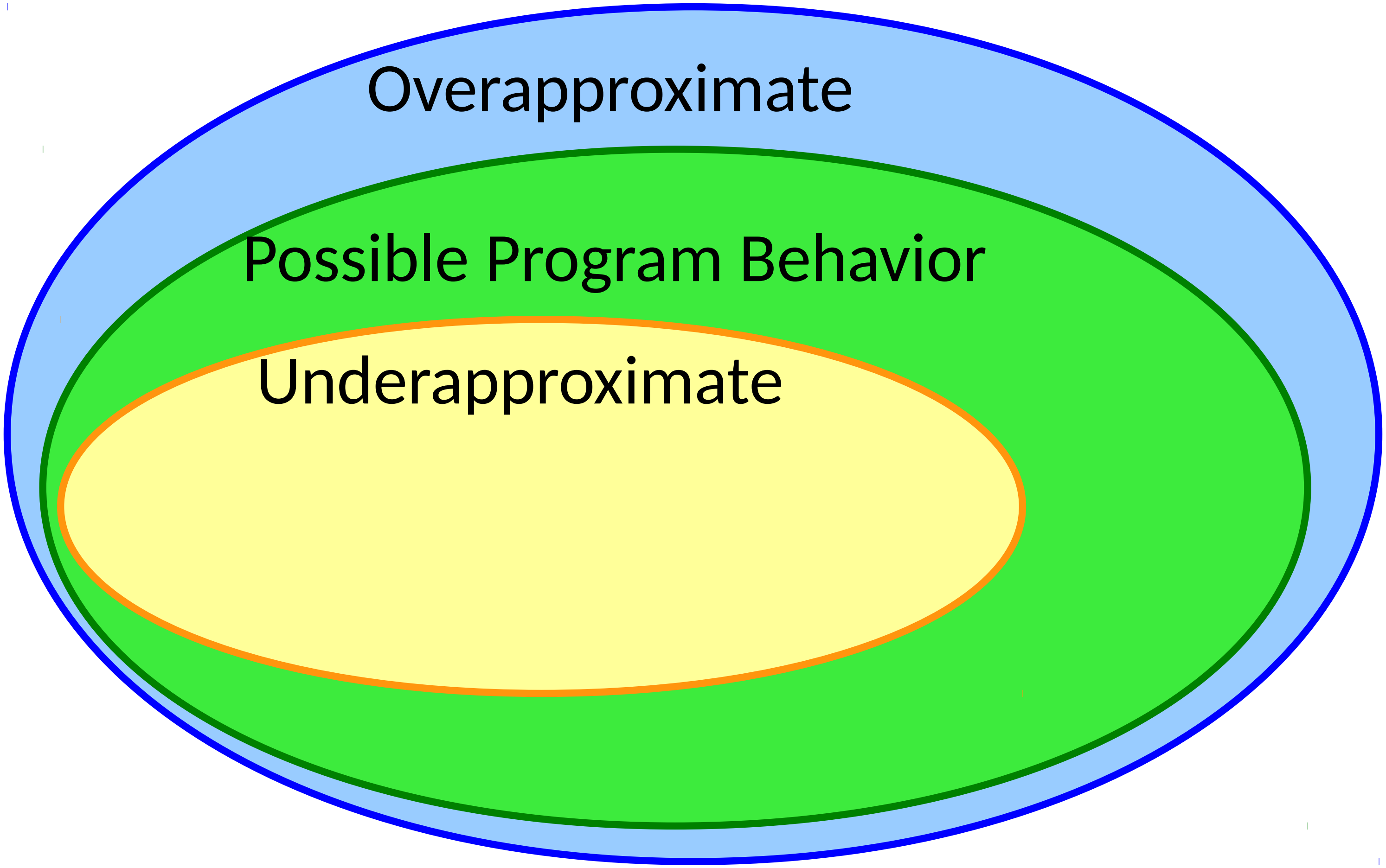

Ignore some behaviors that *are* possible.

