Valence: Variable Length Calling Context Encoding

Tong Zhou, Michael R. Jantz,

Prasad A. Kulkarni, Kshitij A. Doshi, Vivek Sarkar

Common Library Code

Adam

```
void append(List list) {
  lock();
  list.append(…);
  unlock();
}
```

Library code

Common Library Code

Adam

```
void append(List list) {
  lock();
  list.append(…);
  unlock();
}
```

Library code

Conservative

Common Library Code

Adam

```
void append(List list) {
  lock();
  list.append(…);
  unlock();
}
```

Library code

Bob

```
void bob_call() {
  lock();
  append(globalList);
  unlock();
}
```

User code

Common Library Code

Adam

```
void append(List list) {
  lock();
  list.append(…);
  unlock();
}
```

Library code

Bob

```
void bob_call() {
  lock();
  append(globalList);
  unlock();
}
```

User code

Common Library Code

Adam

```
void append(List list) {
   lock();
   list.append(…);
   unlock();
}
```

Library code

Caleb

```
void caleb_call() {
   append(globalList);
}
```

User code

Common Library Code

Adam

```
void append(List list) {
   lock();
   list.append(…);
   unlock();
}
```

Library code

Everything is thread-safe

Caleb

```
void caleb_call() {
   append(globalList);
}
```

User code

Common Library Code

Adam

```
void append(List list) {
   lock();
   list.append(…);
   unlock();
}
```

Library code

Caleb

```
void caleb_call() {
   append(globalList);
}
```

User code

Common Library Code

- If we know the calling context where synchronization is unnecessary, how do we fix it automatically?

After Code Transformation

```
void append(List list) {
  if (call_from_caleb()) {
    lock();
    list.append(…);
    unlock();
  }
  else {
    list.append(…);
  }
}
```

Calling context detection

After Code Transformation

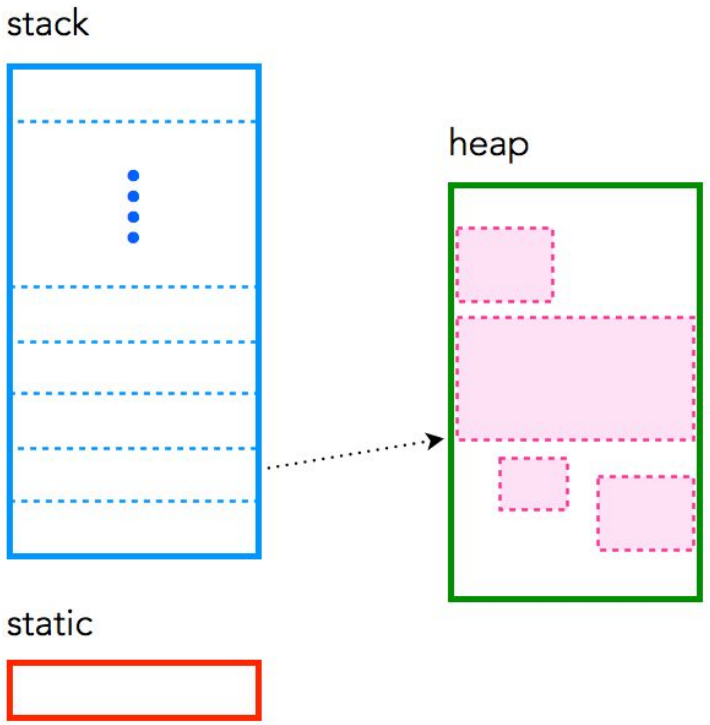
```
void append(List list) {
  if (call_from_caleb()) {
    lock();
    list.append(…);
    unlock();
  }
  else {
    list.append(…);
  }
}
```

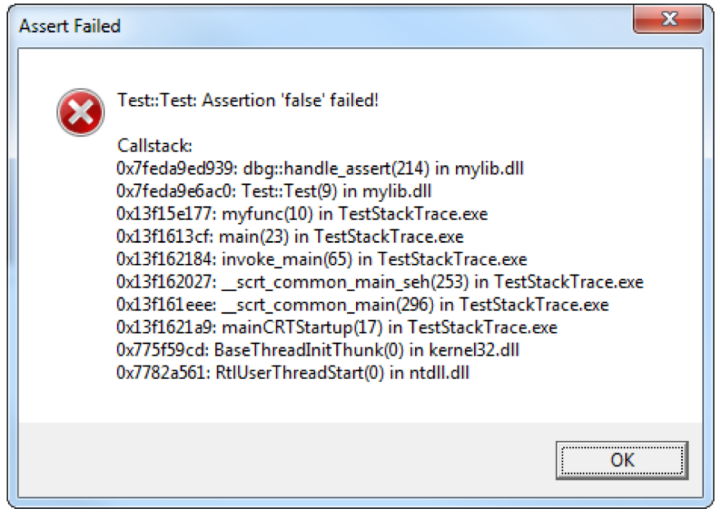
Calling context detection

Synchronization elided

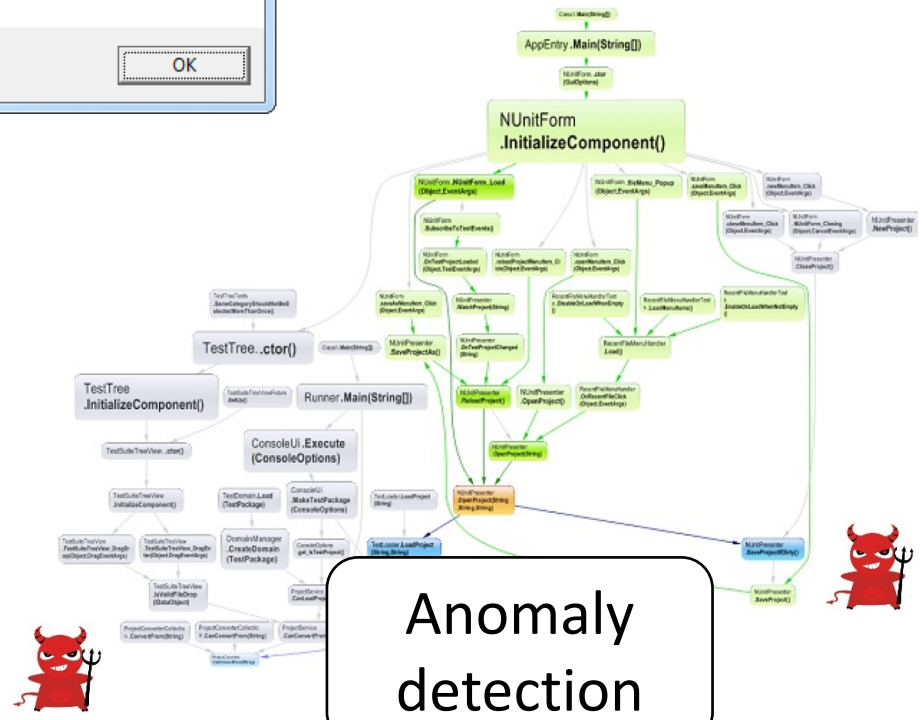
Also Useful For …

Better memory layout





Enhanced Debugging



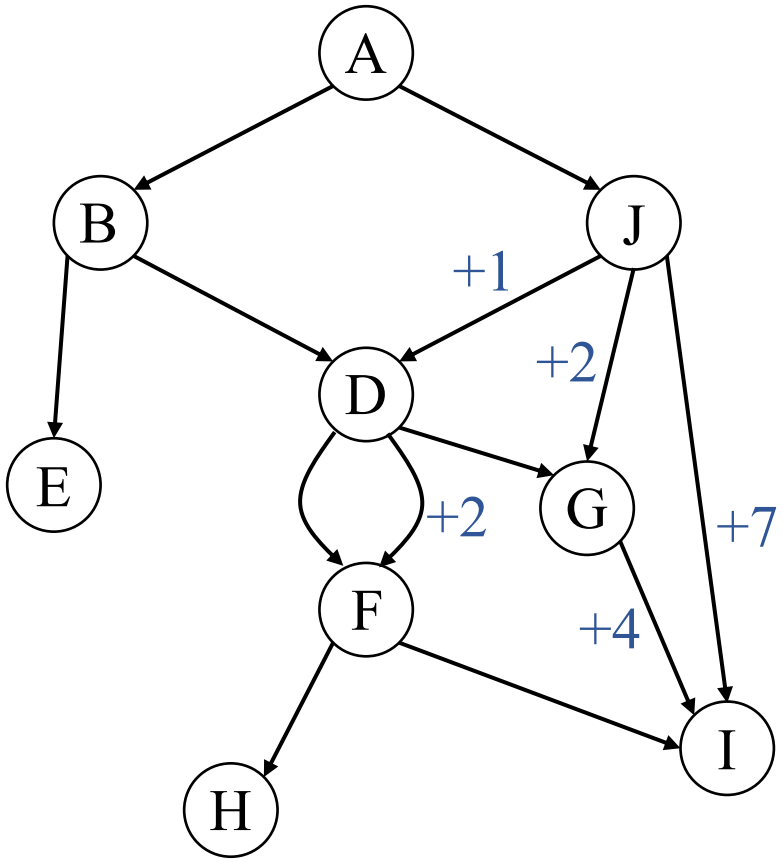
Anomaly detection

However…

- For the current state-of-the-art approach, precise calling context checking could incur:
  - > 8x slowdown when querying at every call site.

