Call Paths for Pin Tools

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Department of Computer Science
Rice University

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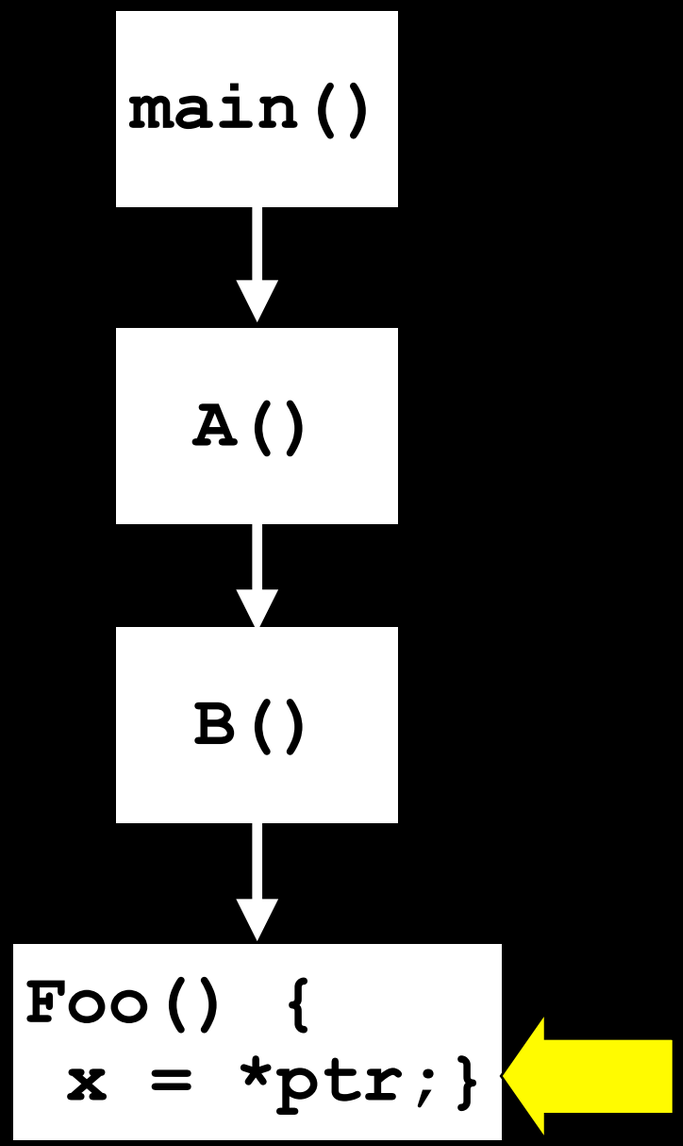
February 17, 2014

What is a Call Path ?



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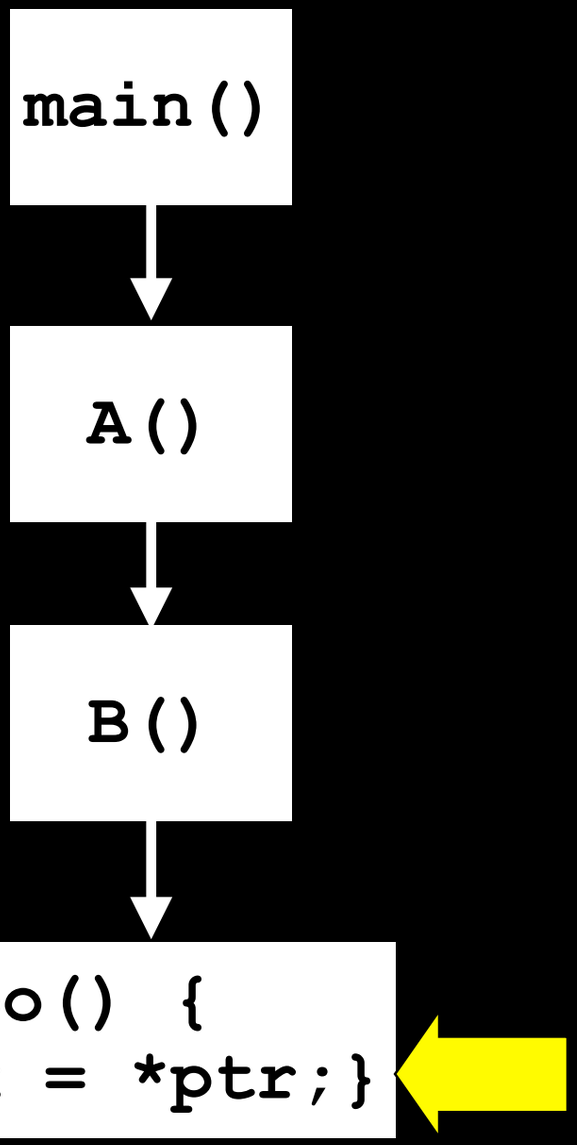
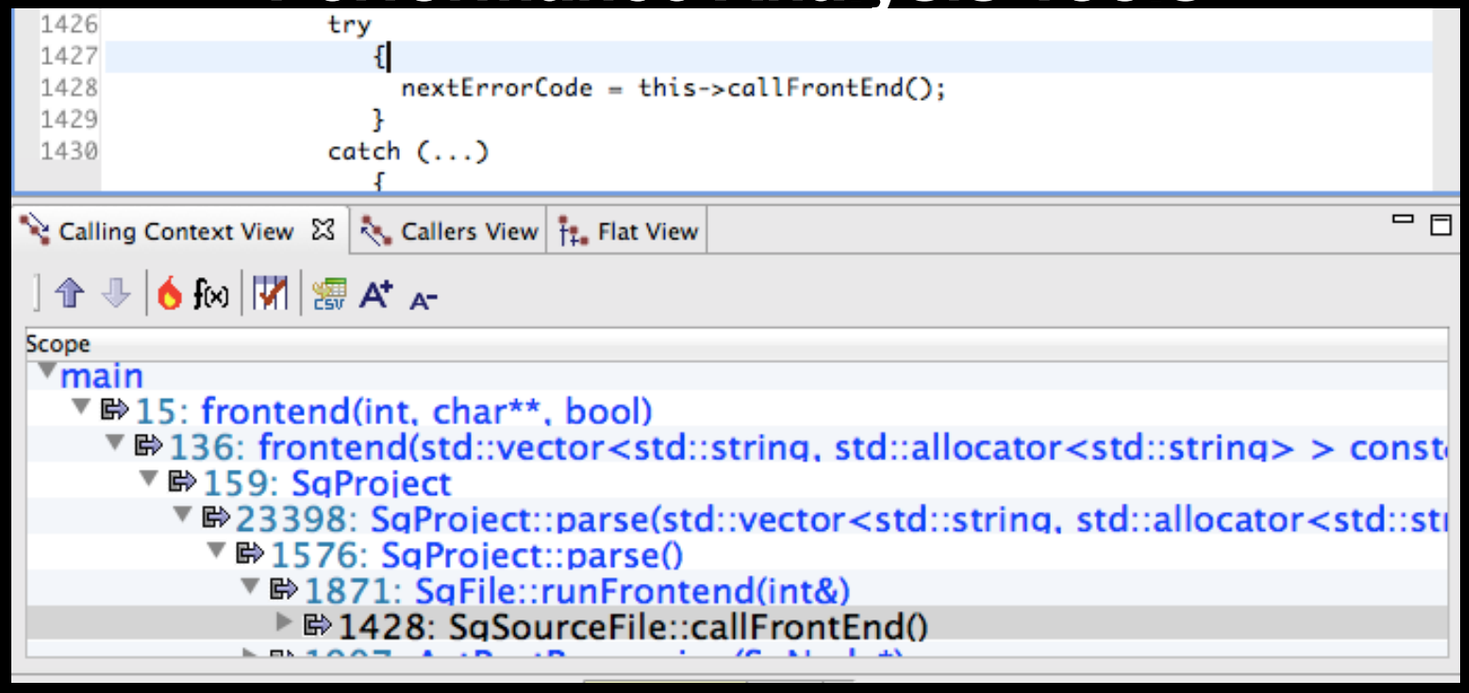
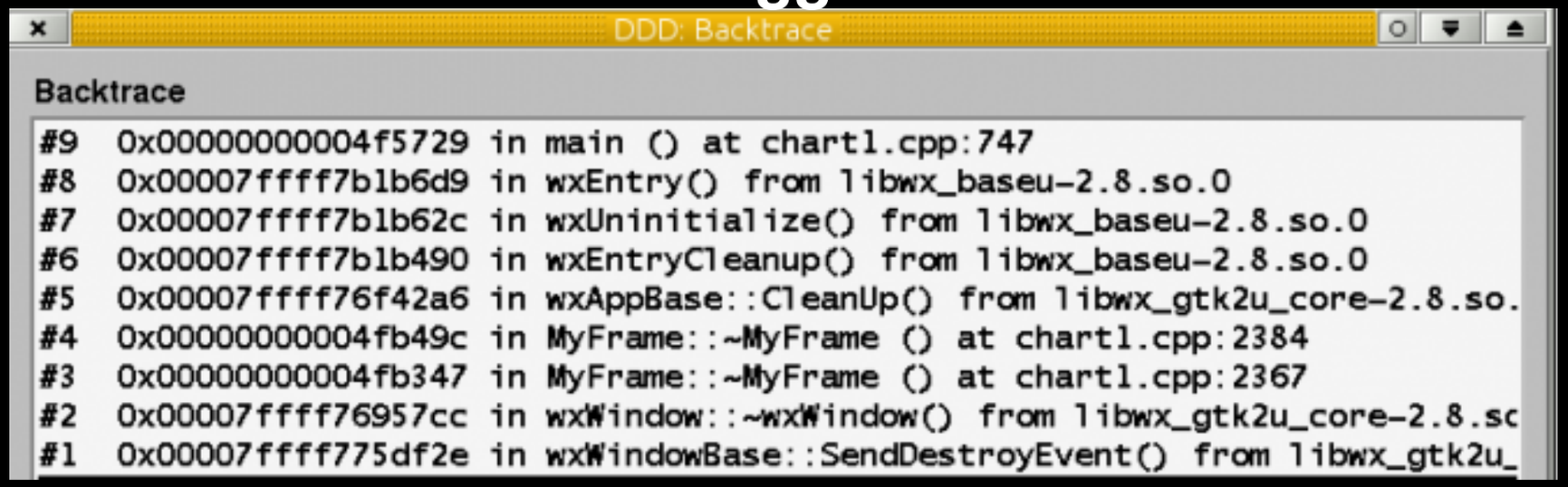


Performance Analysis Tools



Debuggers



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- Correctness
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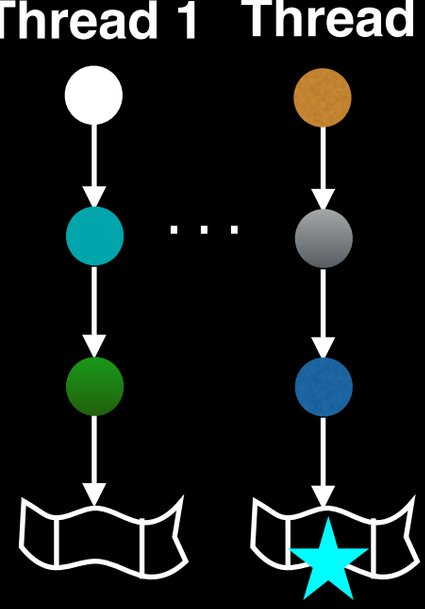
Attribute each conflicting access to its full call path

- Performance



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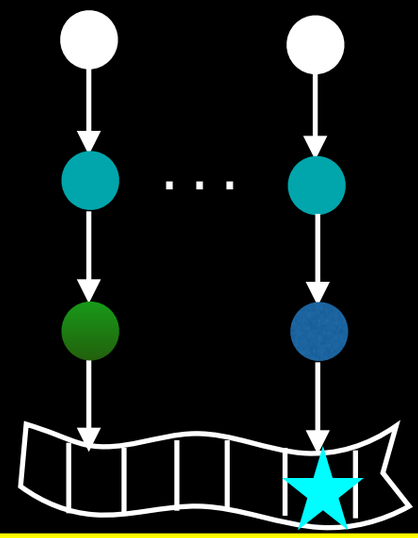

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  - ✦ Redundancy detection (e.g. dead writes)
- Other tools
  - ✦ Debugging, testing, resiliency, replay, etc.

State-of-the-art in Collecting Ubiquitous Call Paths

“It will slow down execution by a factor of several thousand compared to native execution -- I'd guess -- so you'll wind up with something that is unusably slow on anything except the smallest problems.”

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“If you tried to invoke Thread::getCallStack on every memory access there would be very serious performance problems … your program would probably never reach main.”