Approximation

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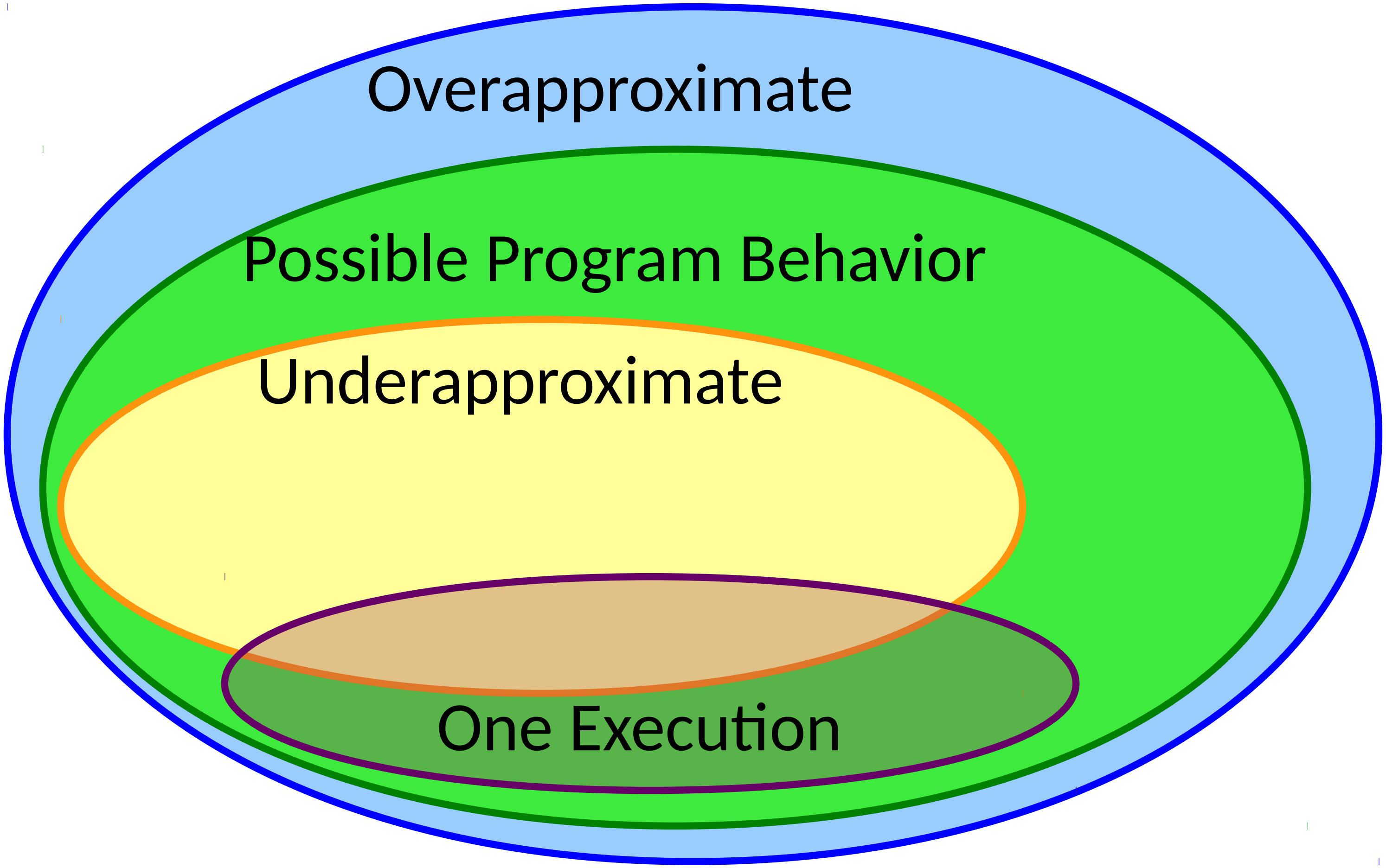