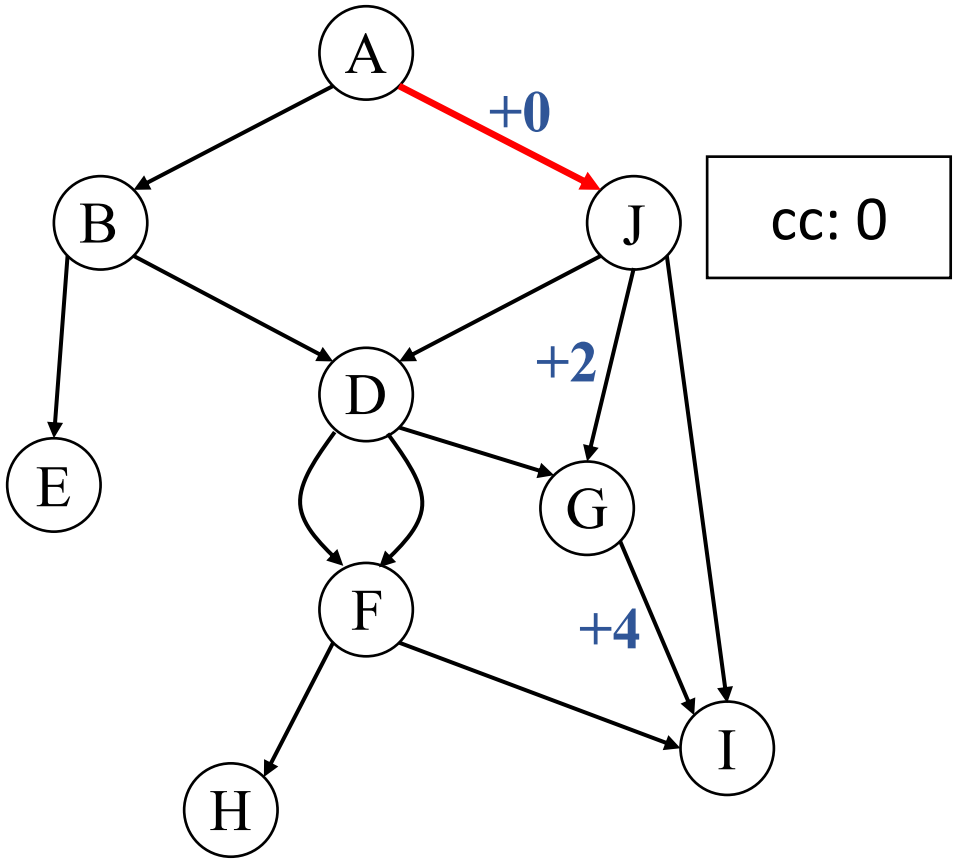
Why this slow? What's the real problem behind it?

Traditional Approach PCCE



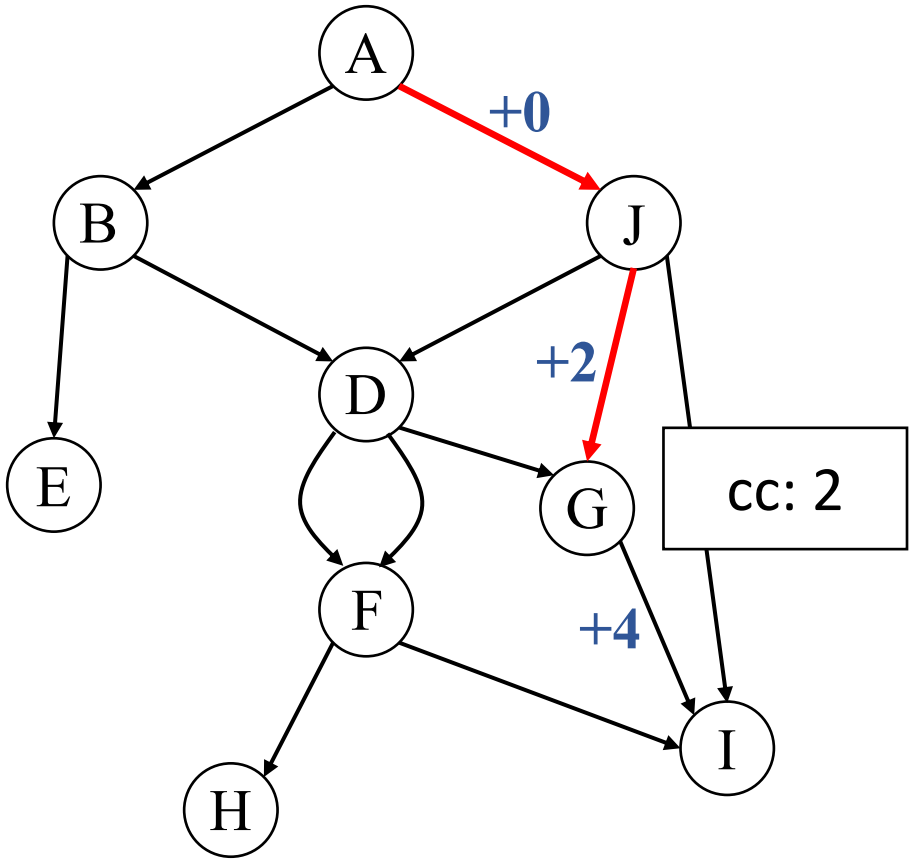
- Use a single integer (*cc*) to encode all contexts
- Assign a unique number to each static context
  - Do integer addition and subtraction on call and call return