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We built one ourselves—**CCTLib**

Roadmap

CCTLib

- Ubiquitous call path collection
- Attributing costs to data objects
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Top Three Challenges

1

2

3

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1 Overhead

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3

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3 Overhead (Parallel scaling)

Store History of Contexts Compactly

Problem:

Deluge of call paths

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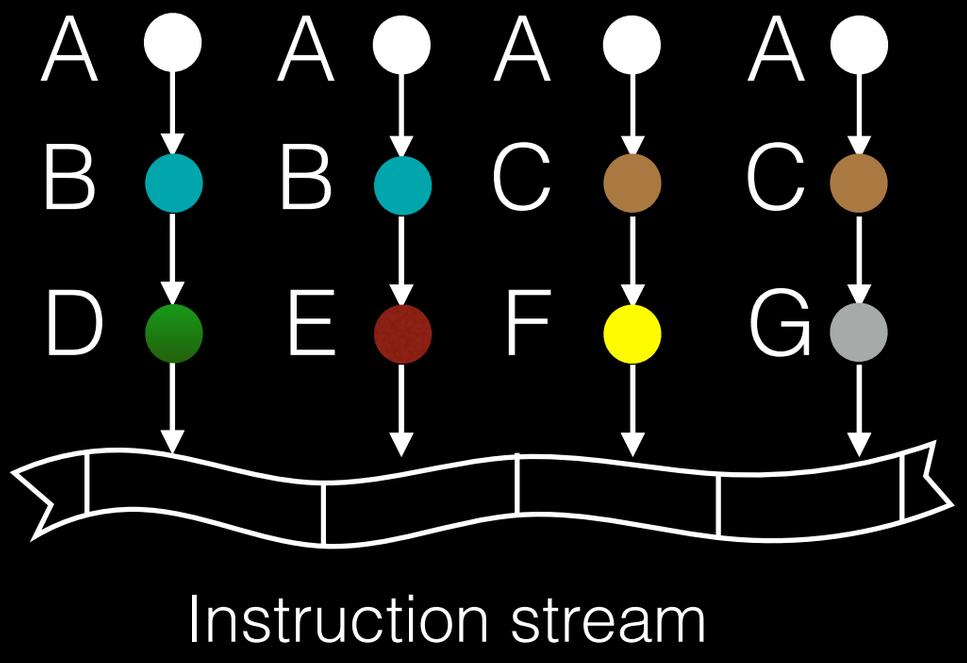

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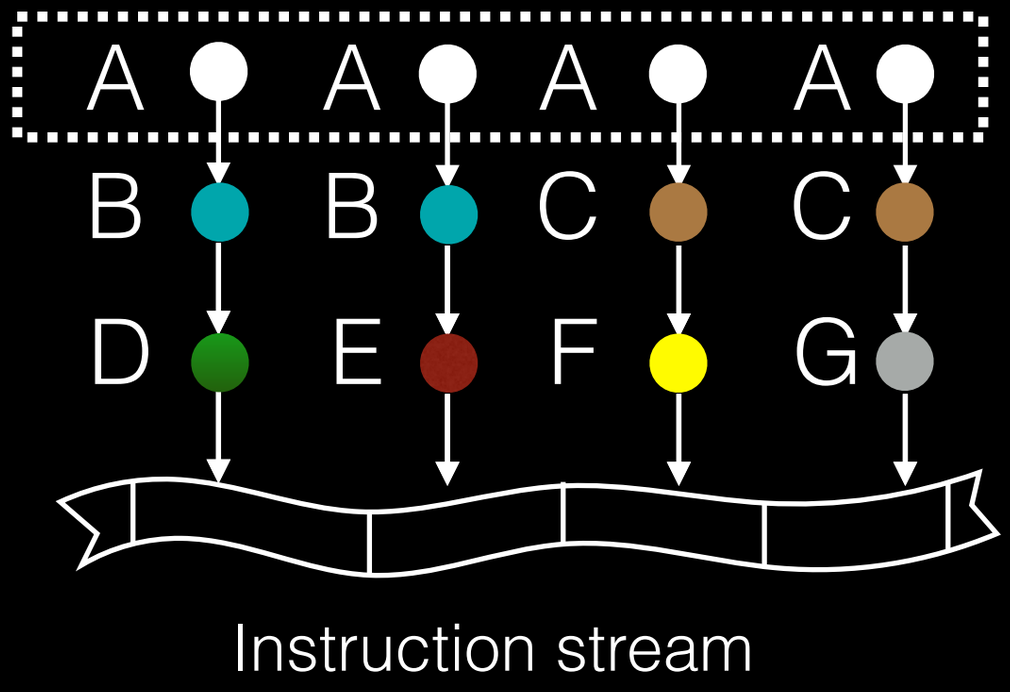

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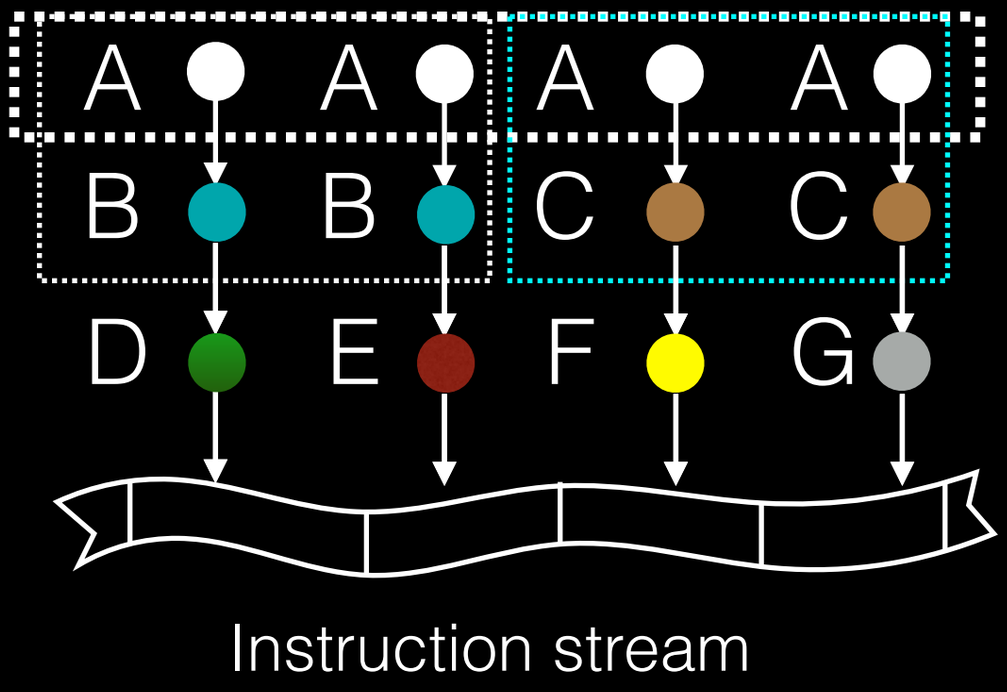

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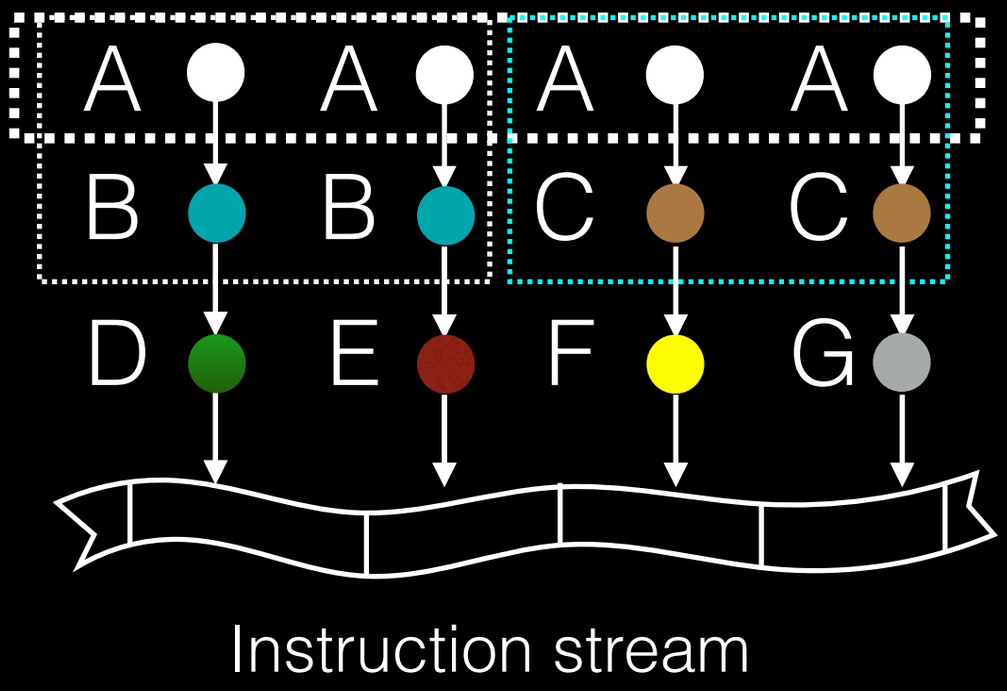
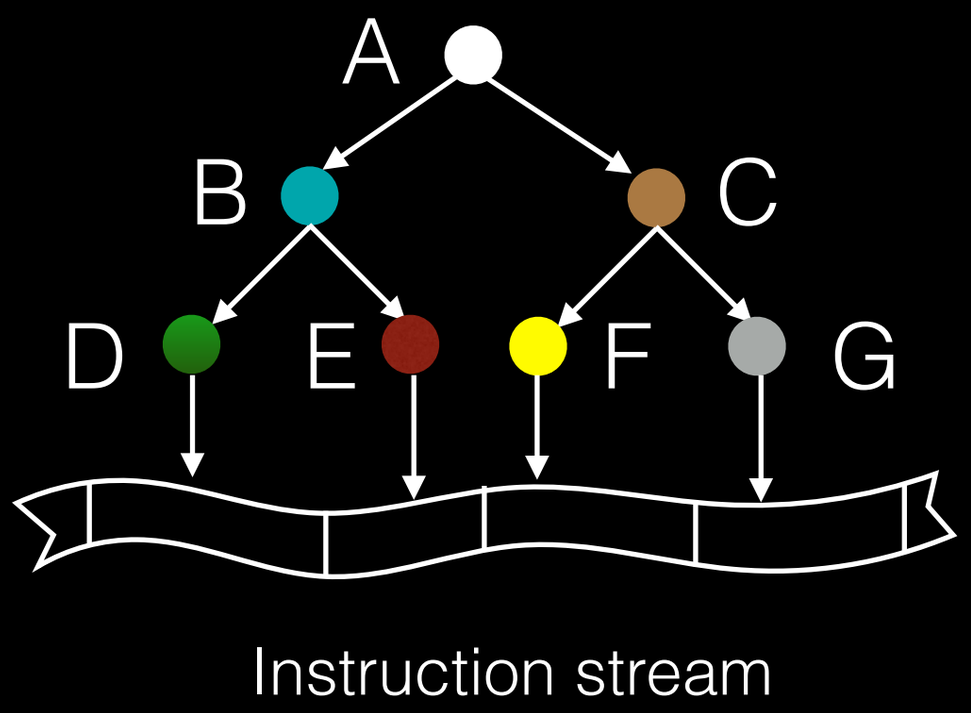


Solution
- Call paths share common prefix
- Store call paths as a calling context tree (CCT)
- One CCT per thread



Shadow Stack to Avoid Unwinding Overhead

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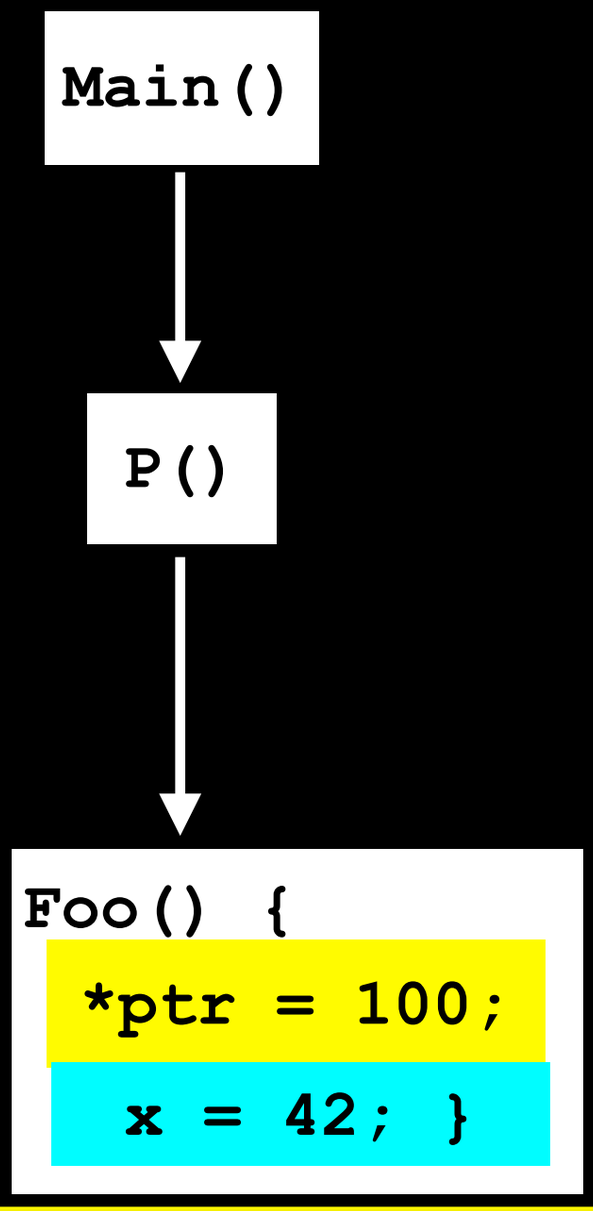

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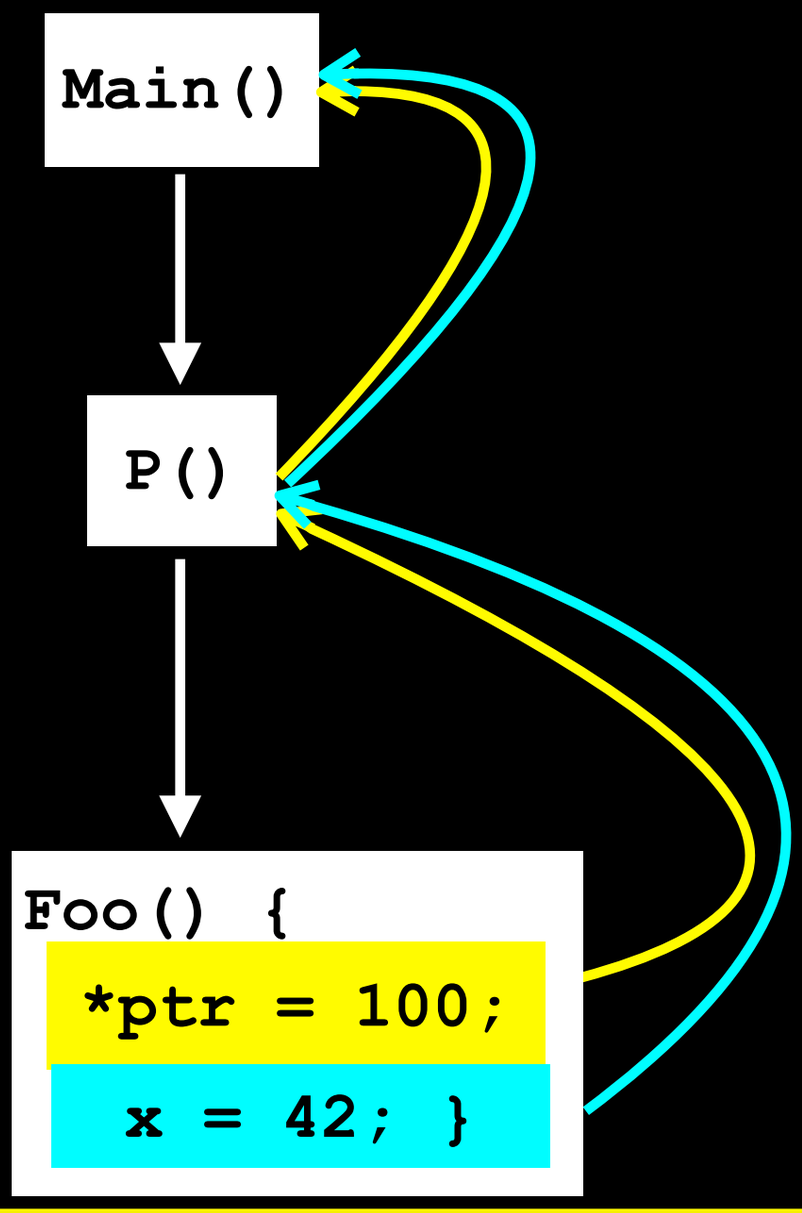