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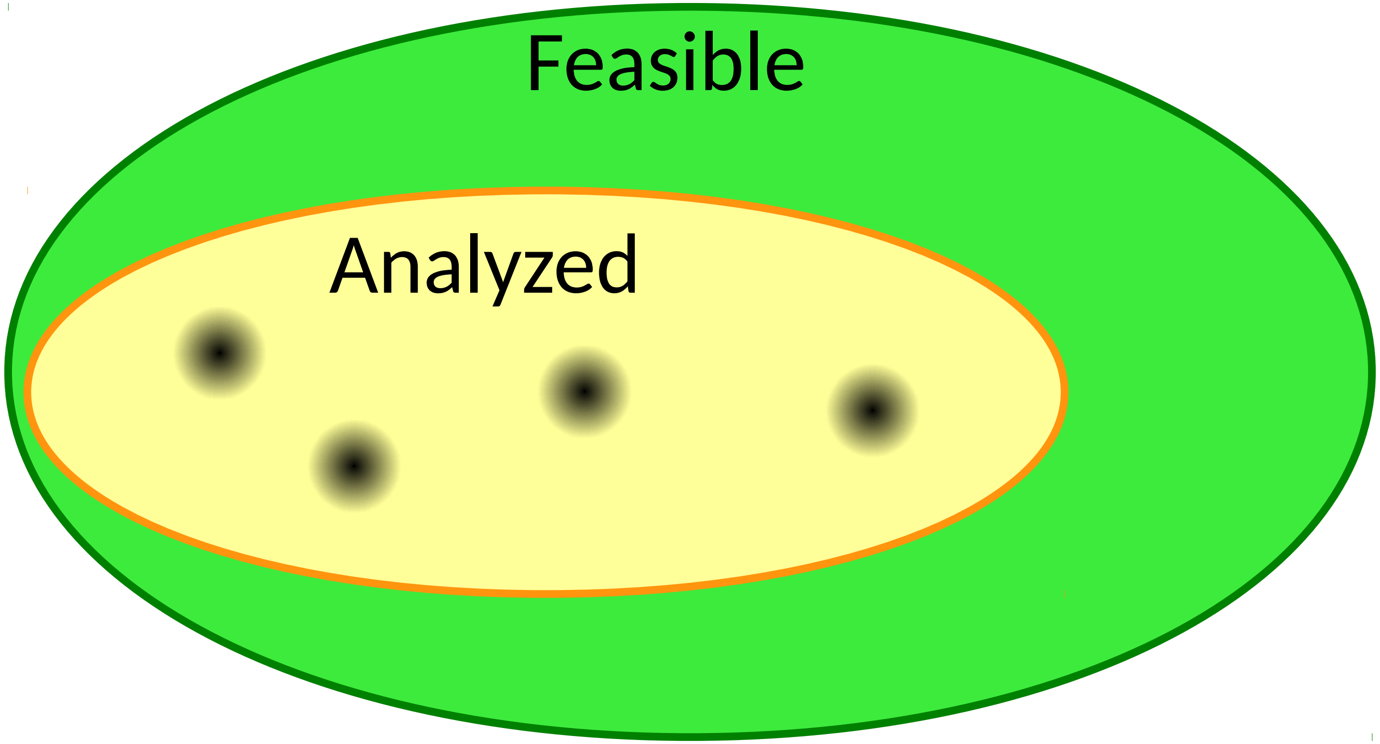