Traditional Approach PCCE



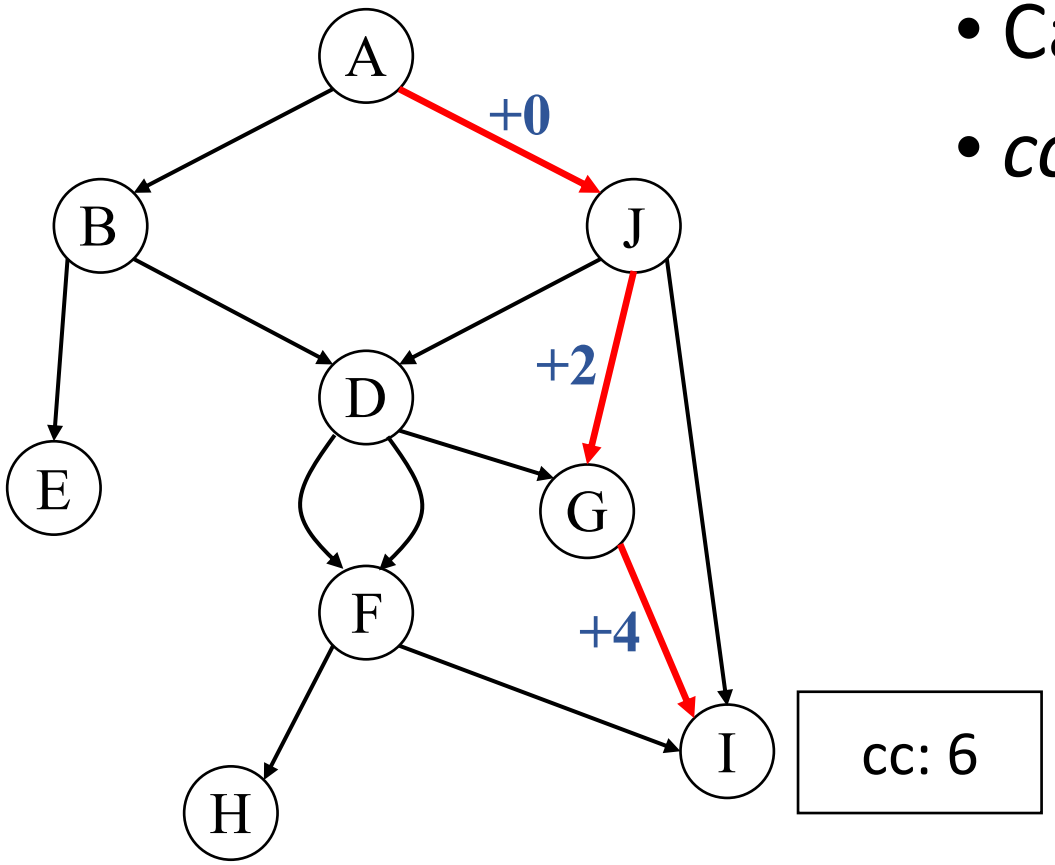
- Calling context: AJ
- *cc*: 0

Traditional Approach PCCE



- Calling context: AJG
- *cc*: 0 + 2 = 2

Traditional Approach PCCE

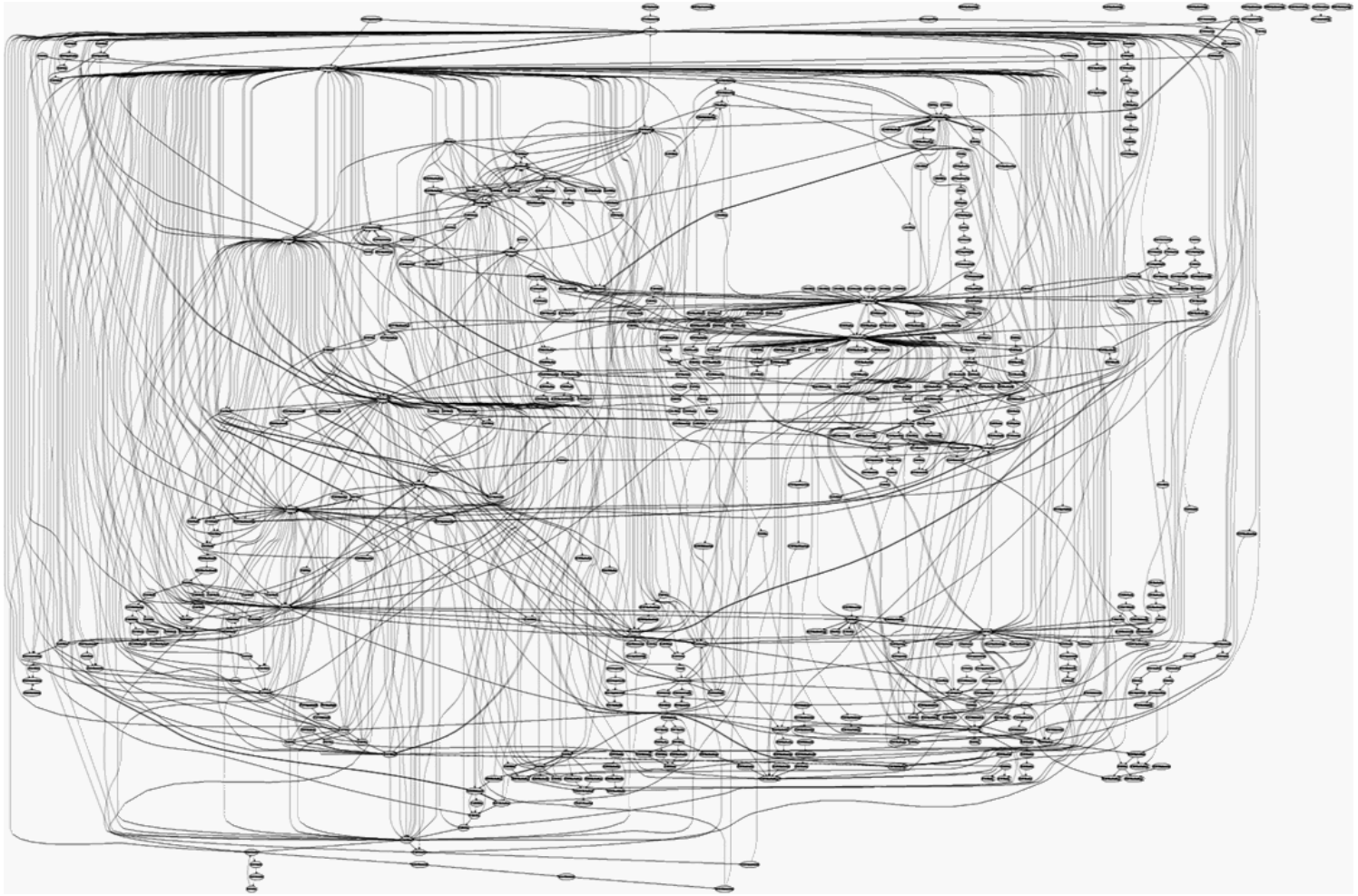


- Calling context: AJGI
- *cc*: 2 + 4 = 6

Problem 1

Massive amount of distinct static calling context for large code base

Linux kernel =>



Problem 1

Massive amount of distinct static calling context for large code base

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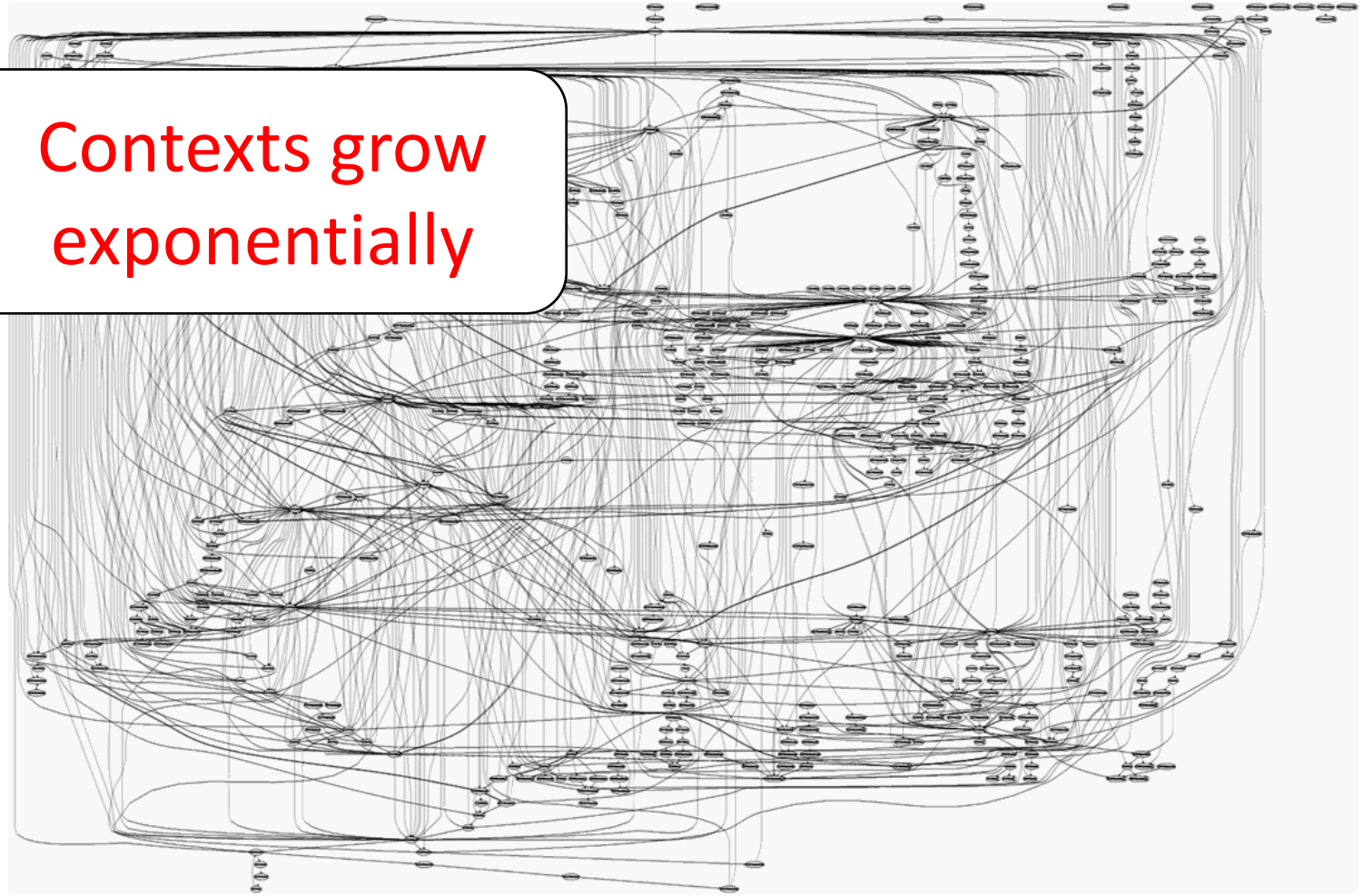

Problem 1

Massive amount of distinct static calling context for large code base

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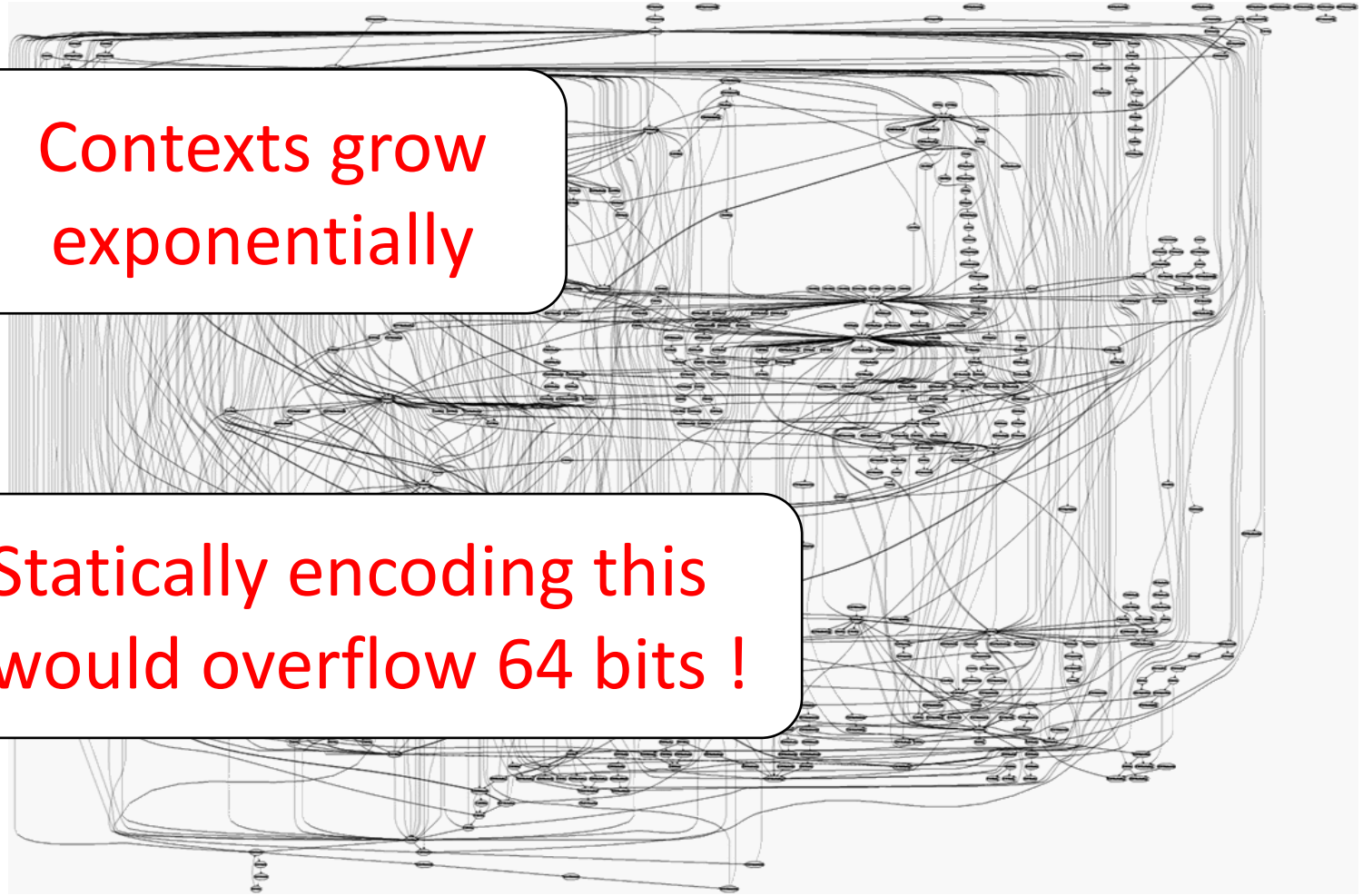
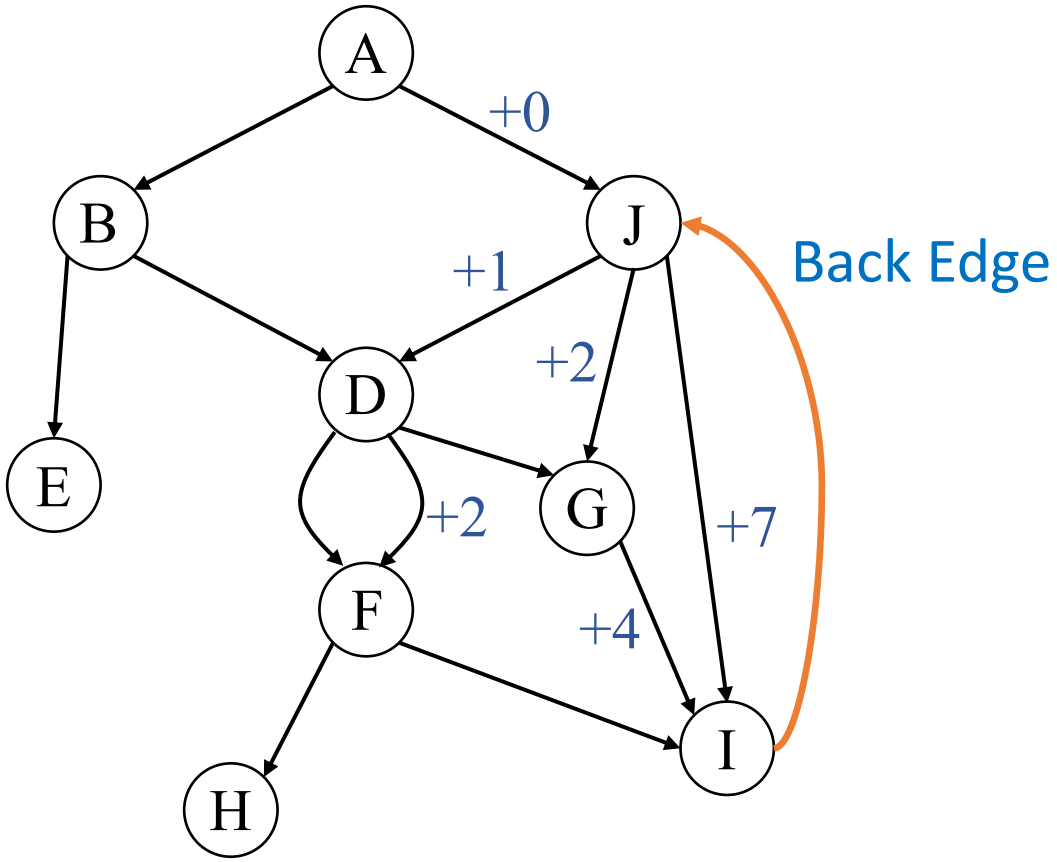
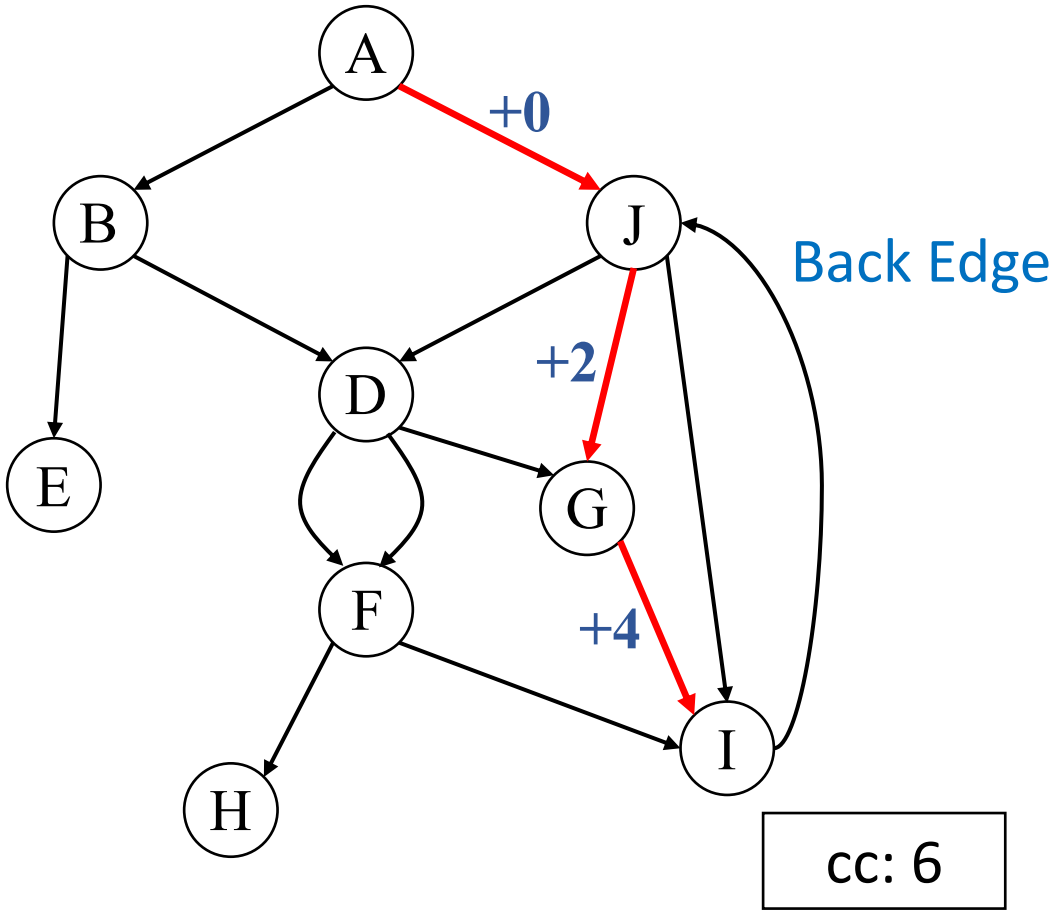