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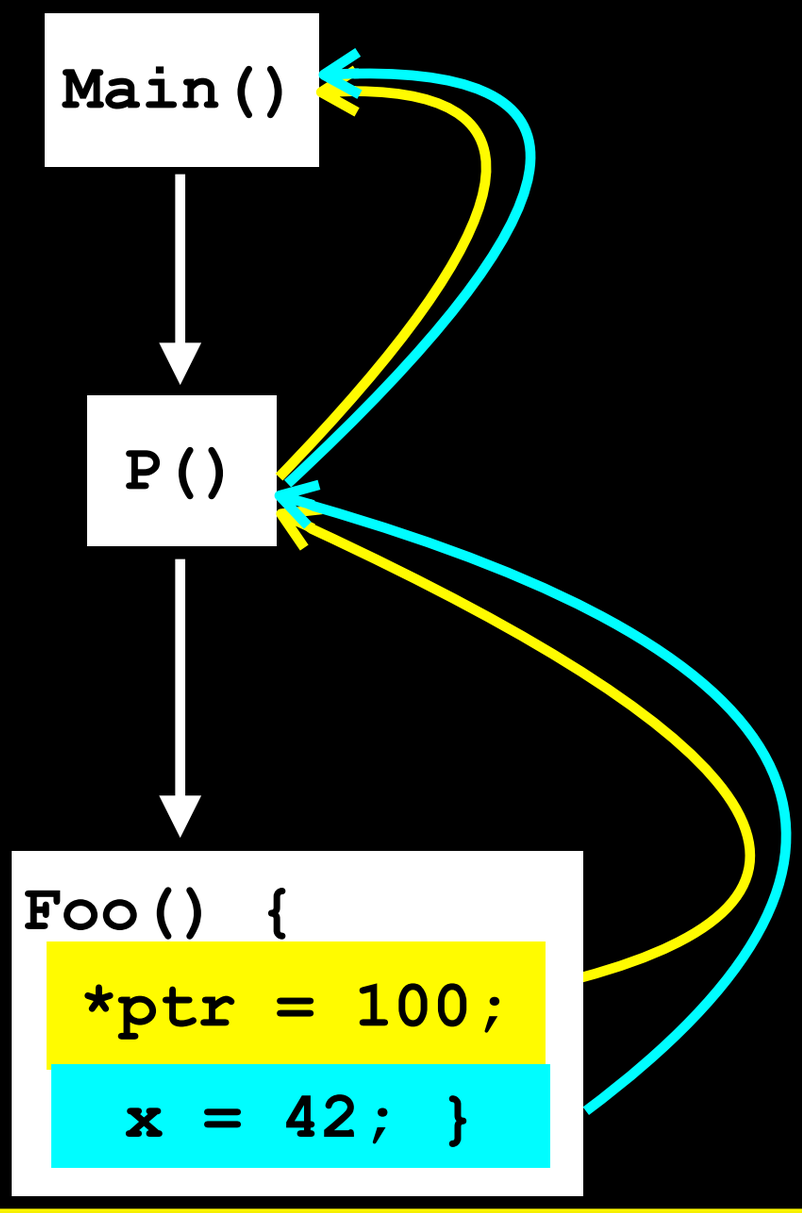

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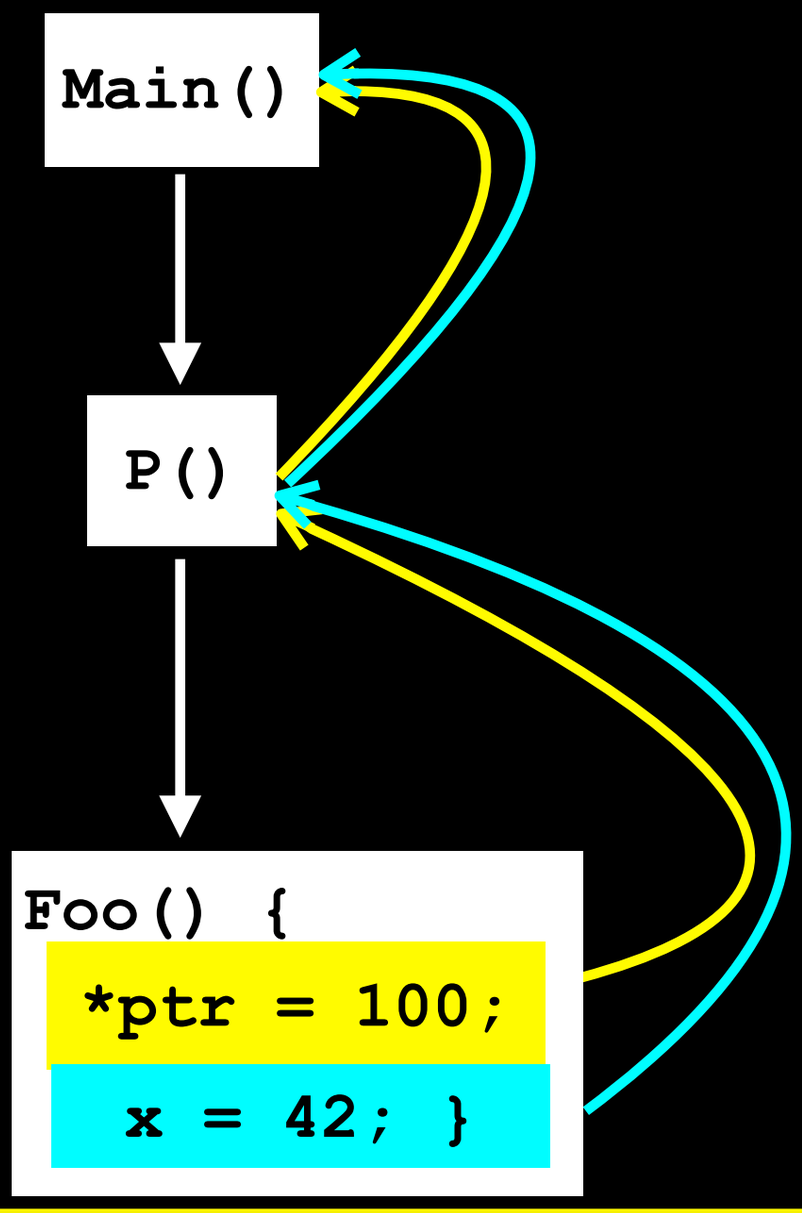

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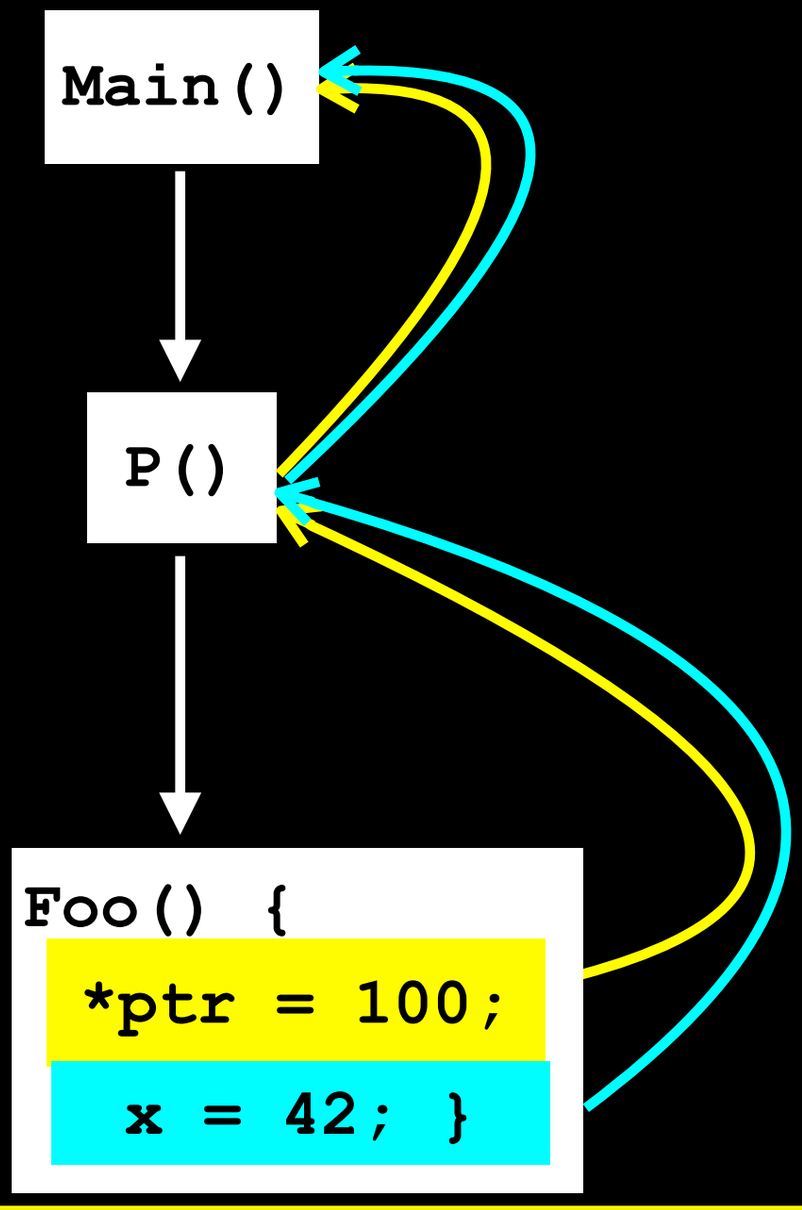

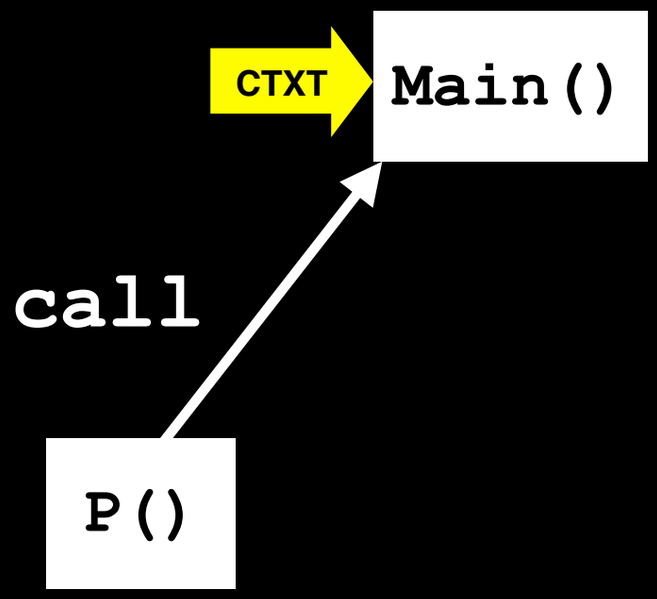

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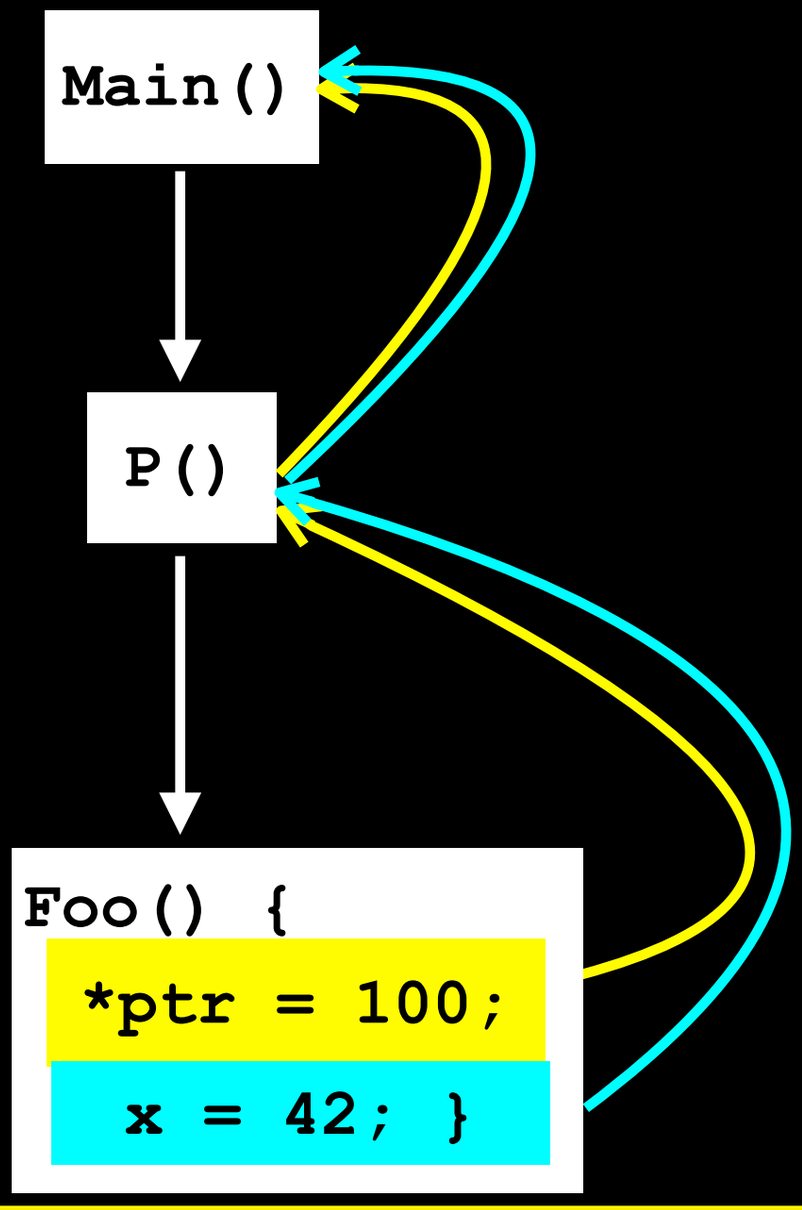