Approximation

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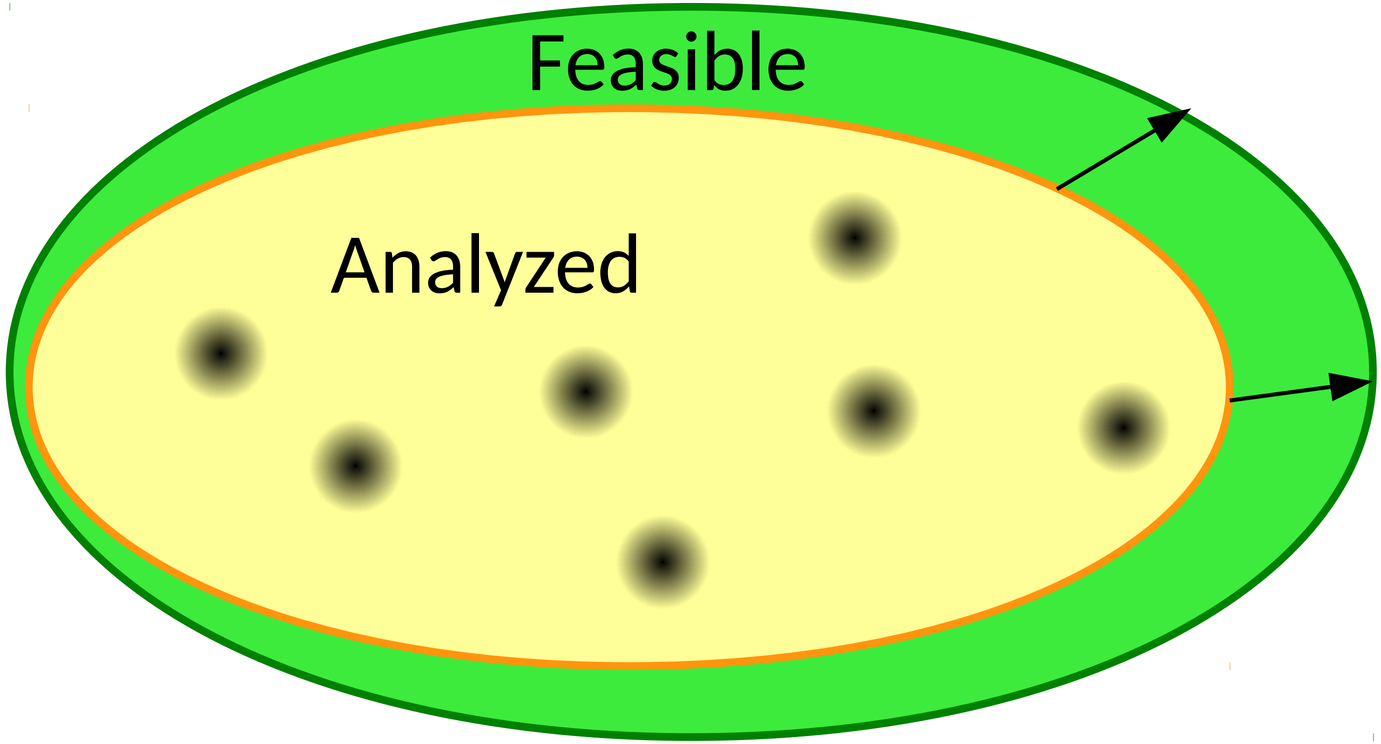

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- Source / IR Instrumentation
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  - Imprecise IR info, but more complete *binary* behavior
- Dynamic Binary Instrumentation
  - Valgrind, Pin, Qemu (& other Vms)
  - Can adapt at runtime, but less info than IR

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In general, 2-3 phases occur:

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Very, ***very*** common mistake to mix 1 & 2.

Static Instrumentation

1) Compile whole program to IR
2) Instrument / add code directly to the IR
3) Generate new program that performs tracing/analysis
4) Execute

Dynamic Binary Instrumentation

1) Compile program as usual
2) Run program under analysis framework

   (Valgrind, PIN, Qemu, etc)
3) Instrument & execute in same command:
   – Fetch & instrument each basic block individually
   – Execute each basic block

```
valgrind --tool=memcheck ./myBuggyProgram
```

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- Static instrumentation
- Finds:
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  - {heap,stack,global}-buffer overflows
- Used extensively in Google programs like Chrome

Example: Address Sanitizer

How?