PCCE Deals With Cycles



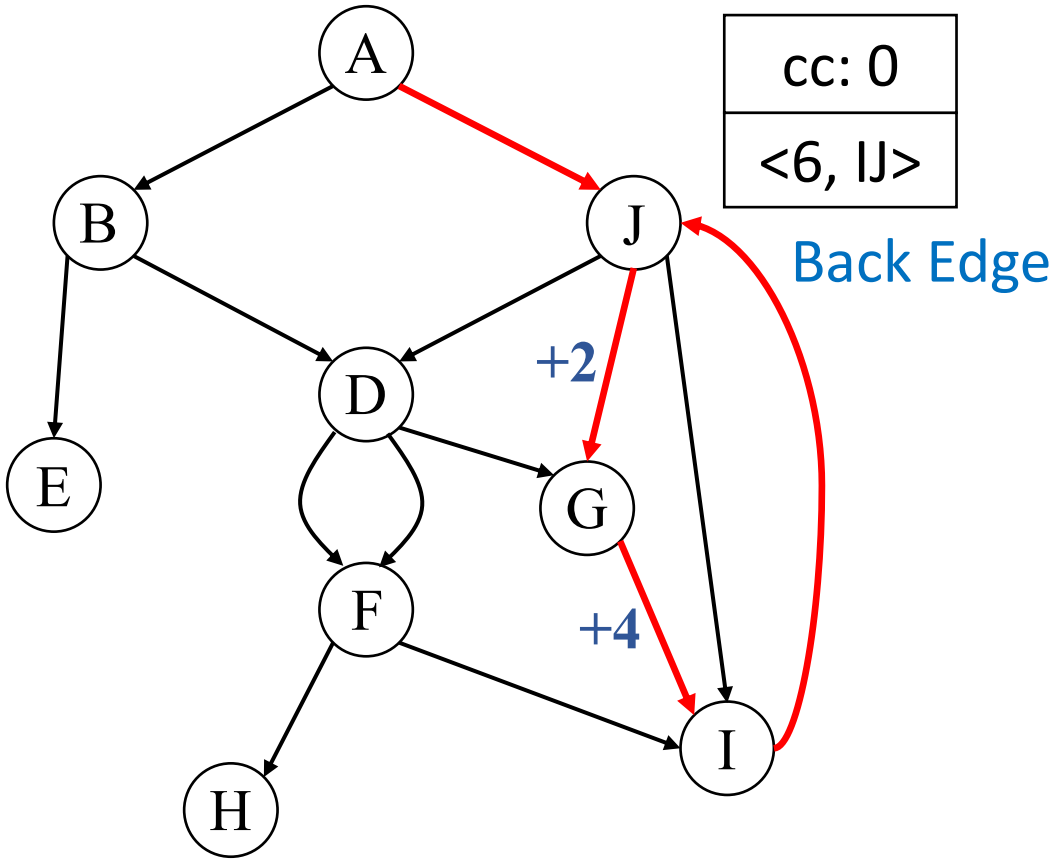
- Push tuple <current *cc*, GJ> onto a stack
- Reset *cc*

Context: AJGI



- Context: AJGI

Context: AJGIJ



- Context: AJGIJ

Problem 2

Need to save the entire acyclic context on each back edge.

- Too much redundant leads to inefficient querying

```
20 ../../../505.mcf_r() [0x40acce]
21 ../../../505.mcf_r() [0x4076fa]
22 ../../../505.mcf_r() [0x4076fa]
23 ../../../505.mcf_r() [0x4076fa]
24 ../../../505.mcf_r() [0x4076fa]
25 ../../../505.mcf_r() [0x4076fa]
26 ../../../505.mcf_r() [0x4076fa]
27 ../../../505.mcf_r() [0x4076fa]
28 ../../../505.mcf_r() [0x4076fa]
29 ../../../505.mcf_r() [0x4076fa]
30 ../../../505.mcf_r() [0x4076fa]
31 ../../../505.mcf_r() [0x4076fa]
32 ../../../505.mcf_r() [0x4076fa]
33 ../../../505.mcf_r() [0x4076fa]
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39 ../../../505.mcf_r() [0x4076fa]
40 ../../../505.mcf_r() [0x4076fa]
41 ../../../505.mcf_r() [0x4076fa]
42 ../../../505.mcf_r() [0x403a4b]
43 ../../../505.mcf_r() [0x400e14]
44 ../../../505.mcf_r() [0x400fc2]
45 /lib64/libc.so.6(__libc_start_main+0xf5) [0x7f6331010b35]
46 ../../../505.mcf_r() [0x400c39]
47
```

Problem 2

Need to save the entire acyclic context on each back edge.

- Too much redundant leads to inefficient querying

```
20 ../../../505.mcf_r() [0x40acce]
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26 ../../../505.mcf_r() [0x
27 ../../../505.mcf_r() [0
28 ../../../505.mcf_r() [0
29 ../../../505.mcf_r() [0
30 ../../../505.mcf_r() [0
31 ../../../505.mcf_r() [0
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41 ../../../505.mcf_r() [0x4076fa]
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45 /lib64/libc.so.6(__libc_start_main+0xf5) [0x7f6331010b35]
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47
```

Redundancy accumulates

Two Identified Problems

- Current approach
  - > 8x slowdown when querying at every call site.
- Problem 1
  - Unscalable encoding for the massive amount of static calling contexts.
- Problem 2
  - Inefficient encoding for infinite amount of dynamic calling contexts.