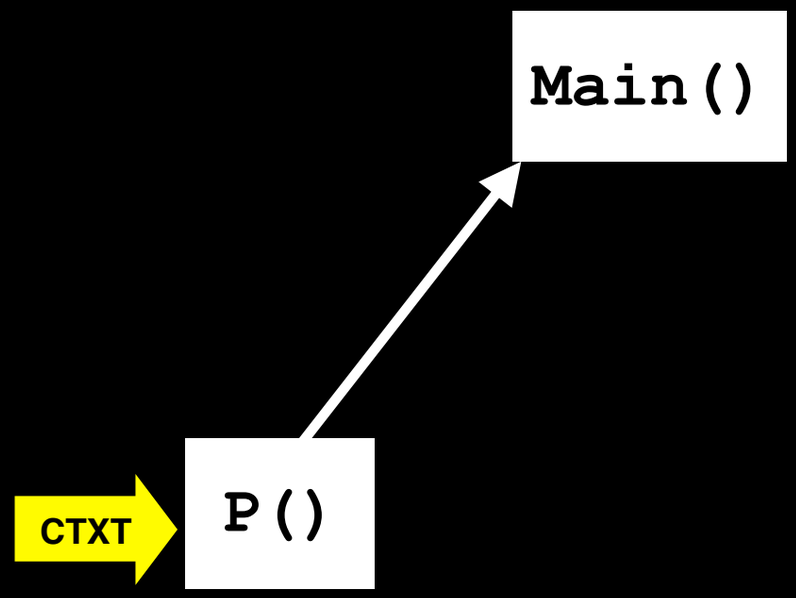

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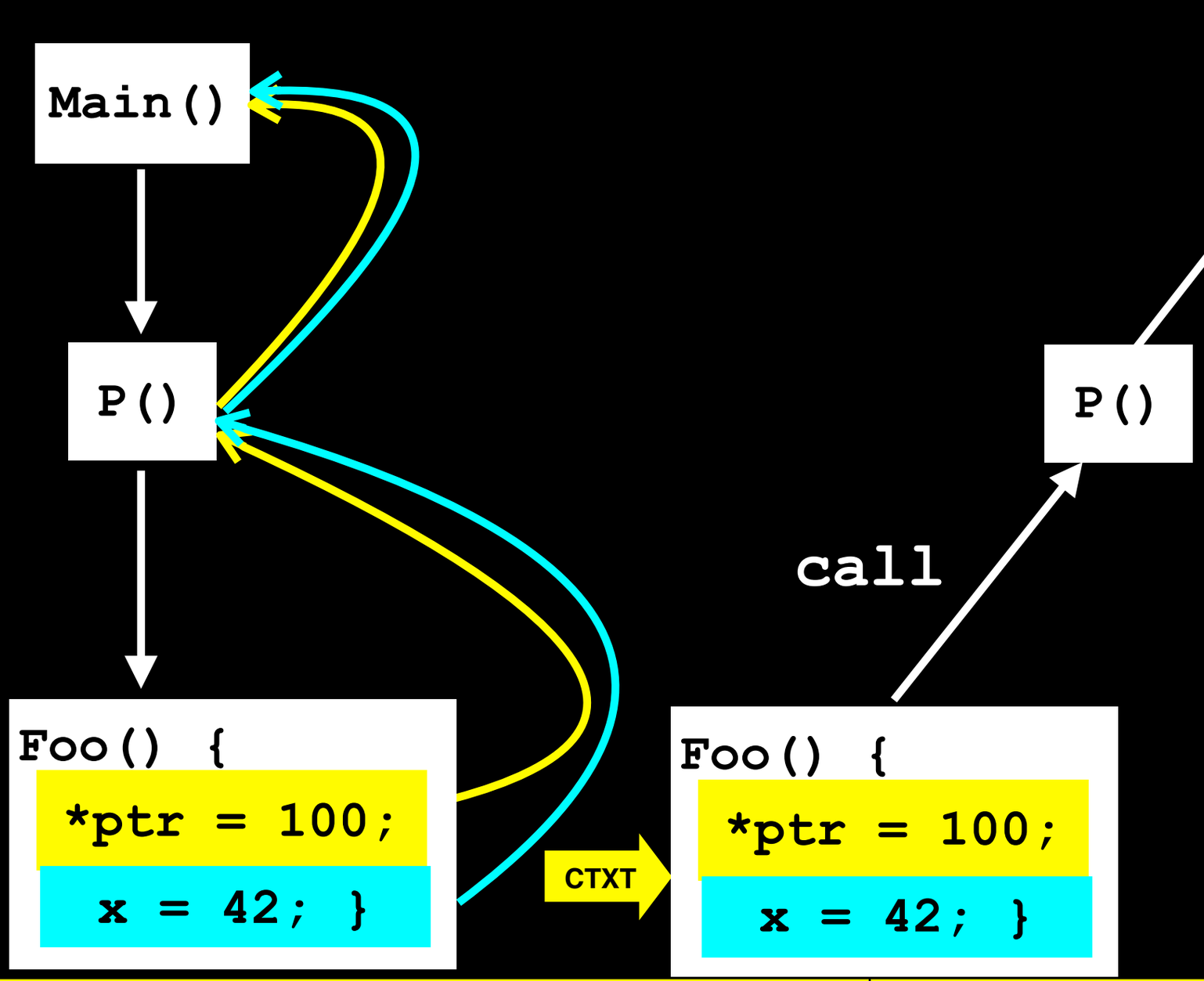

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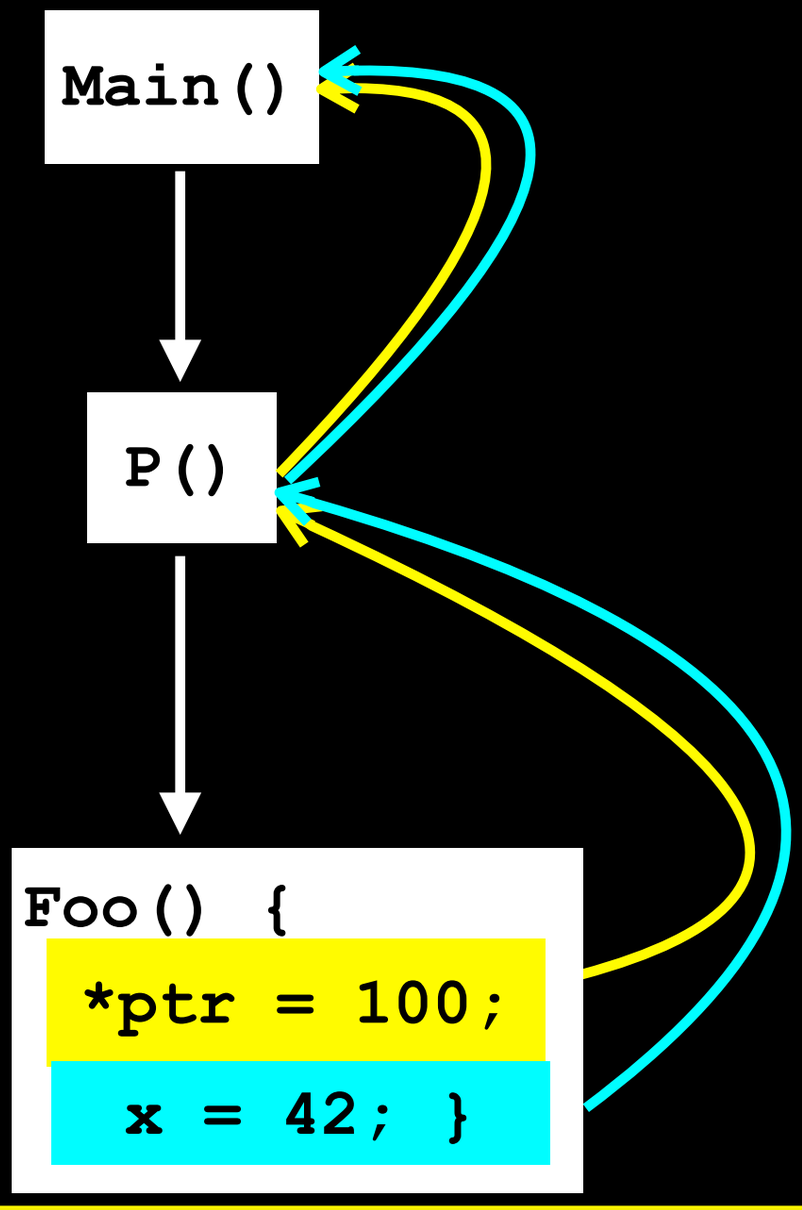