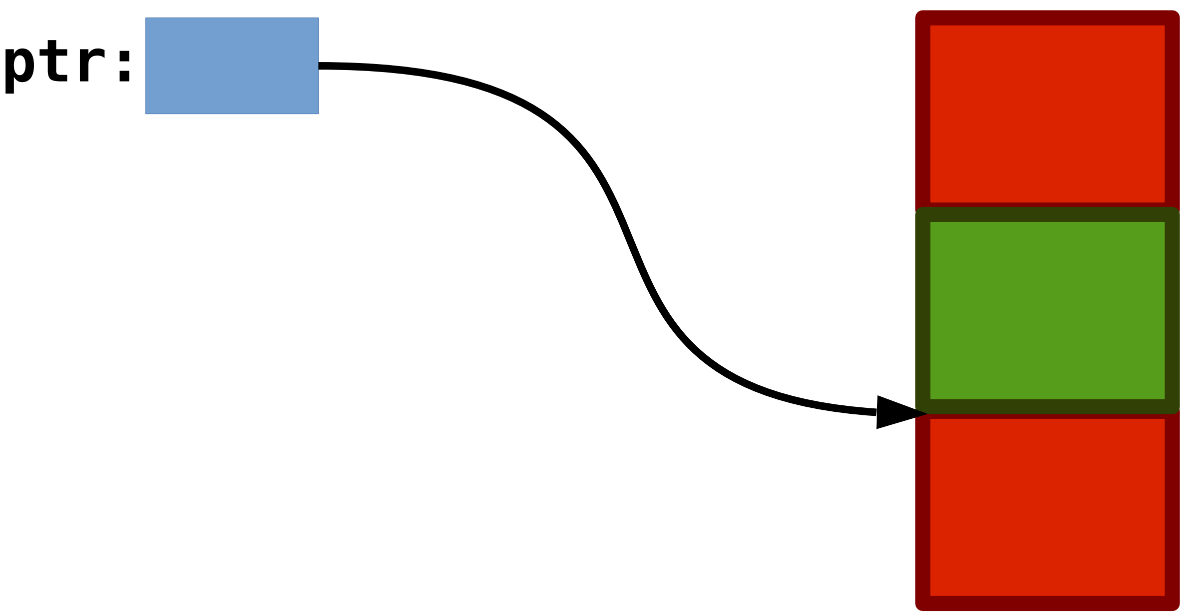
- Replaces `malloc` & `free`

Example: Address Sanitizer

How?