Valence Solved Them All

- The most compact scalable precise calling context encoding
- Compared to the current state-of-the-art approach for SPEC CPU2017 benchmarks. On average, Valence achieves
  - > 60% space overhead reduction (from 4.3 to 1.6 64-bit words) for storing calling contexts.
  - > 70% time overhead reduction for querying calling contexts.

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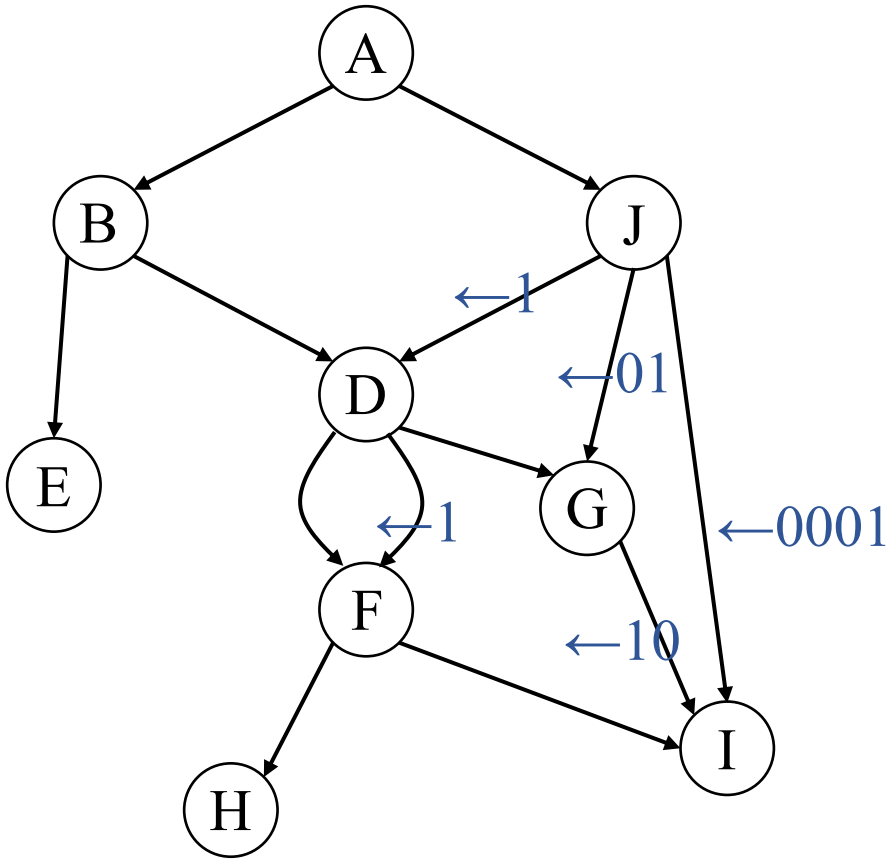
Solution To Scalability Problem

- Encode the context in a logical statically-sized bit vector.
  - Naturally scalable
- Instrumentations
  - Before the call: append a value to the bit vector
  - After the call: pop out the value

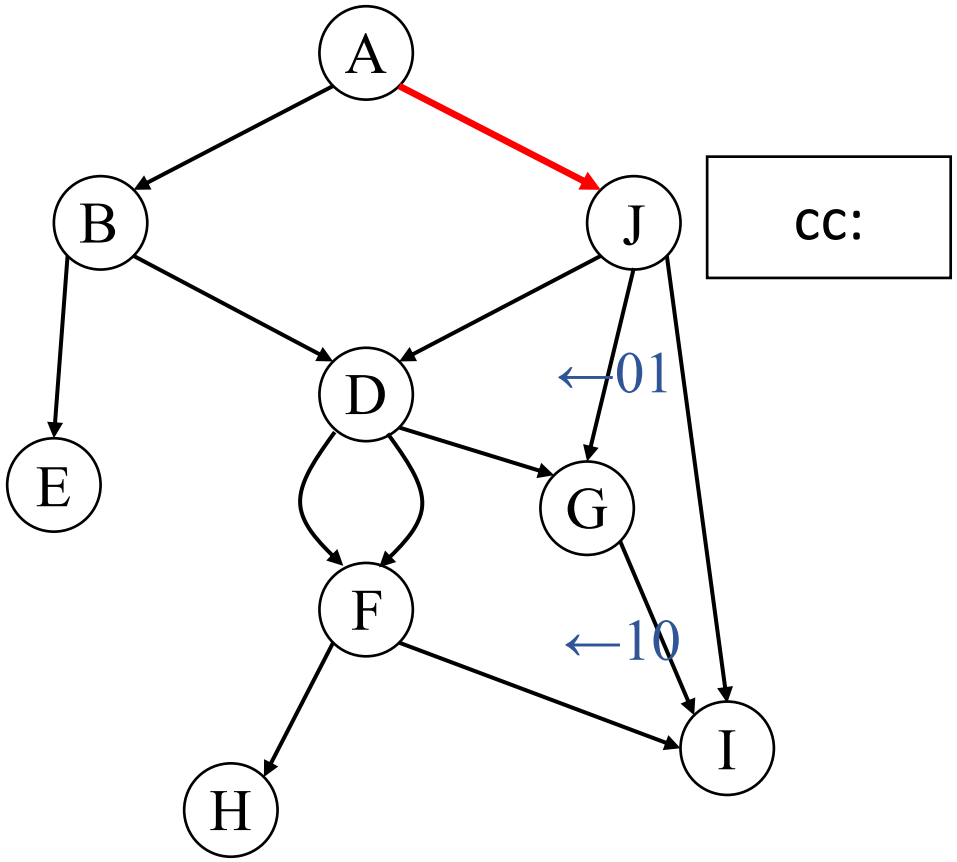
Valence Acyclic Encoding



← : append a binary number

- Use a static bit vector to encode all contexts
- Assign a unique bit pattern to each static context
  - Do bits appending and poping on call and call return (logical)

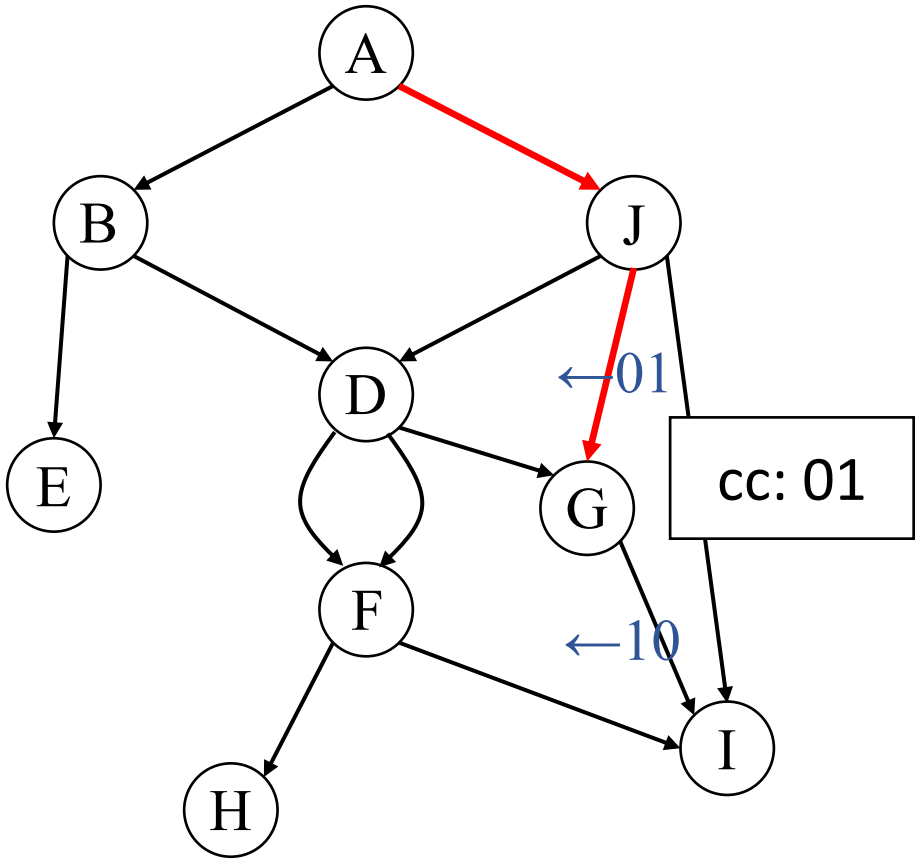
Valence Acyclic Encoding



- Calling context: AJ
- *cc*: (nil)

← : append a binary number

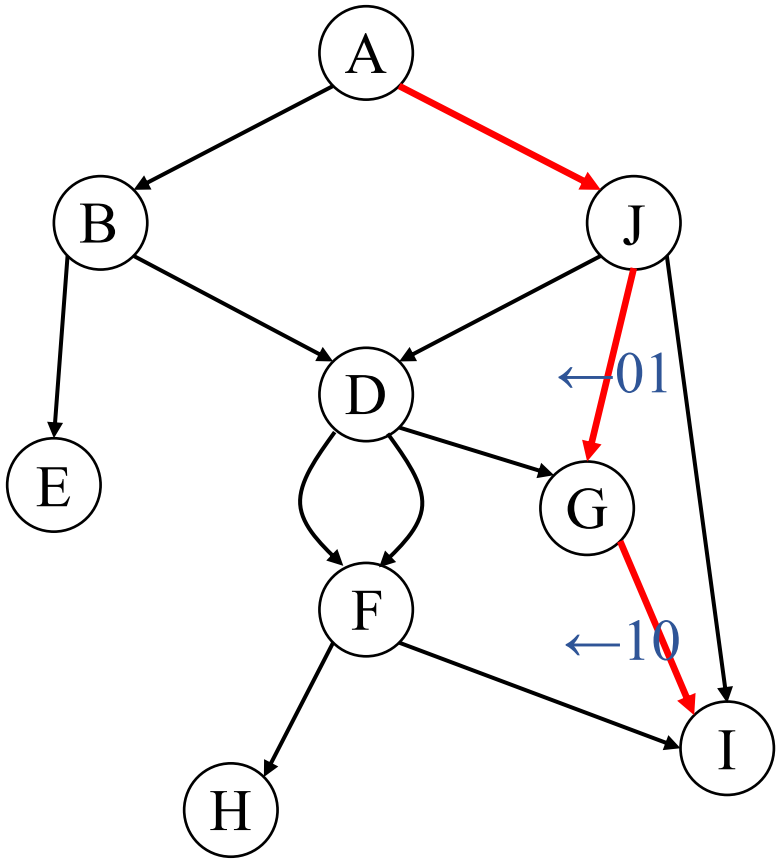
Valence Acyclic Encoding



- Calling context: AJG
- *cc*: 01

← : append a binary number

Valence Acyclic Encoding



cc: 01 10

- Calling context: AJGI
- *cc*: 0110

← : append a binary number

Details Are In The Paper

- How do we statically determine what range in the bit vector to update at each call site?
- How to ensure each bit pattern is unique?
- Check out the algorithms in the paper.