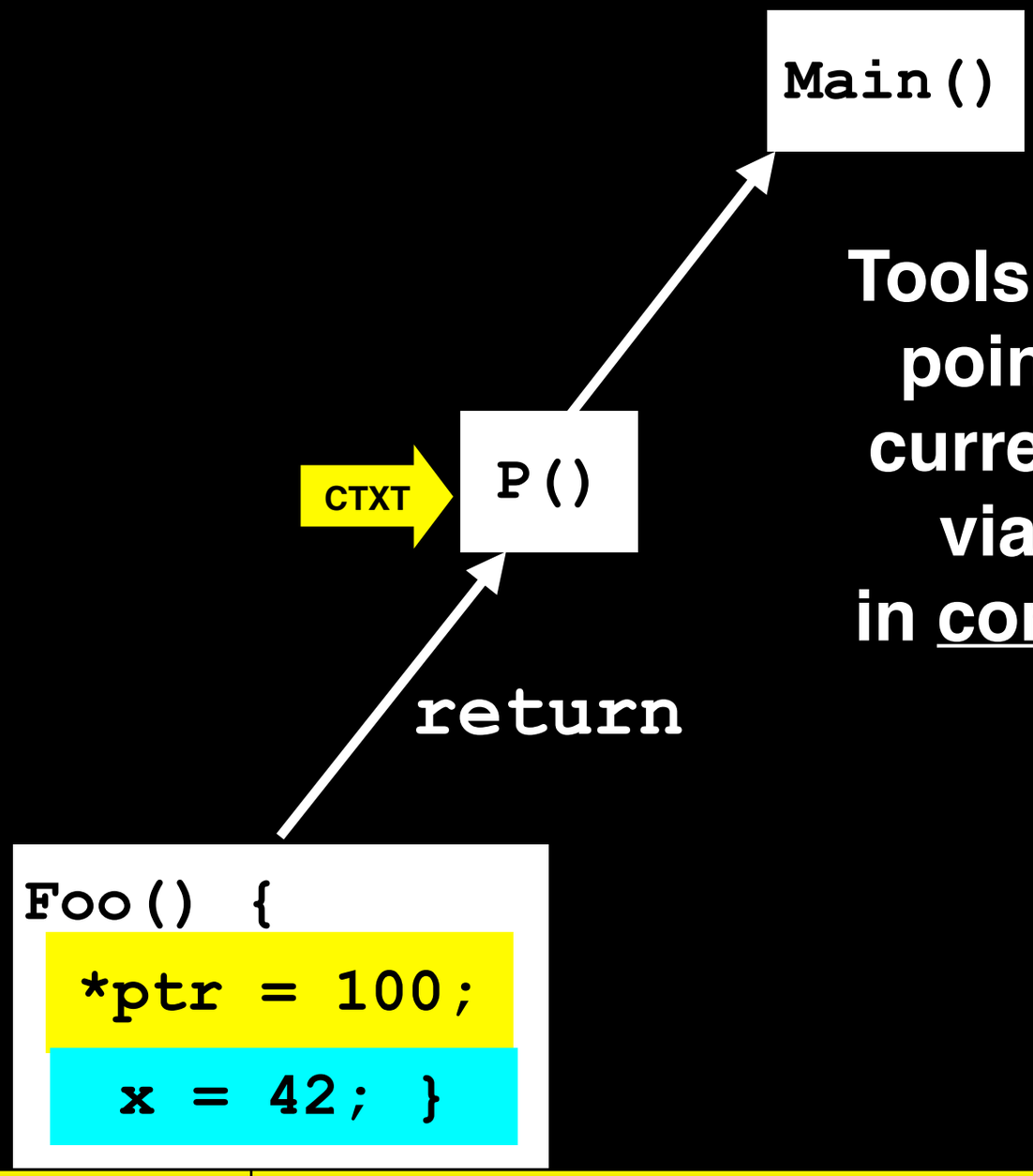

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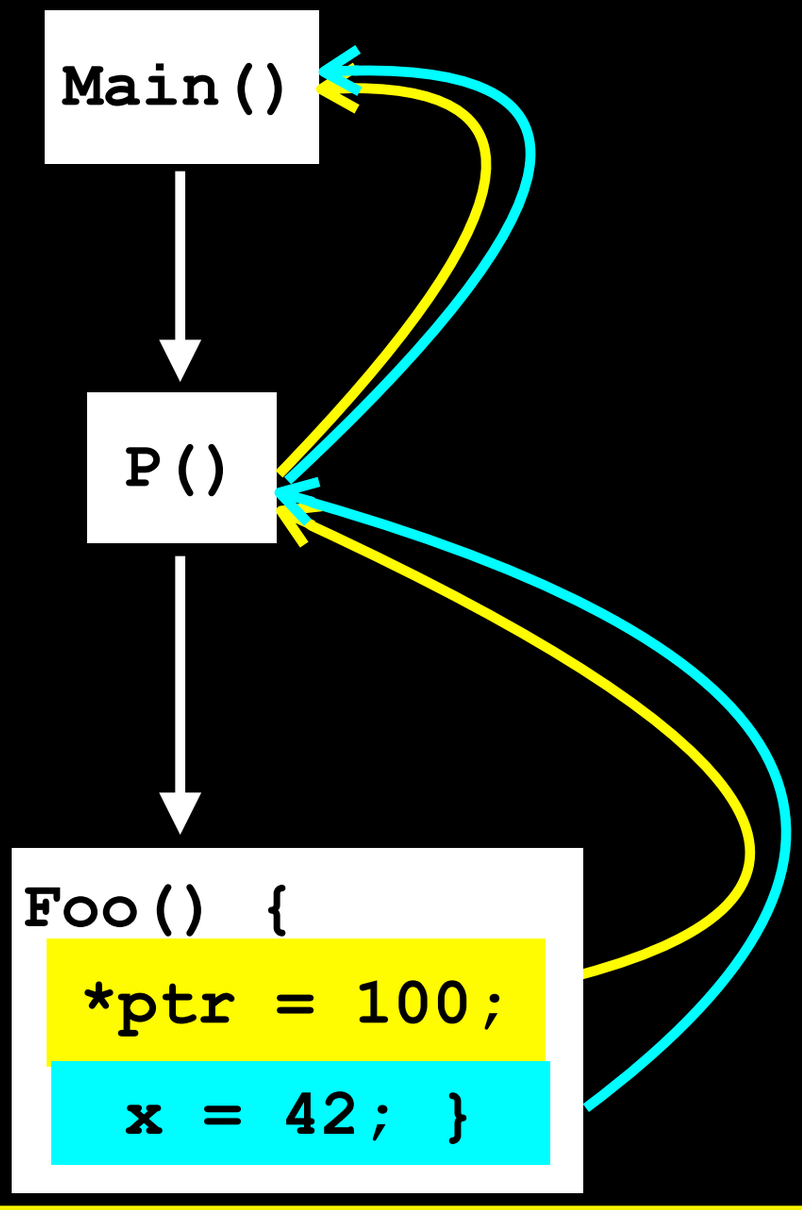

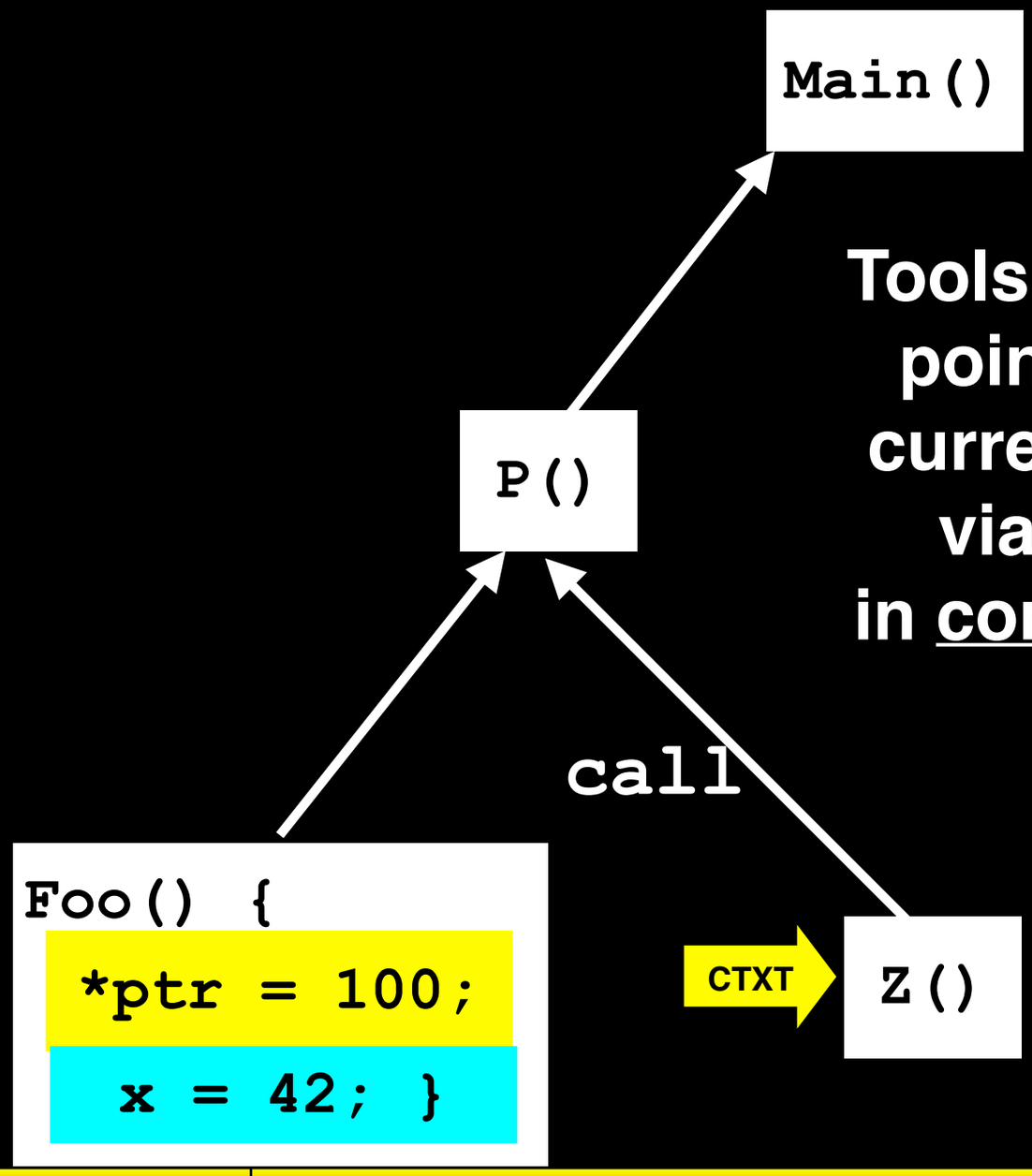

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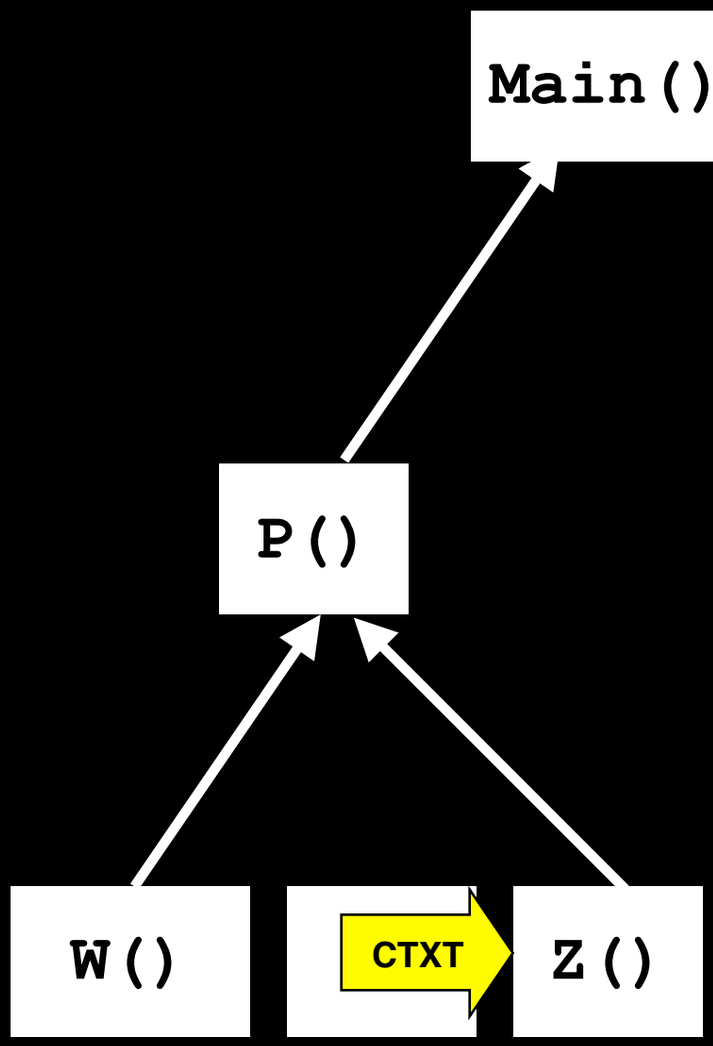
Maintaining CTXT



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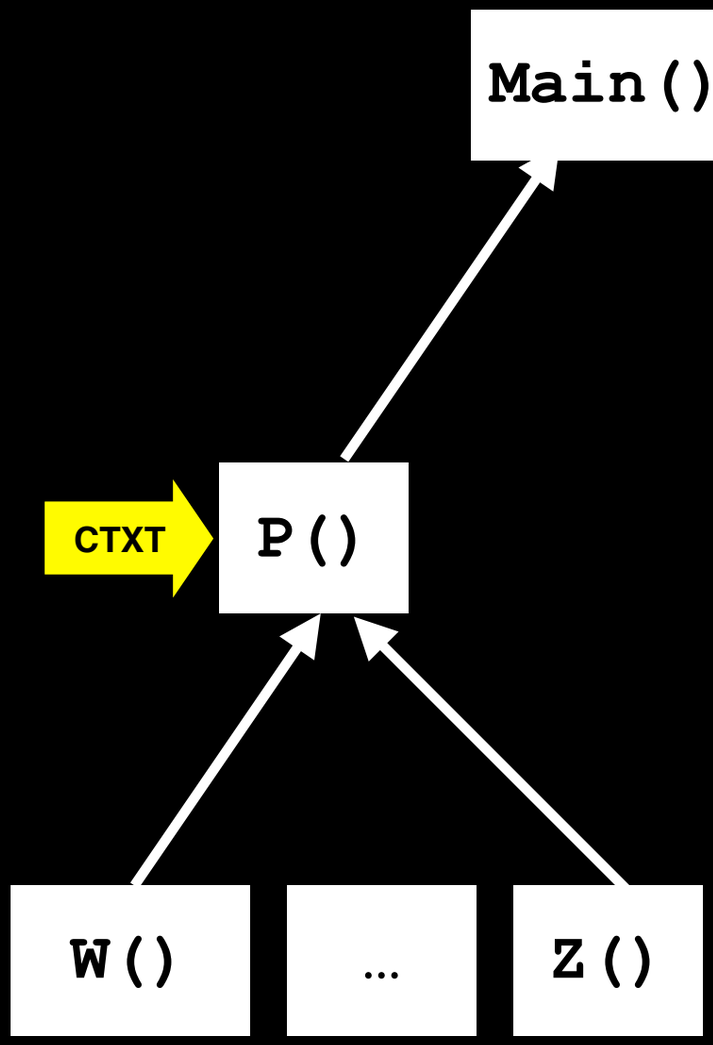

Return to caller:
Constant time update

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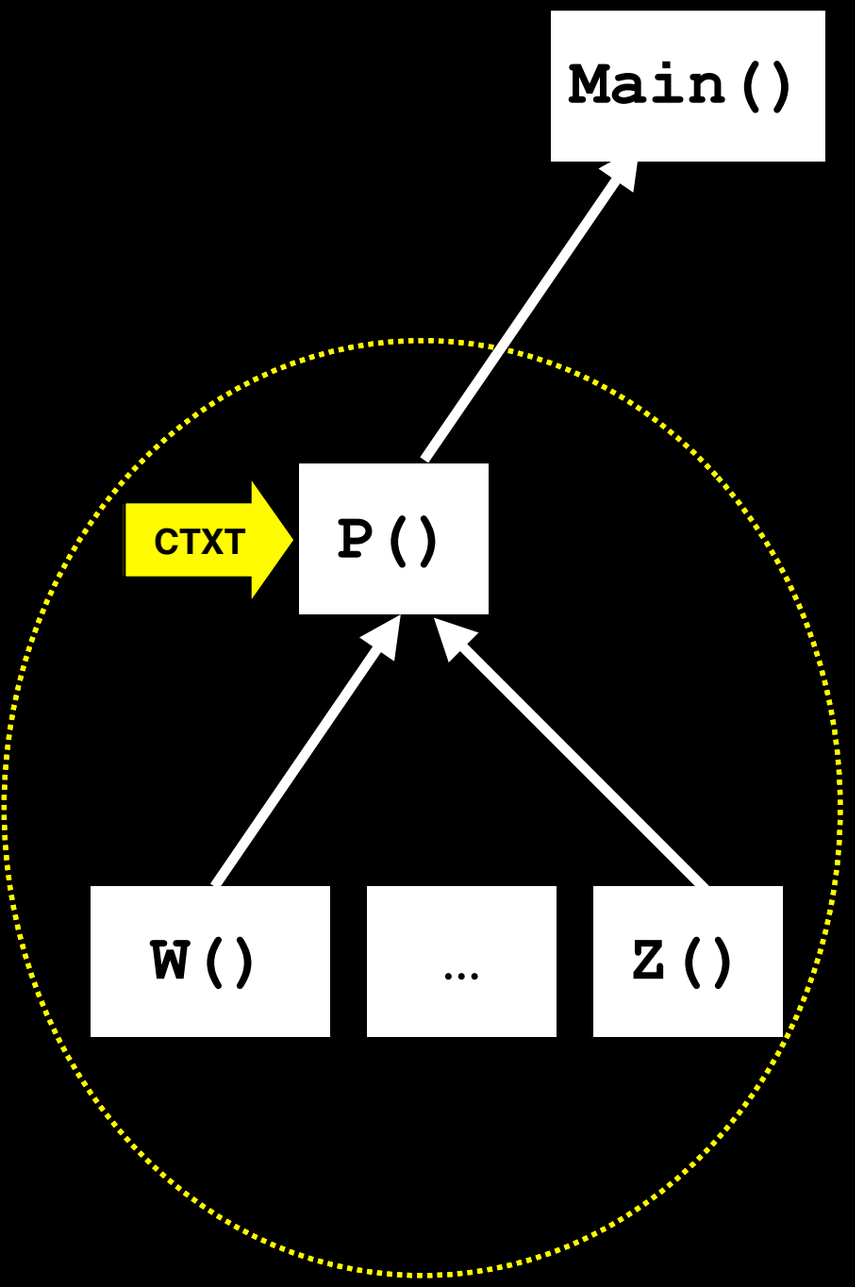