- Replaces `malloc` & `free`
- Memory around malloced chunks is *poisoned*

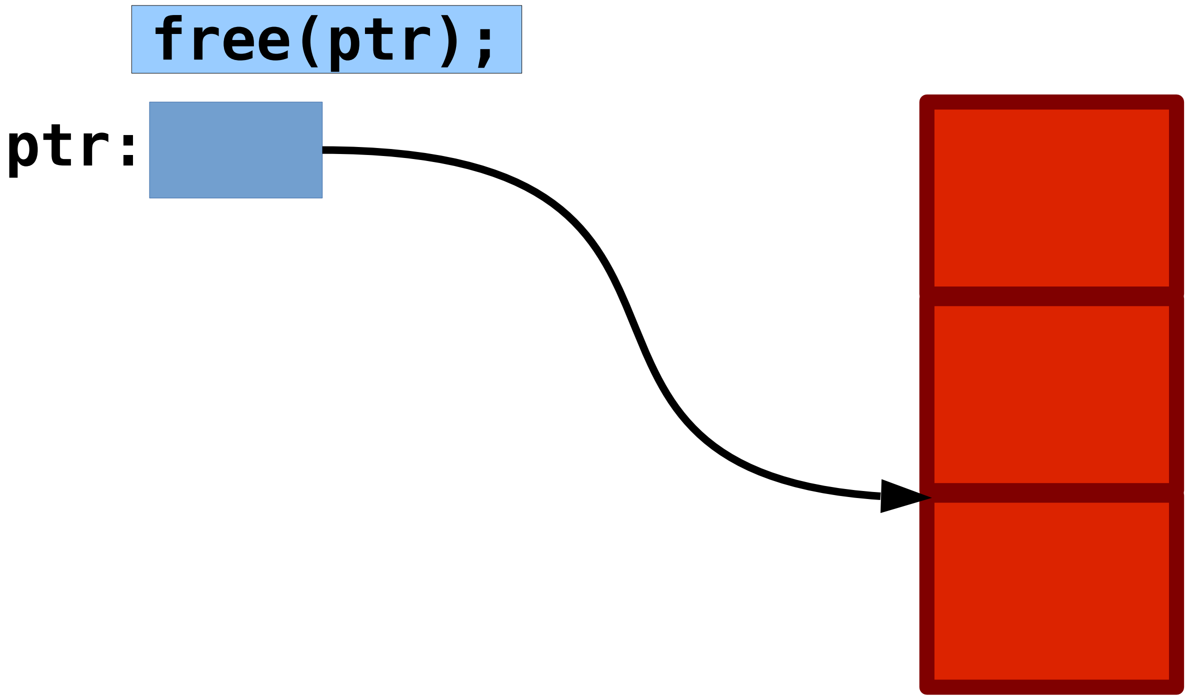
```
ptr = malloc(sizeof(MyStruct));
```



Example: Address Sanitizer

How?

- Replaces `malloc` & `free`
- Memory around malloced chunks is *poisoned*
- Freed memory is *poisoned*

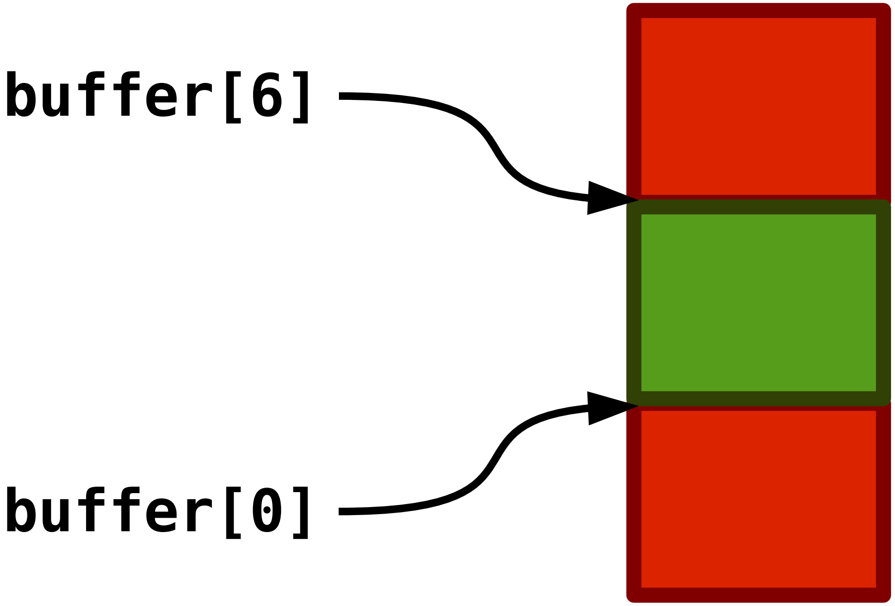


Example: Address Sanitizer

How?

- Replaces `malloc` & `free`
- Memory around malloced chunks is *poisoned*
- Freed memory is *poisoned*
- Space around buffers is *poisoned*

```
void foo() {
  int buffer[5];
}
```



Example: Address Sanitizer

How?

- Replaces `malloc` & `free`

- Memory around malloced chunks is *poisoned*
- Freed memory is *poisoned*
- Space around buffers is *poisoned*

- Any access of a poisoned value reports an error.

…

Example: Address Sanitizer

How?

```
*address = ...
```

Instrumentation

Example: Address Sanitizer

How?

```
*address = ...
```

Instrumentation

```
if (IsPoisoned(address)) {
  ReportError(address, kAccessSize, kIsWrite);
}
*address = ...;
```