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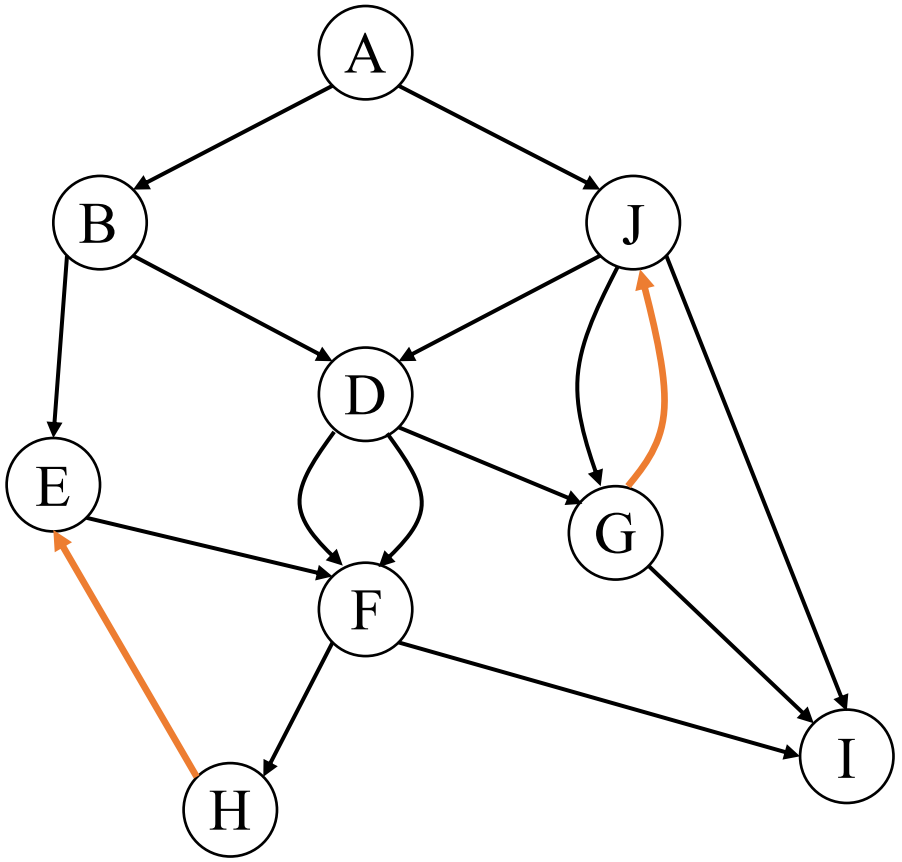
Solution To Cycle Problem

- Goal: to reduce encoding sizes and thus improve performance

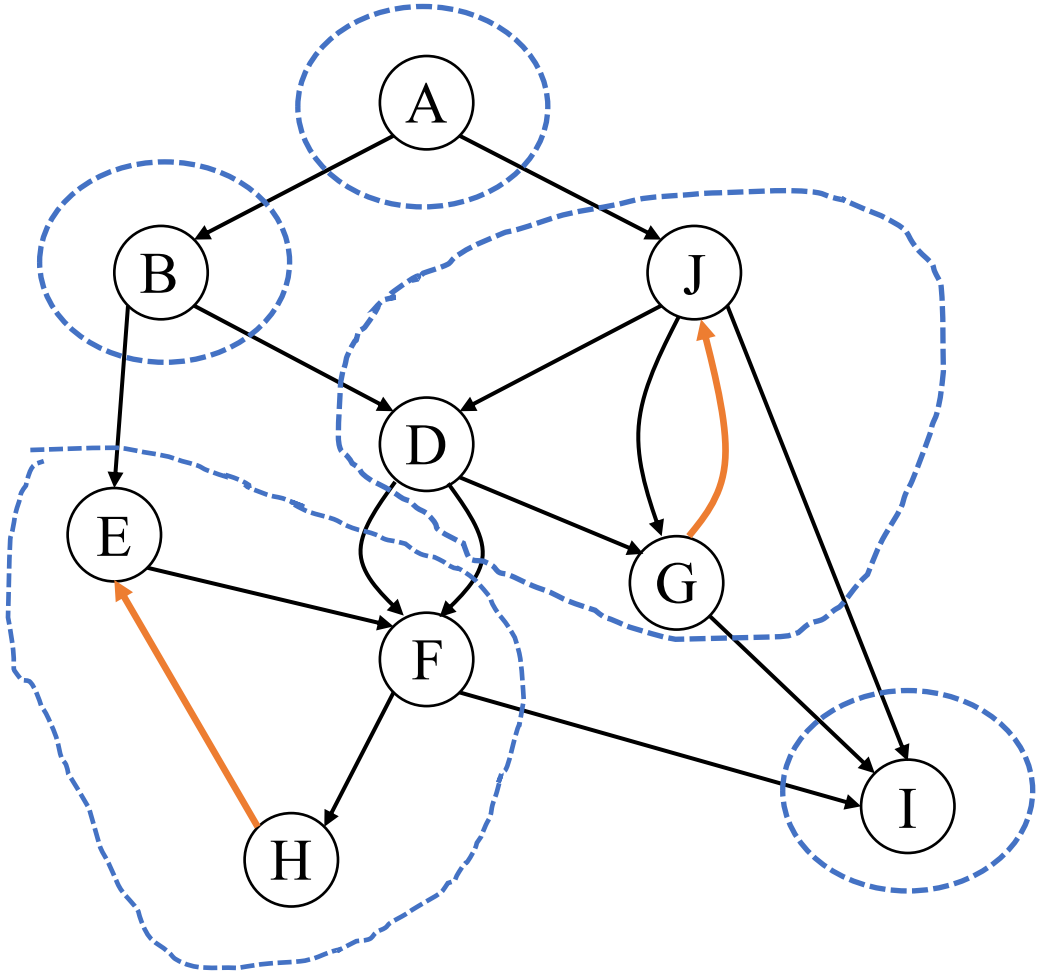
- A different way to define cycle edges.
- First calculate the strongly-connected components (SCCs) of the call graph.