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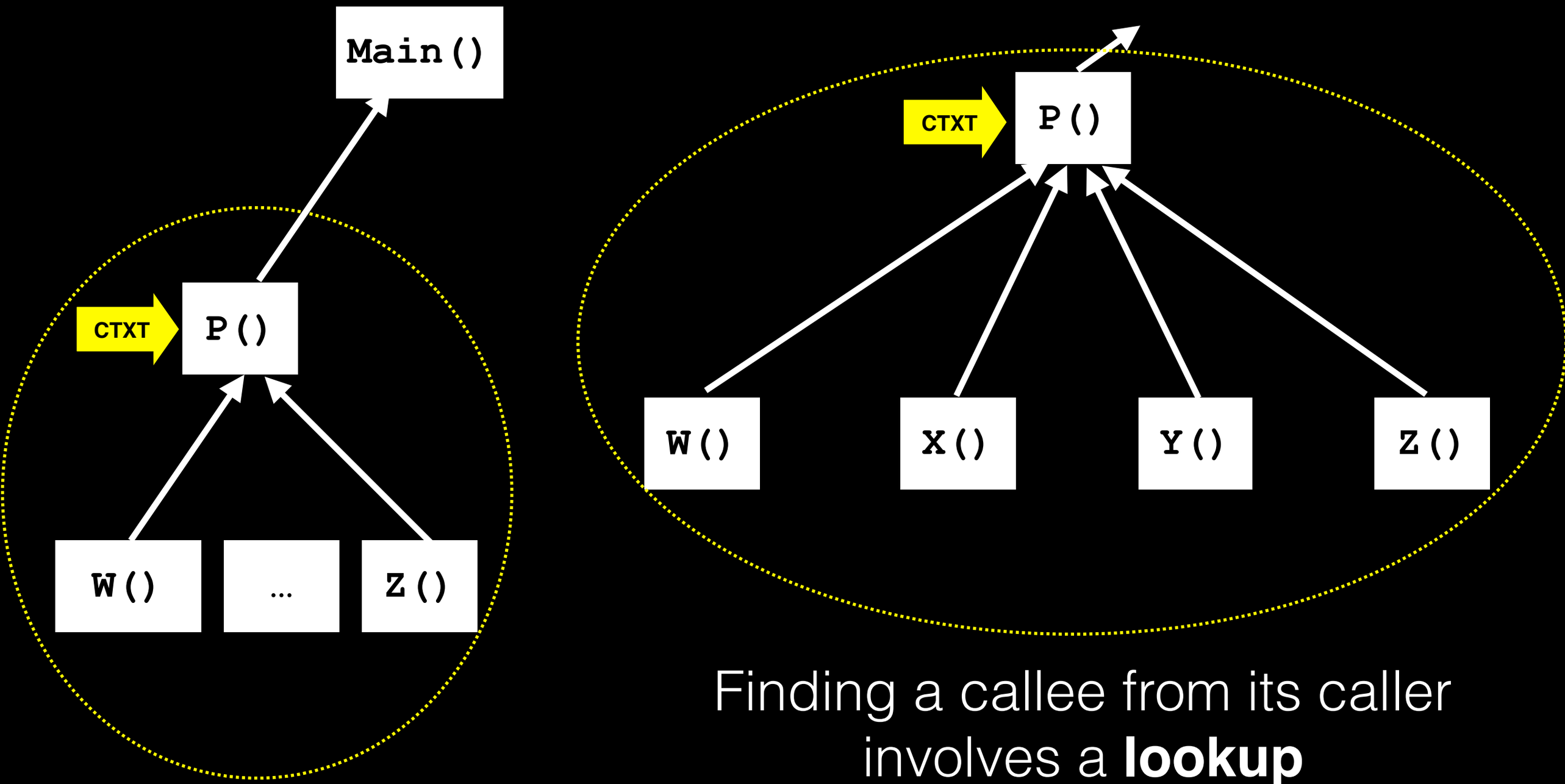

Finding a callee from its caller involves a **lookup**

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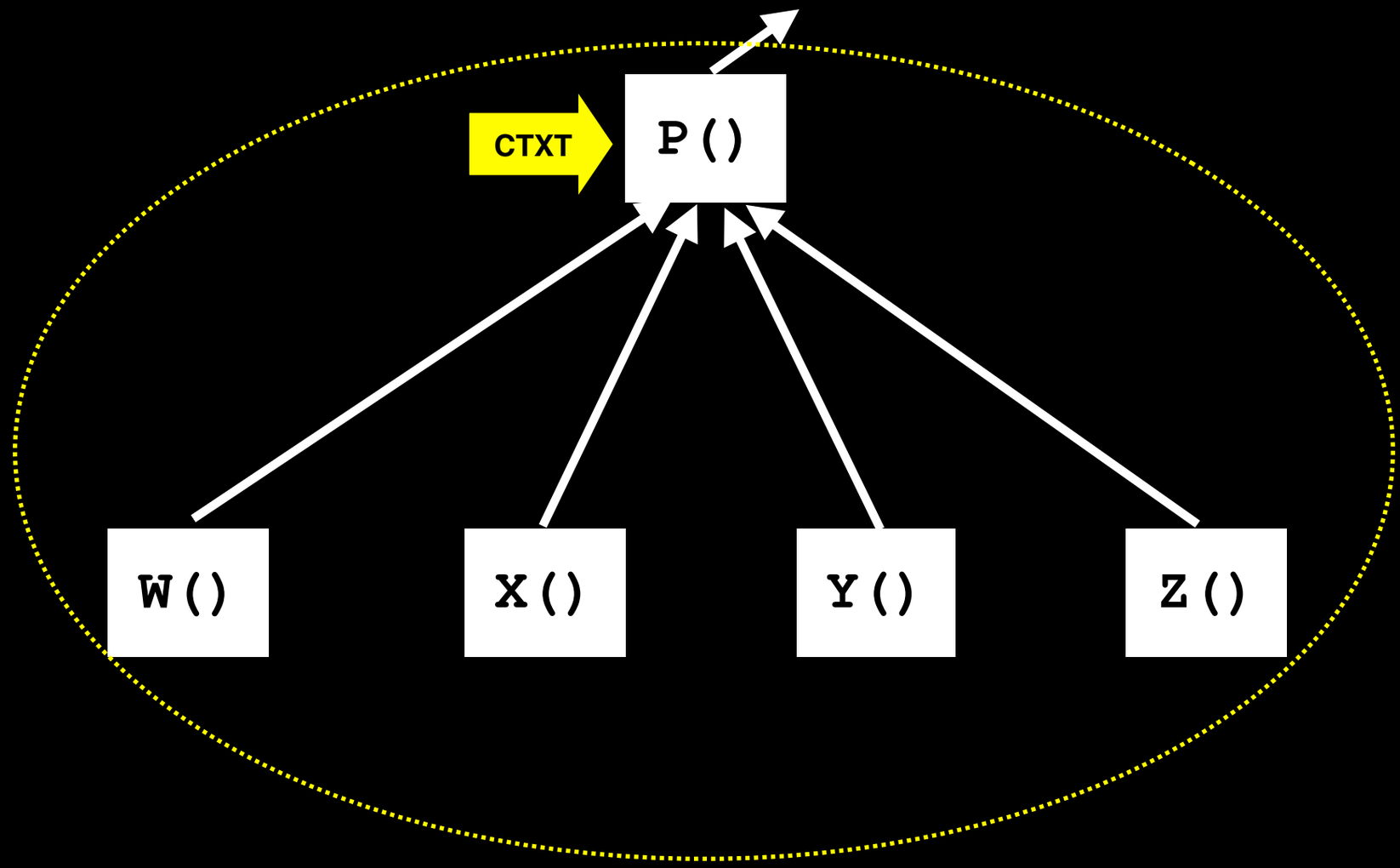

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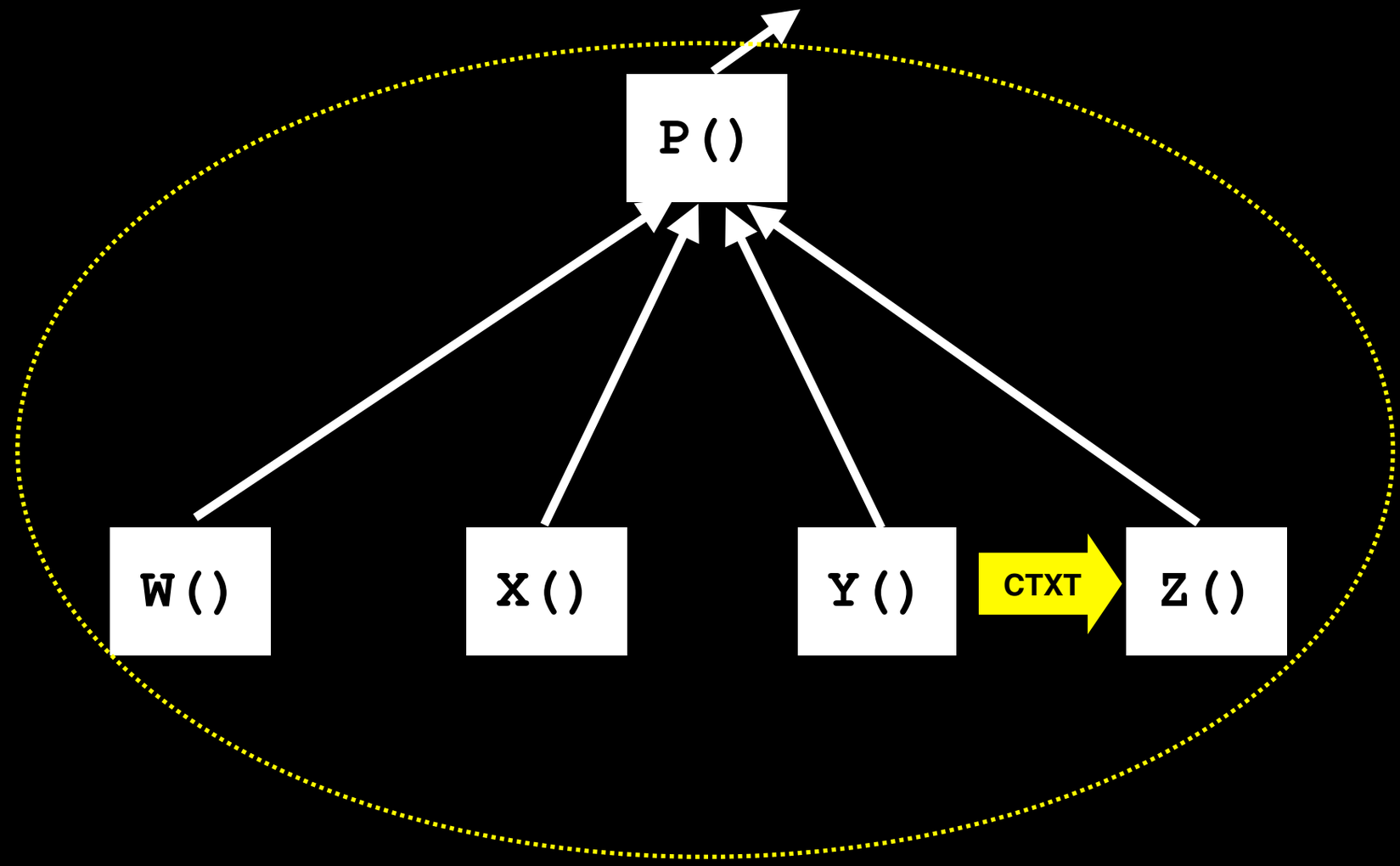

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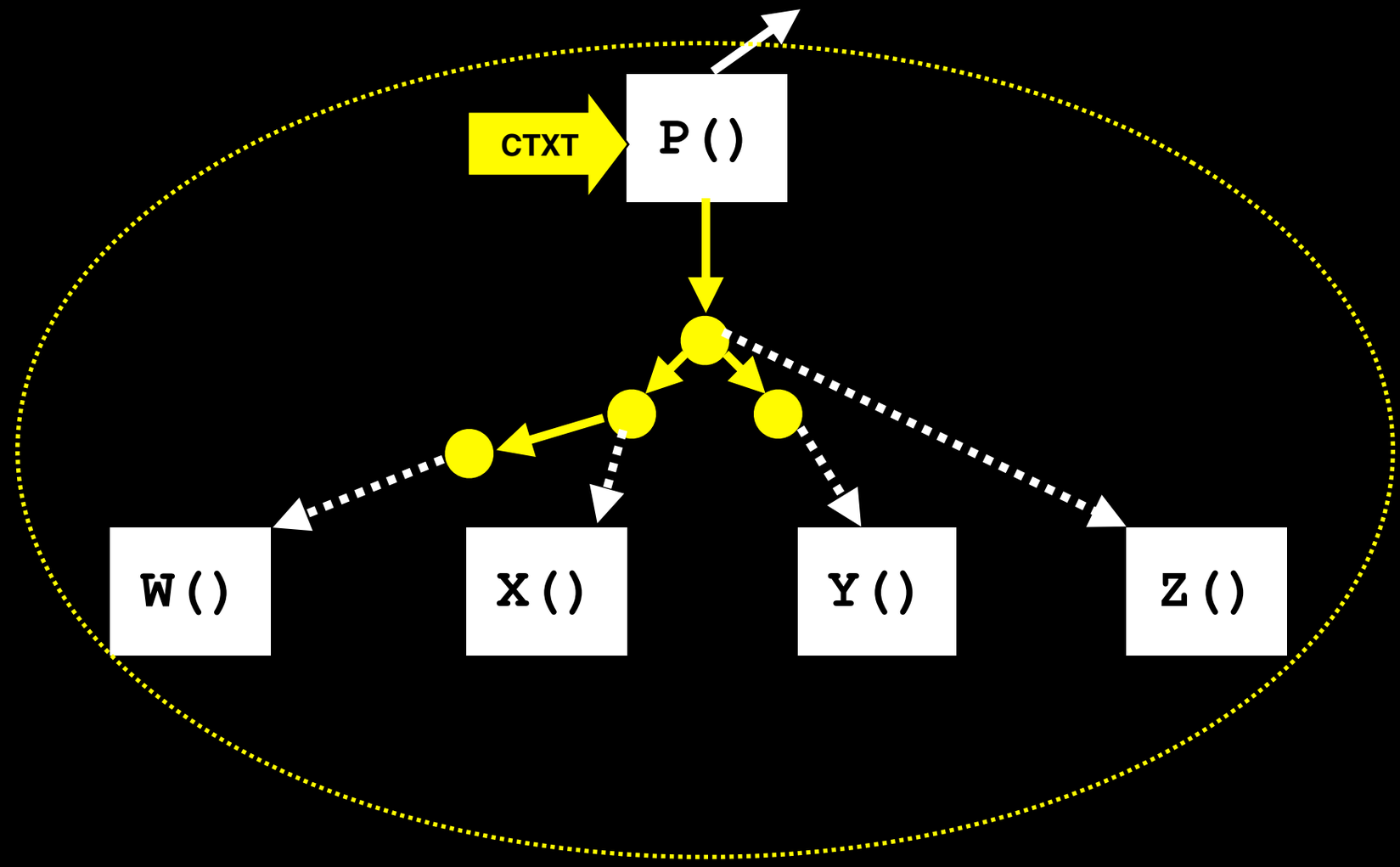
Accelerate Lookup with Splay Trees