Example: Address Sanitizer

How?

```
*address = ...
```

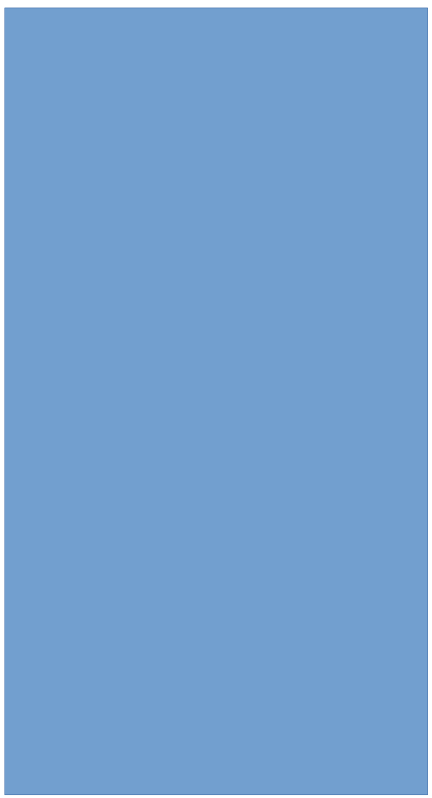
Instrumentation

```
if (IsPoisoned(address)) {
  ReportError(address, kAccessSize, kIsWrite);
}
*address = ...;
```

Difficult! Why?

- Instrumenting every memory access is costly
- Tracking the status of *all memory* is tricky