A Call Graph With Cycles



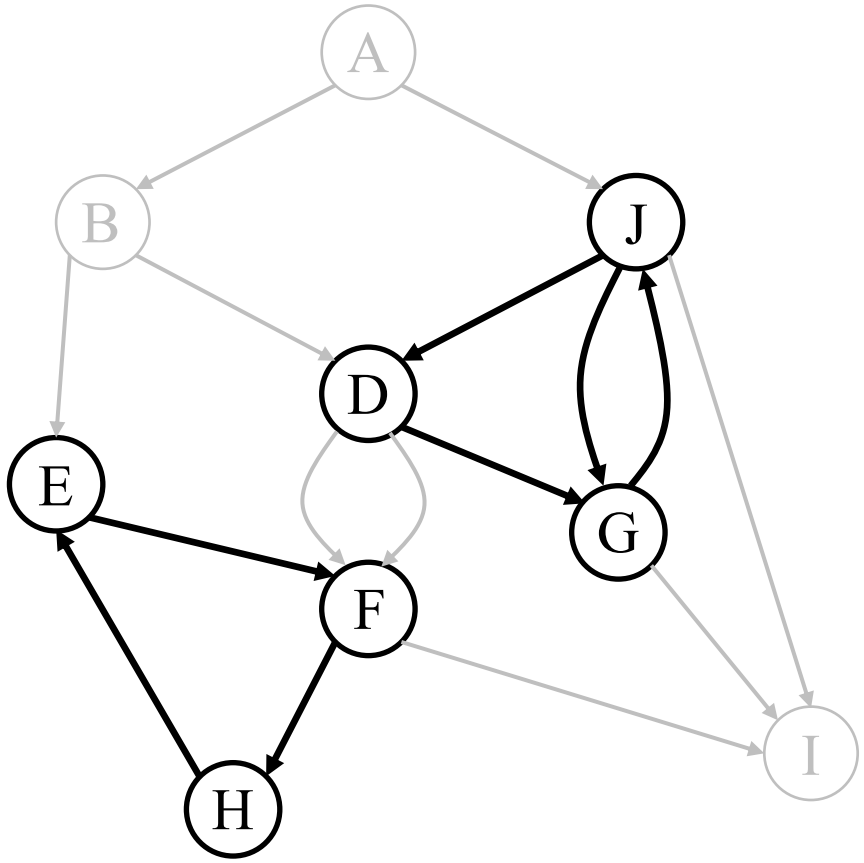
- Back edges: HE, GJ

A Call Graph With Cycles



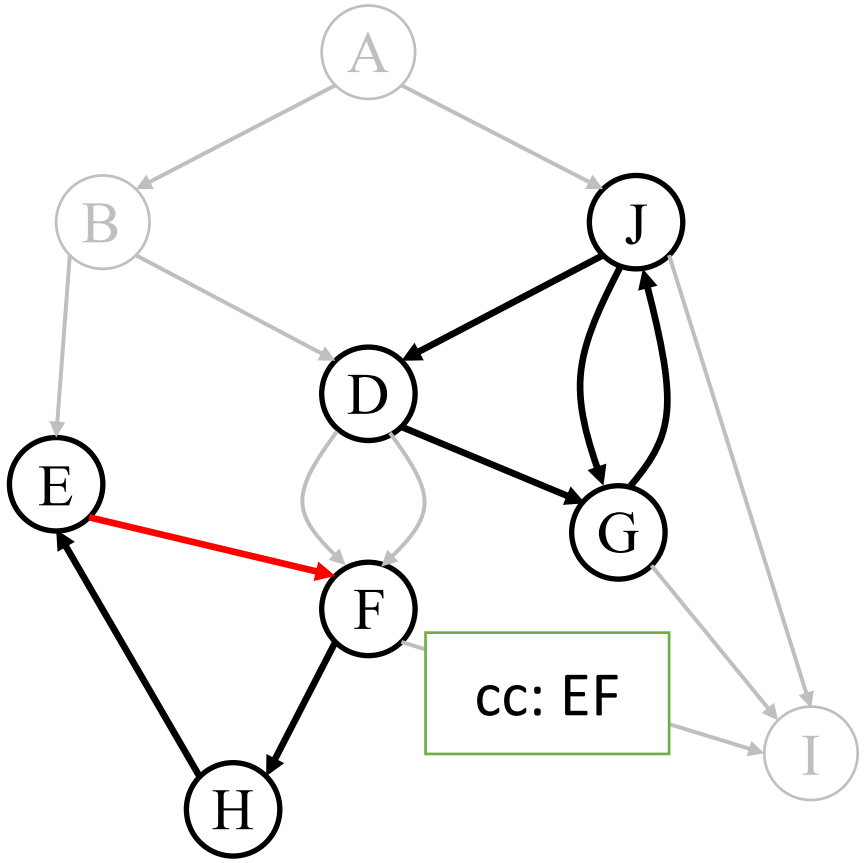
- Five SCCs

Cycle Edges



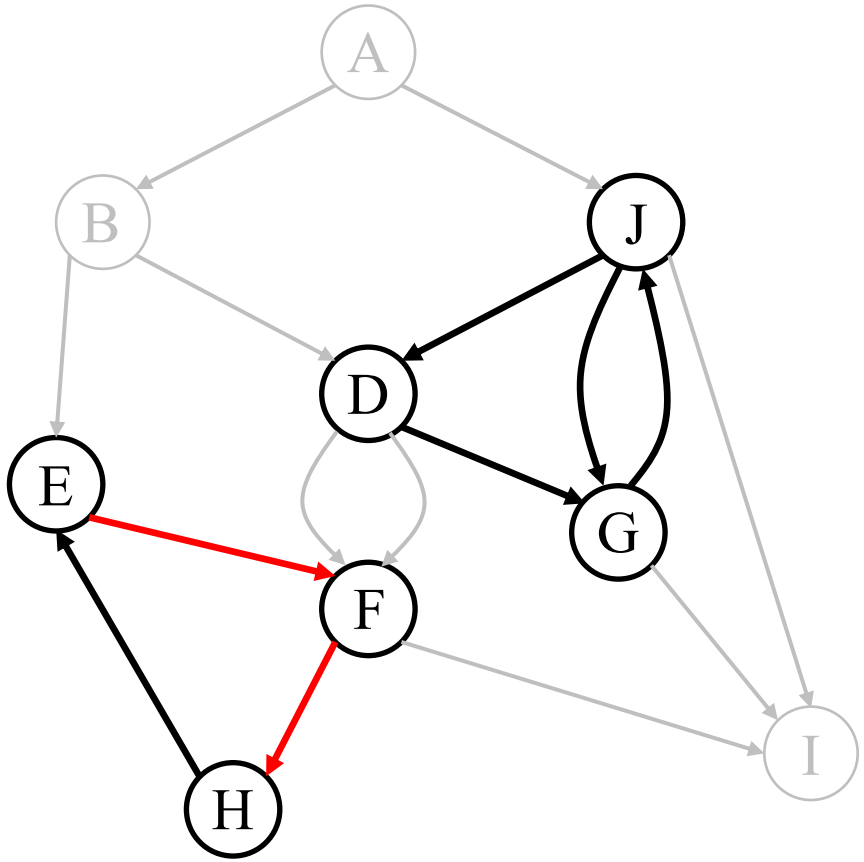
- SCC EFH and DGJ have edges inside
  - Cycle edges
- Only need to store these edges for cycle encoding
  - Store in a dynamic bit vector

Cycle Encoding



- Cyclic context: EF

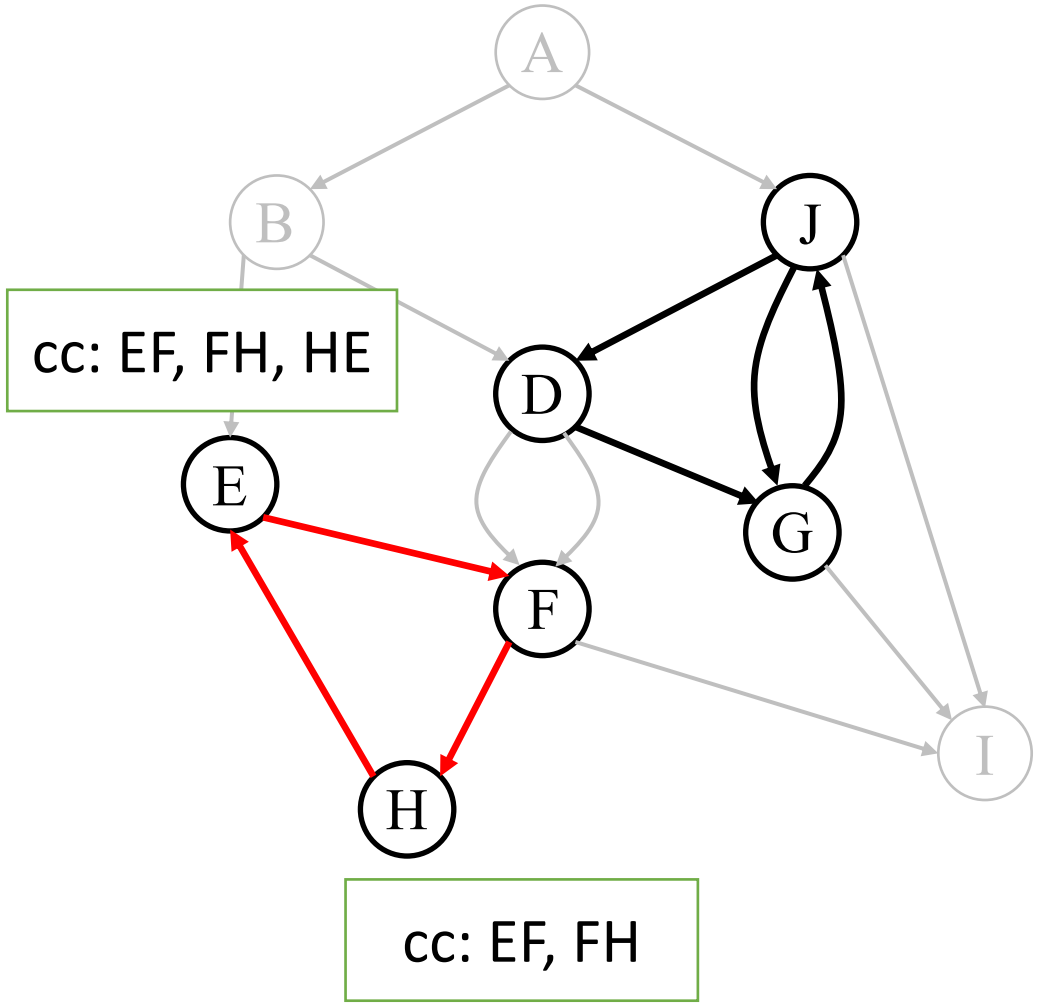
Cycle Encoding



cc: EF, FH

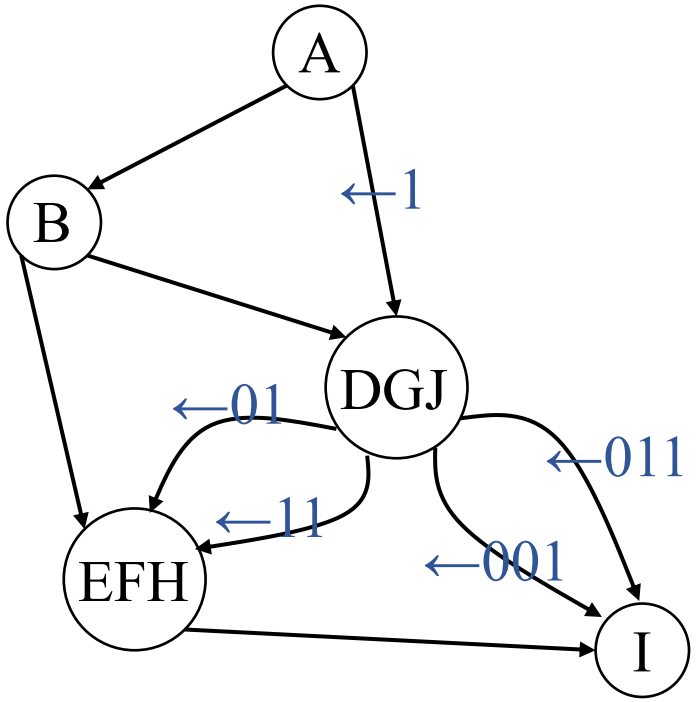
- Cyclic context: EFH

Cycle Encoding



- Cyclic context: EFHE

Instrument Acyclic Edges



- The SCCs form an acyclic graph
- Use the previous acyclic encoding scheme

Takeaways

- Encode call graphs without cycles
  - Use a statically-sized bit vector
  - Scale efficiently
- Encode cycles in the call graphs
  - Use a separate dynamically-sized bit vector
  - Space efficient

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We Want To Know…

- Acyclic call graph
  - how much more space Valence requires than PCCE?
- Cyclic call graph
  - how much more compact Valence is?
    - A more compact encoding makes querying more efficient (less memory traffic)
- Valence v.s. PCCE
  - Instrumentation overhead
  - Detection overhead

Evaluation

- Configurations
  - Each encoding strategy (PCCE, Valence) is implemented as a LLVM pass.
- Hardware
  - 3.30GHz Intel CPU and 16G DRAM.
- Benchmark
  - SPEC CPU2017 C/C++ Benchmark suite.