Splay tree ["Self-adjusting binary search trees" by Sleator et al. 1985]
ensures frequently called functions are near the root of the tree

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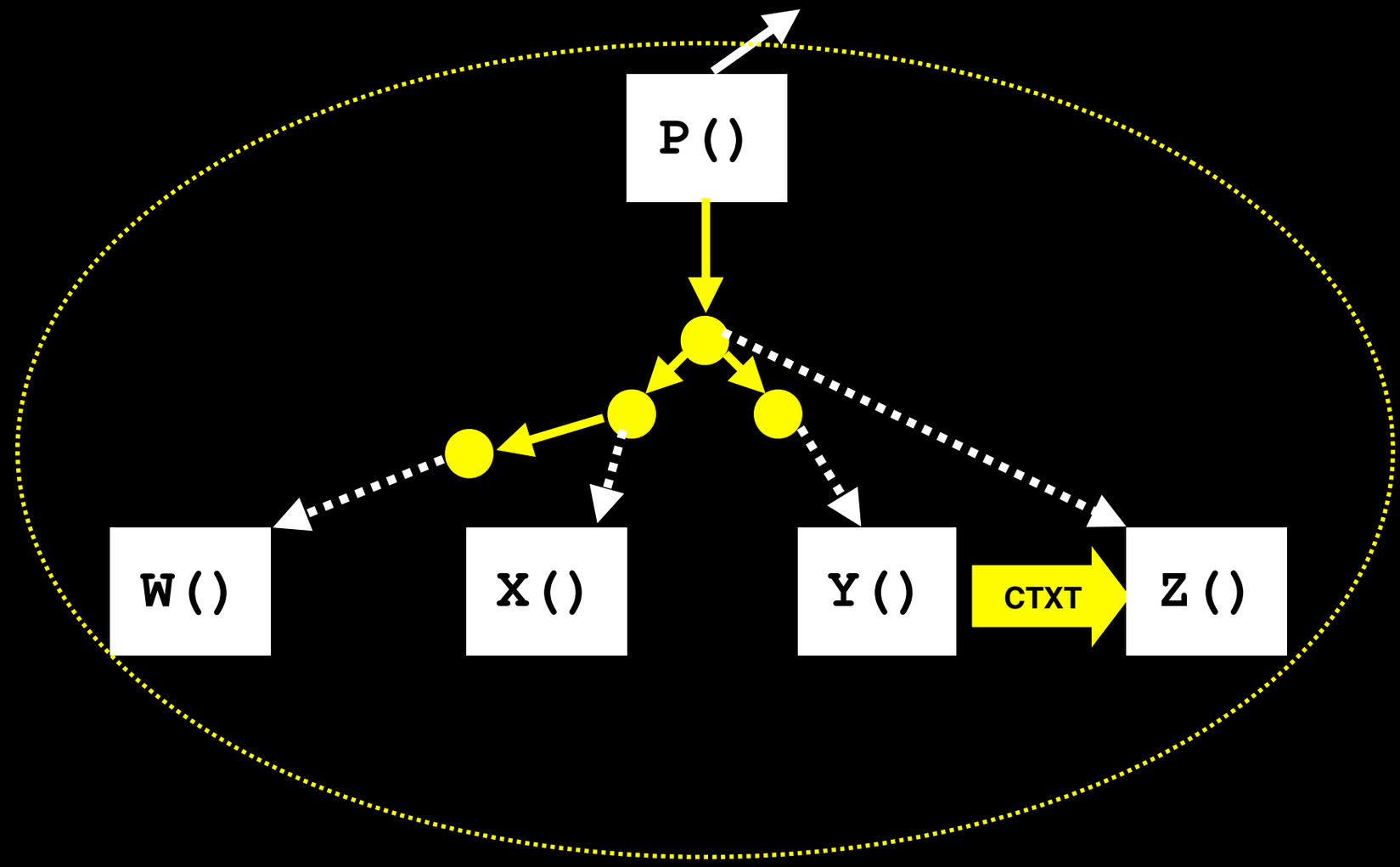

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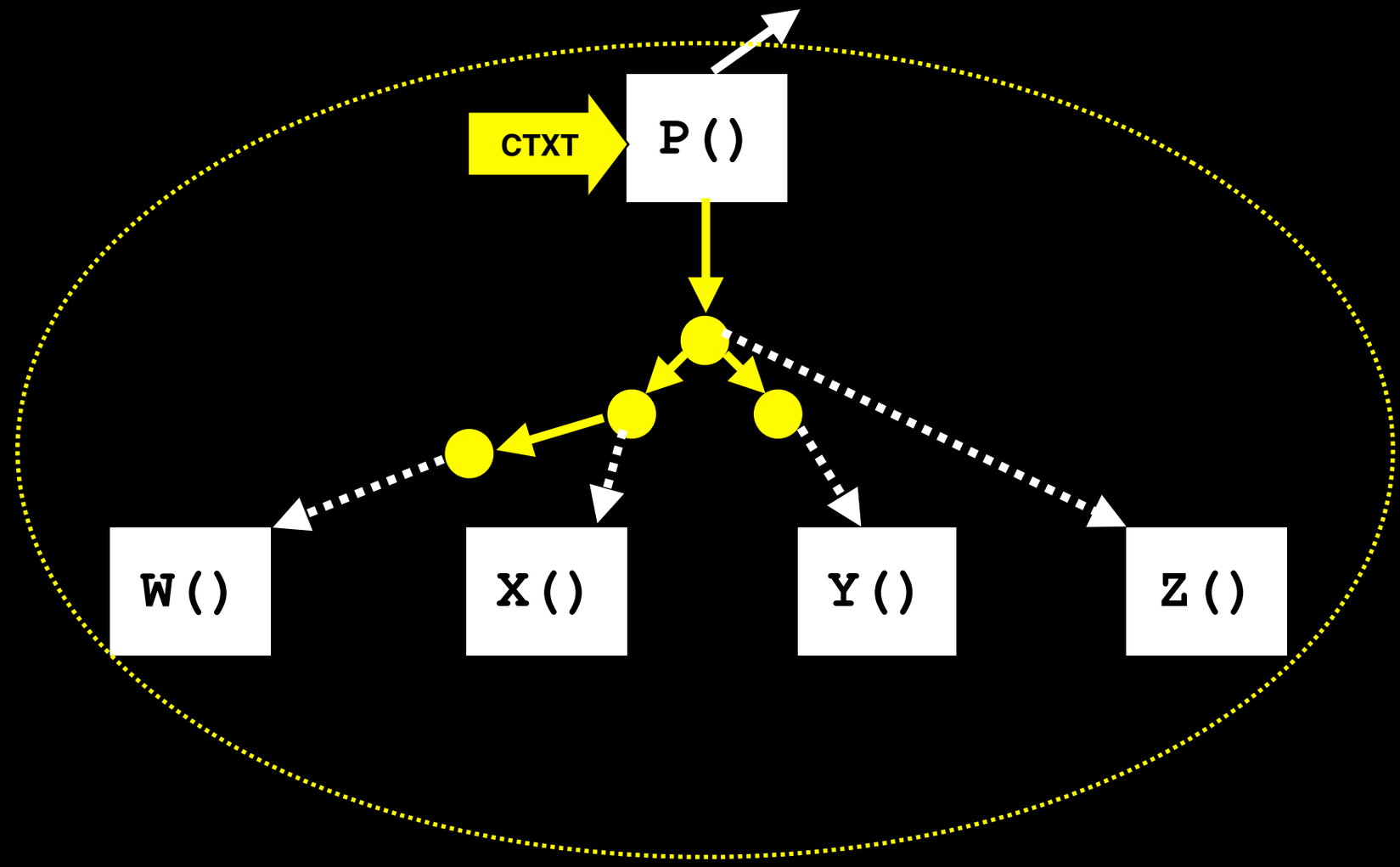

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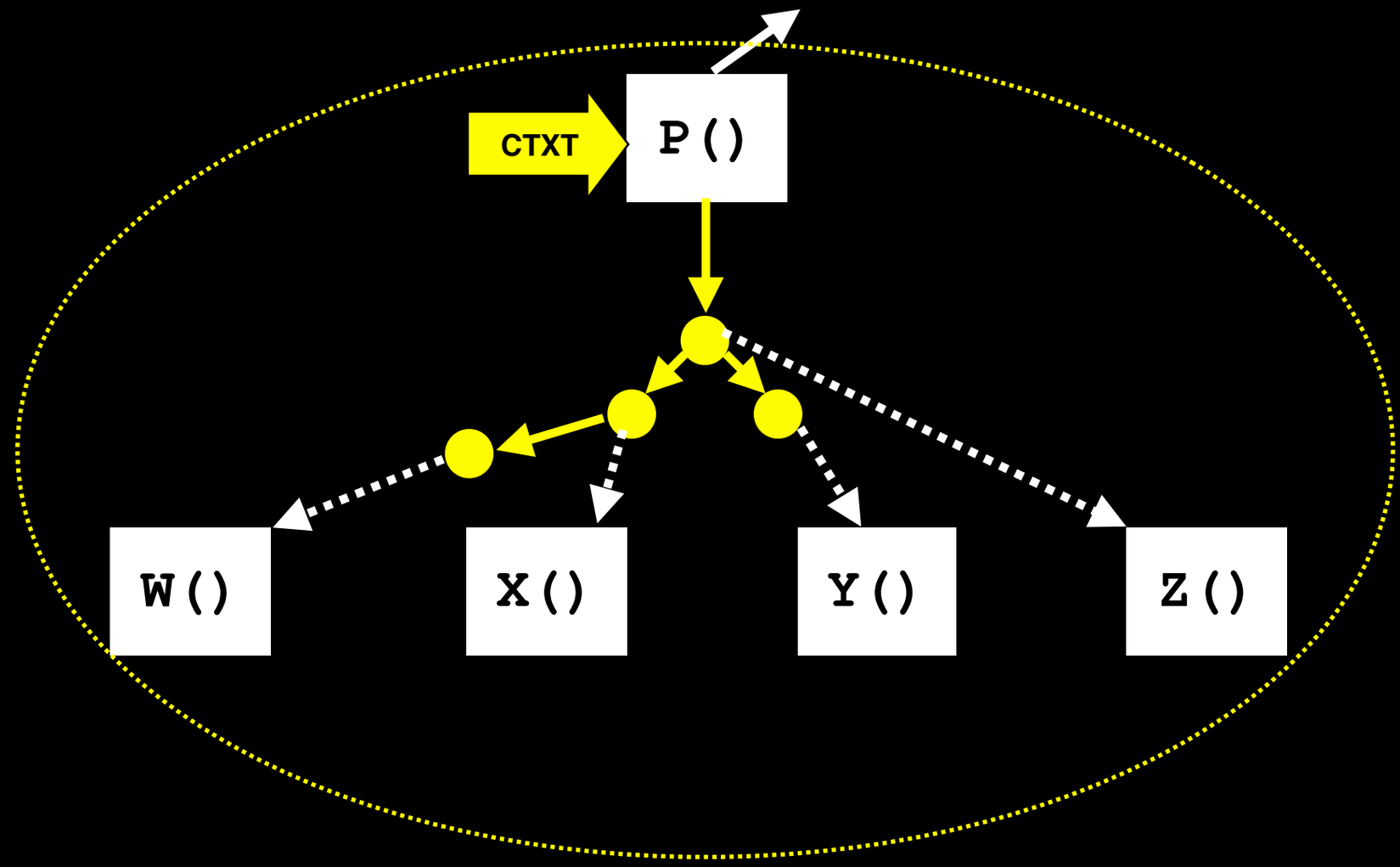