Example: Address Sanitizer

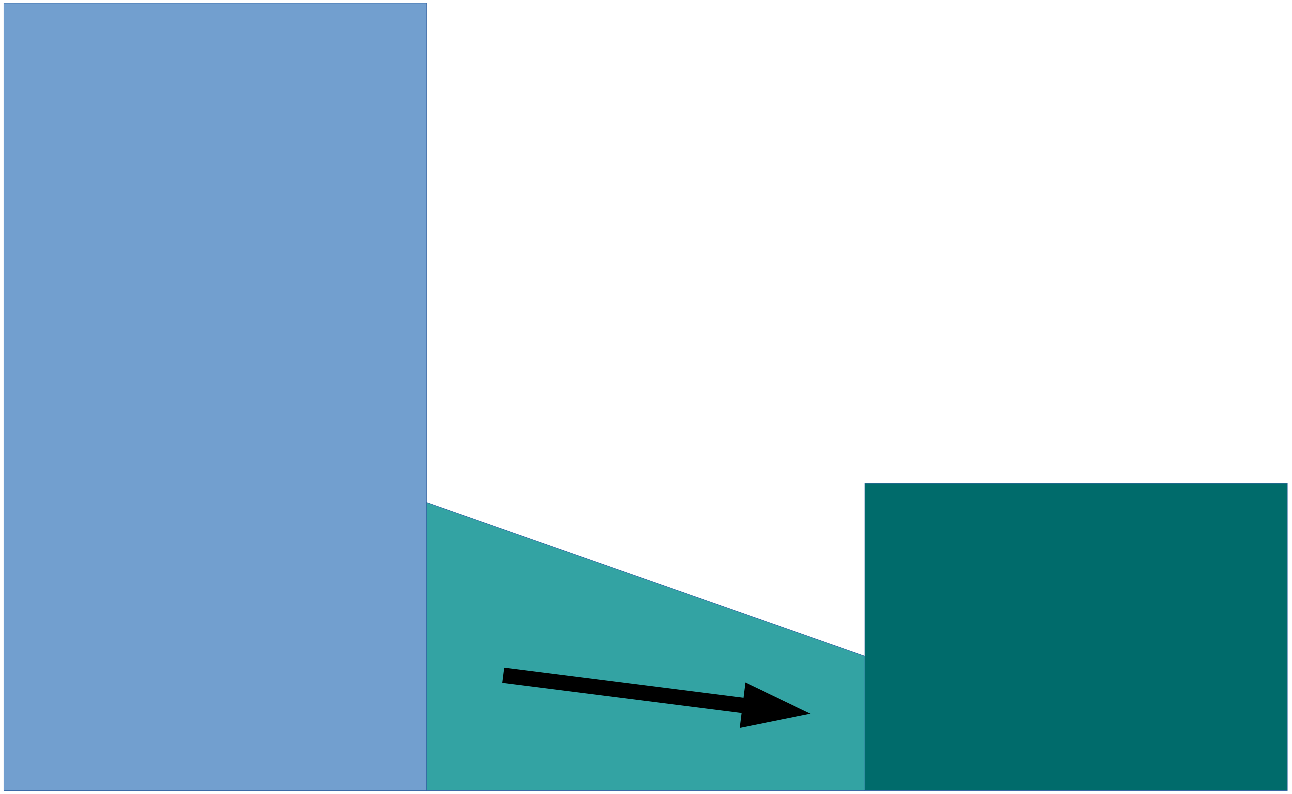


Application Memory

Need to know whether *any byte* of application memory is poisoned.

Example: Address Sanitizer

- Maintain 2 views on memory:



Application Memory *Shadow* Memory

Example: Address Sanitizer

- Shadow memory is a pervasive dynamic analysis tool
  - For every bit/byte/word/chunk/allocation/page, maintain information in a compact table

Example: Address Sanitizer

- Shadow memory is a pervasive dynamic analysis tool
  - For every bit/byte/word/chunk/allocation/page, maintain information in a compact table

Where have you encountered this before?
(Think OS)

Example: Address Sanitizer

- Shadow memory is a pervasive dynamic analysis tool
  - For every bit/byte/word/chunk/allocation/page, maintain information in a compact table
  - Common in runtime support: e.g. page tables

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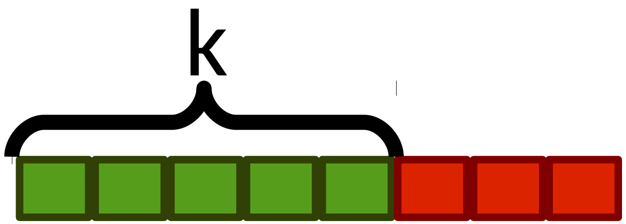
  - In an 8 byte chunk, only first k may be addressable

Memory:  Shadow: ?

Example: Address Sanitizer

- Shadow memory is a pervasive dynamic analysis tool
  - For every bit/byte/word/chunk/allocation/page, maintain information in a compact table
  - Common in runtime support: e.g. page tables
- In Asan:
  - In an 8 byte chunk, only first k may be addressable
  - All 8 bytes unpoisoned: shadow value is 0.

Memory:  Shadow: 0

Example: Address Sanitizer

- Shadow memory is a pervasive dynamic analysis tool
  - For every bit/byte/word/chunk/allocation/page, maintain information in a compact table
  - Common in runtime support: e.g. page tables
- In Asan:
  - In an 8 byte chunk, only first k may be addressable
  - All 8 bytes unpoisoned: shadow value is 0.
  - All 8 bytes poisoned: shadow value is negative.

Memory:  Shadow: -1

Example: Address Sanitizer

- Shadow memory is a pervasive dynamic analysis tool
  - For every bit/byte/word/chunk/allocation/page, maintain information in a compact table
  - Common in runtime support: e.g. page tables
- In Asan:
  - In an 8 byte chunk, only first k may be addressable
  - All 8 bytes unpoisoned: shadow value is 0.
  - All 8 bytes poisoned: shadow value is negative.
  - First k bytes are unpoisoned: shadow value is k.

Memory:  Shadow: 5

Example: Address Sanitizer

- (64bit) Shadow Mapping:
  - Preallocate large block of memory
  - Shadow = (Mem >> 3) + 0x7fff8000;

Example: Address Sanitizer

- (64bit) Shadow Mapping:
  - Preallocate large block of memory
  - Shadow = (Mem >> 3) + 0x7fff8000;
- The shadow memory itself must also be considered poisoned.

Why?!

Dynamic Analysis

- Analyze the actual/observed behaviors of a program.

Dynamic Analysis

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- Modify the program's behavior in order to collect information.

Dynamic Analysis

- Analyze the actual/observed behaviors of a program.
- Modify the program's behavior in order to collect information.
- Analyze this information either online or offline.

Moving Forward

- Yet often you will want to deeply analyze a program without running it at all…