Table of Contents

Benchmark Static Characteristics

Benchmark	Call Graph Statistics				
	Nodes	Edges	SCCs	Complex SCCs	Cyclic Edges
gcc	19,011	131,388	17,182	459	28,330
mcf	32	126	32	1	1
cactuBSSN	1,048	22,820	1,040	12	67
namd	61	553	61	0	0
parest	1,315	15,080	1,234	46	200
povray	519	8,258	377	57	2,380
lbm	17	27	17	0	0
xalancbmk	4,055	22,848	3,700	181	1,566
x264	367	2,318	366	1	2
deepsjeng	87	573	87	3	12
imagick	915	18,864	807	40	524
leela	204	1,013	202	15	23
nab	79	730	79	10	25
xz	149	359	140	3	18

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Cycle problem

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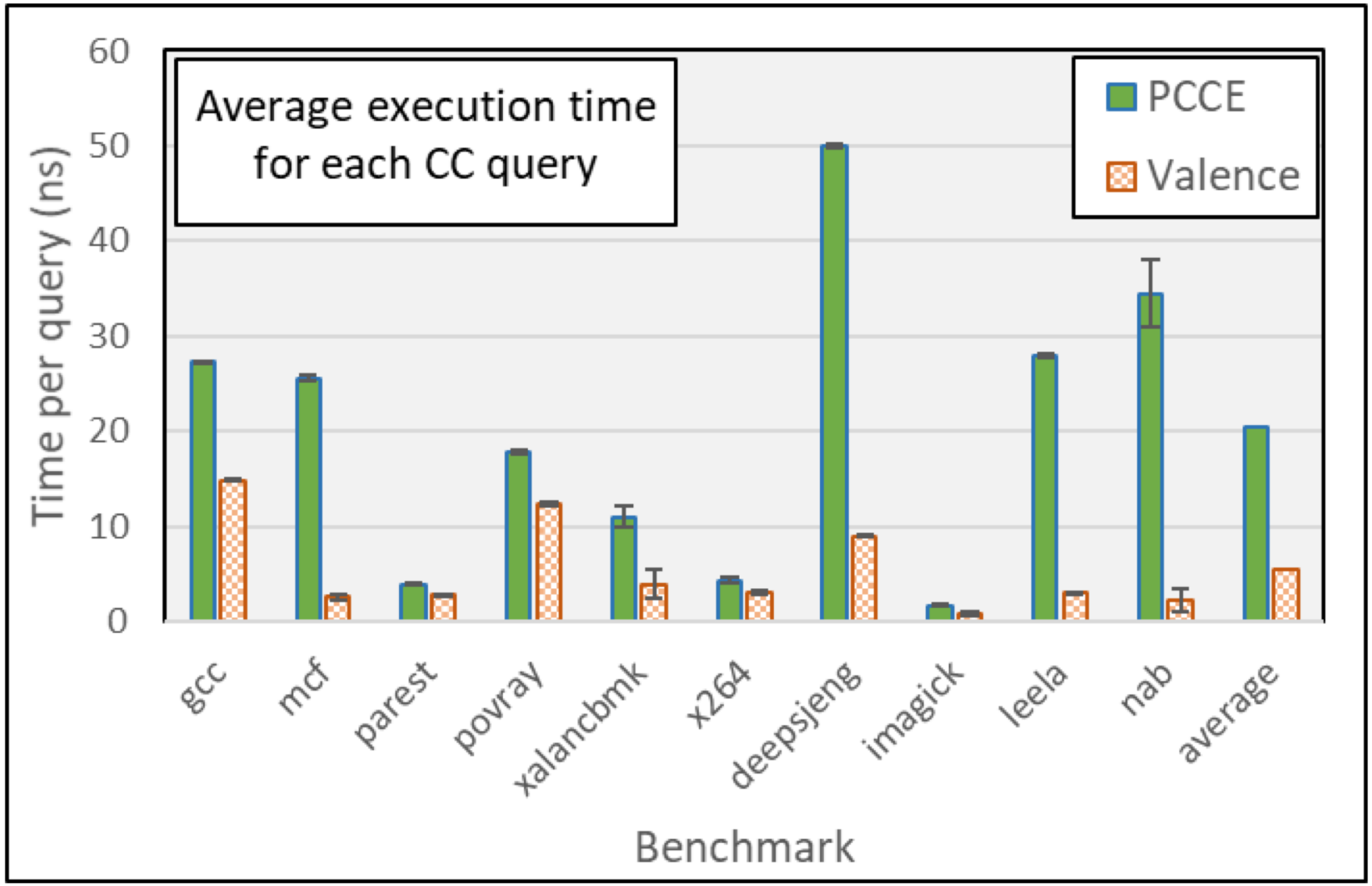
At most 15 bits to encode a cycle edge

Cyclic Encoding Cost Estimation

Benchmark	PCCE (bits)	Valence (bits)	Valence/PCCE
gcc	1E+06	424950	34%
mcf	6	1	17%
cactusBSSN	1802	469	26%
parest	2656	1600	60%
povray	62913	28560	45%
xalancbmk	48932	17226	35%
x264	18	2	11%
deepsjeng	228	48	21%
imagick	18144	5240	29%
leela	378	115	30%
nab	450	125	28%
xz	126	90	71%

Geomean:
49%

Detection Overhead



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Benchmark Static Characteristics

Benchmark	Acyclic Encoding Bits	
	PCCE	Valence
gcc	214	148
mcf	6	7
cactuBSSN	28	55
namd	10	13
parest	25	42
povray	57	57
lbm	2	2
xalancbmk	42	87
x264	18	27
deepsjeng	15	21
imagick	64	113
leela	13	17
nab	13	16
xz	10	18

Benchmark Static Characteristics

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	PCCE	
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mcf	6	
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parest	25	42
povray	57	57
lbm	2	2
xalancbmk	42	87
x264	18	27
deepsjeng	15	21
imagick	64	113
leela	13	17
nab	13	16
xz	10	18

PCCE Cannot operate on 214-bit integer efficiently

Benchma

Average Acyclic Words

PCCE 1.21

Valence 1.29

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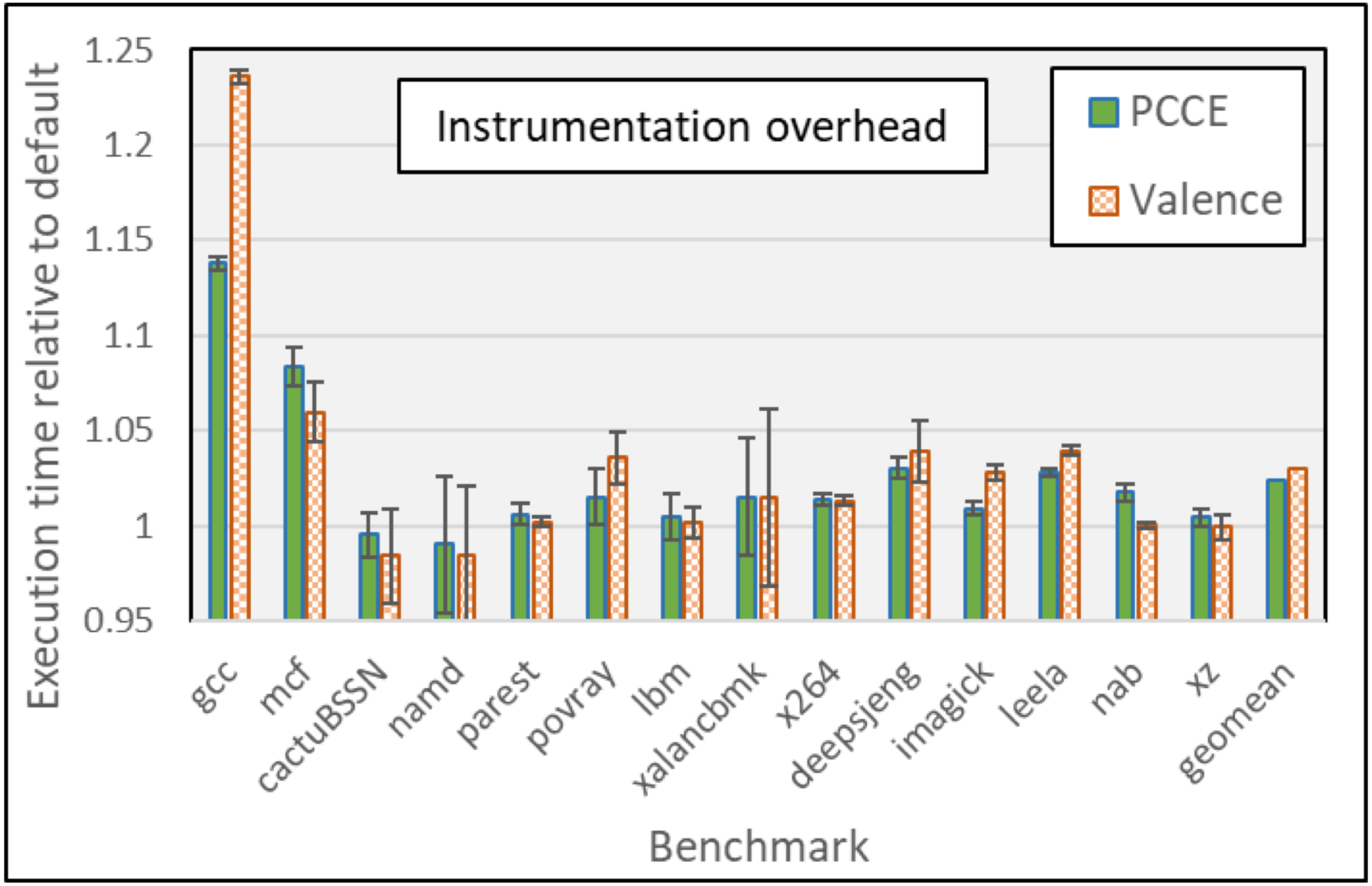
Low cost for scalability!

Instrumentation Overhead



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Conclusion & Future

- We presented Valence: a precise context encoding scheme that is both scalable and low overhead to query.
- Overall, our approach reduces the length of calling context encoding from 4.3 words to 1.6 words on average (> 60% reduction), thereby improving the efficiency of applications that frequently store or query calling contexts.
- See how Valence can enhance some program analysis and software engineering fields.

Thank you! Questions?

Contact info: tz@gatech.edu

Back up slides

DeltaPath: A Scalable Version of PCCE

- Encode context using a list of <cc, anchor node> pairs
- Tuple list operation is difficult to implement efficiently
- Still inherits PCCE's inefficient cycle encoding

DeltaPath: A Scalable Version of PCCE

- Divide the call graph into sub-graphs
  - Each subgraph is encodable with PCCE
- Introduce the notion of “anchor node” as entry point for each subgraph

DeltaPath: A Scalable Version of PCCE