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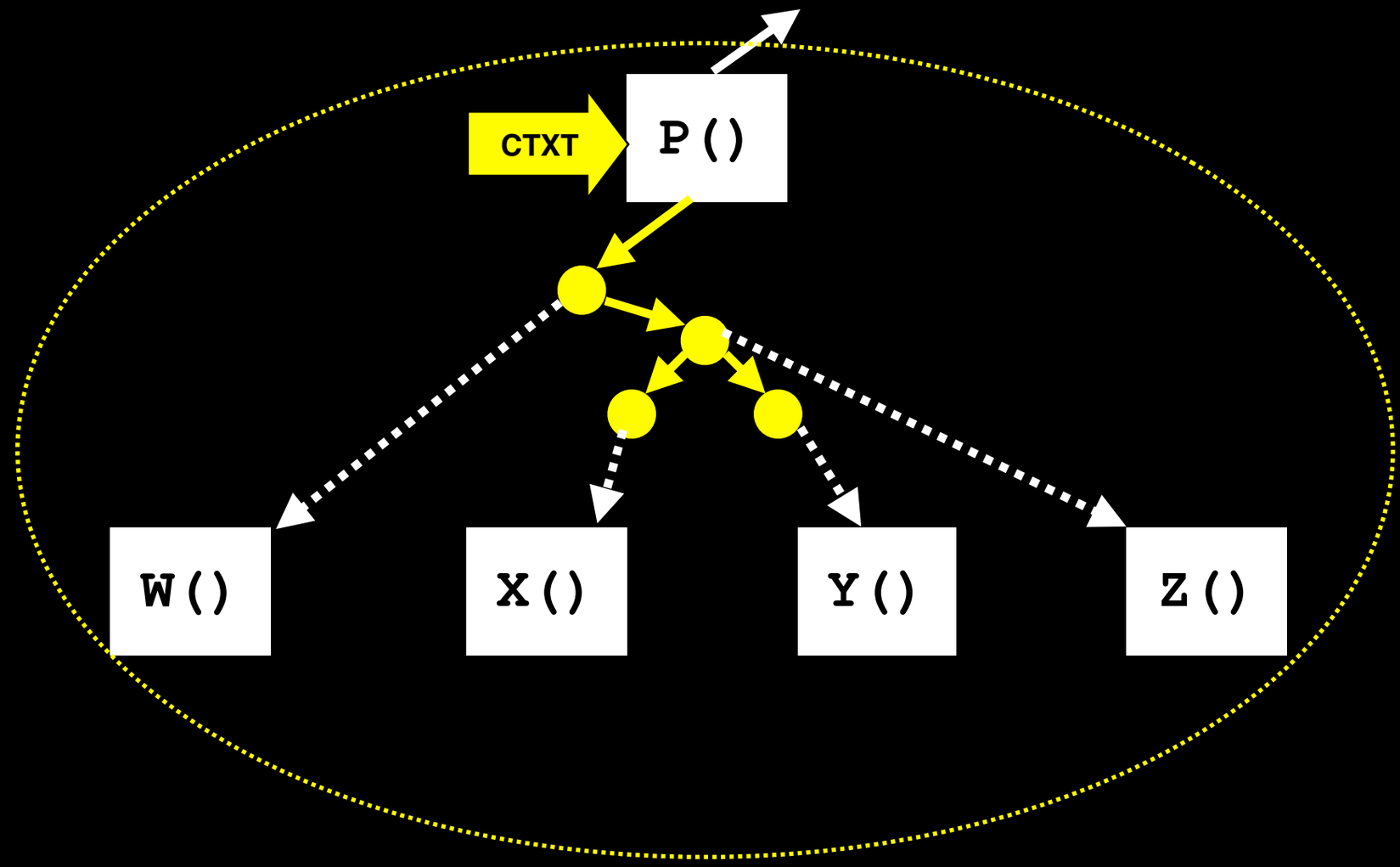

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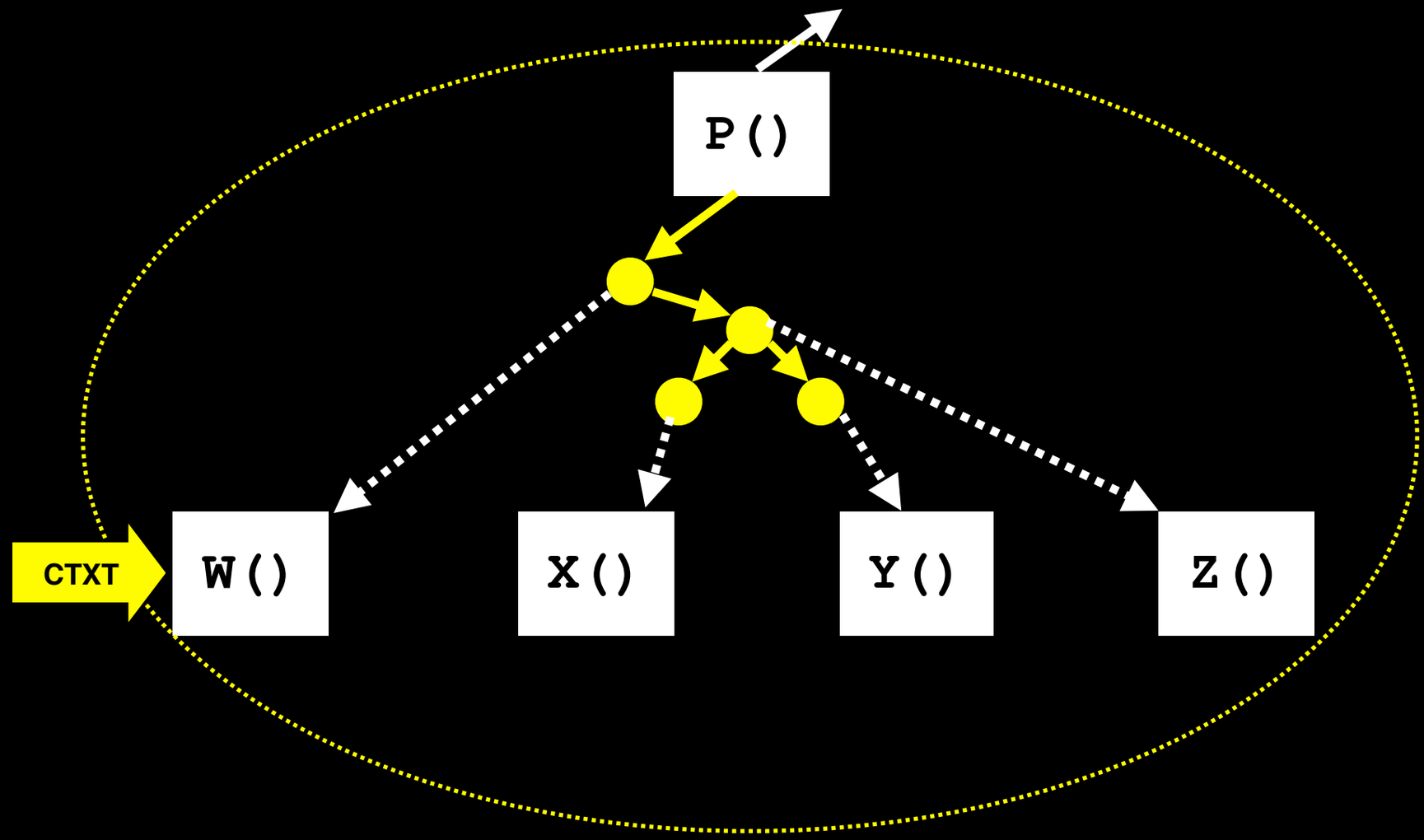

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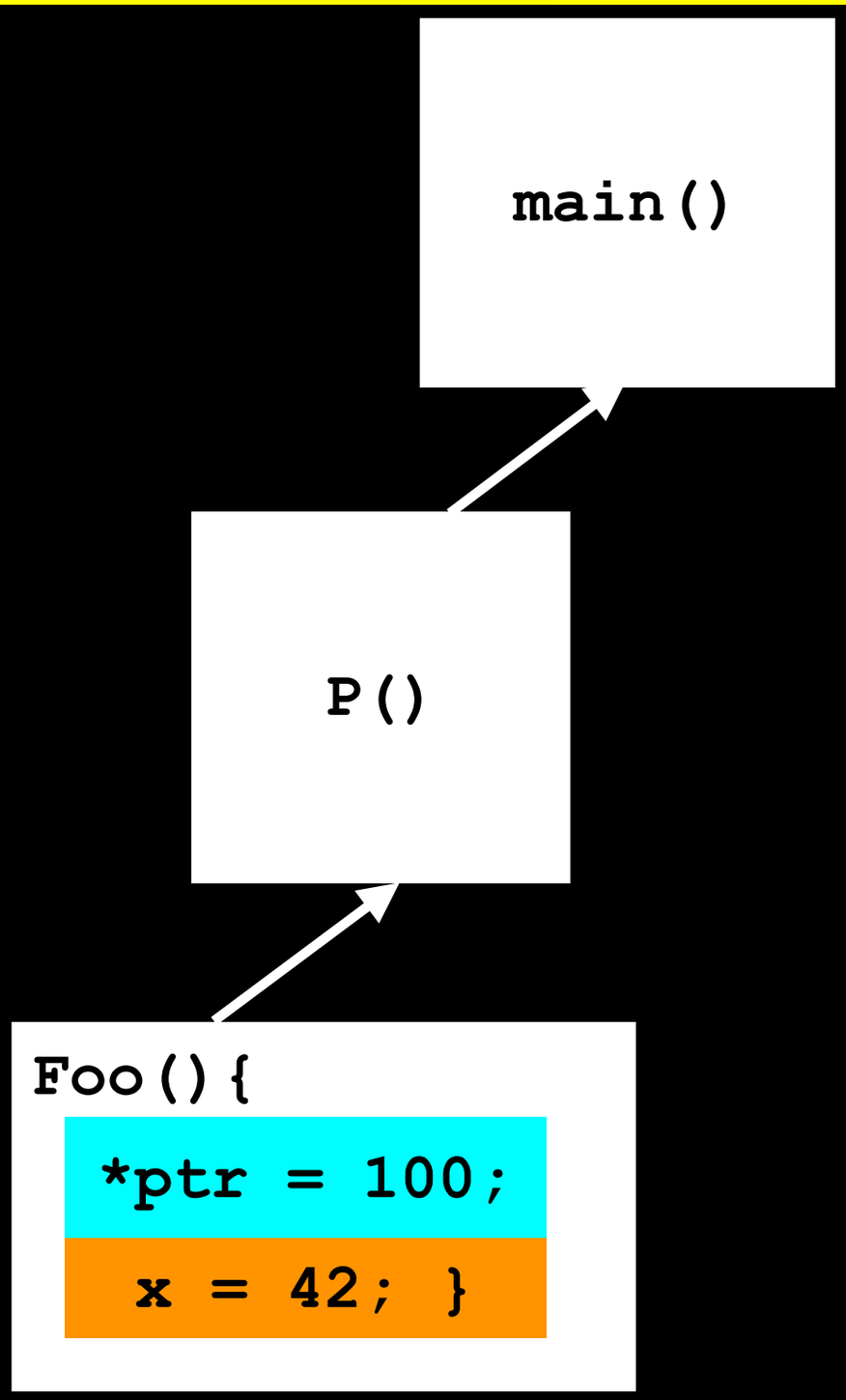

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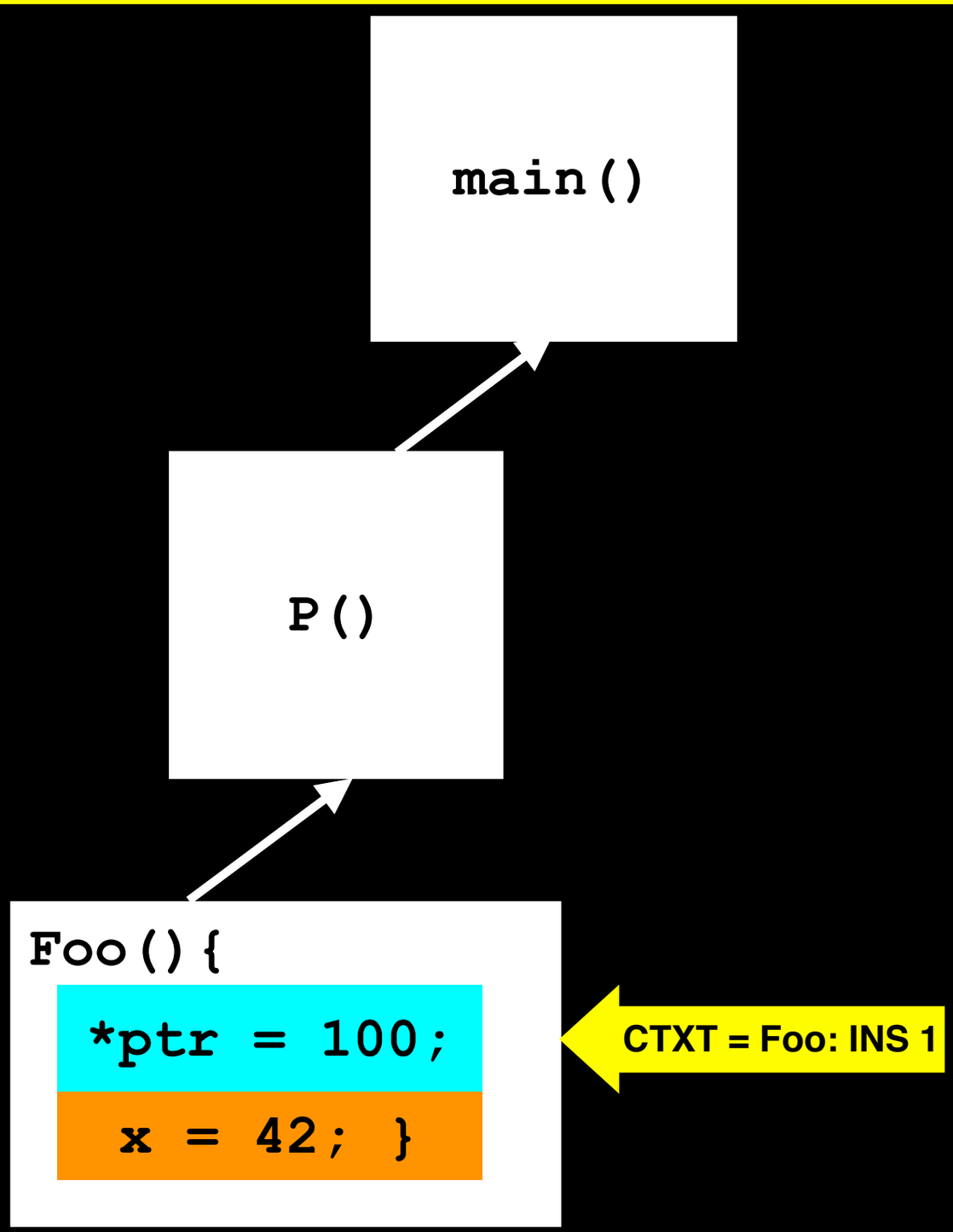

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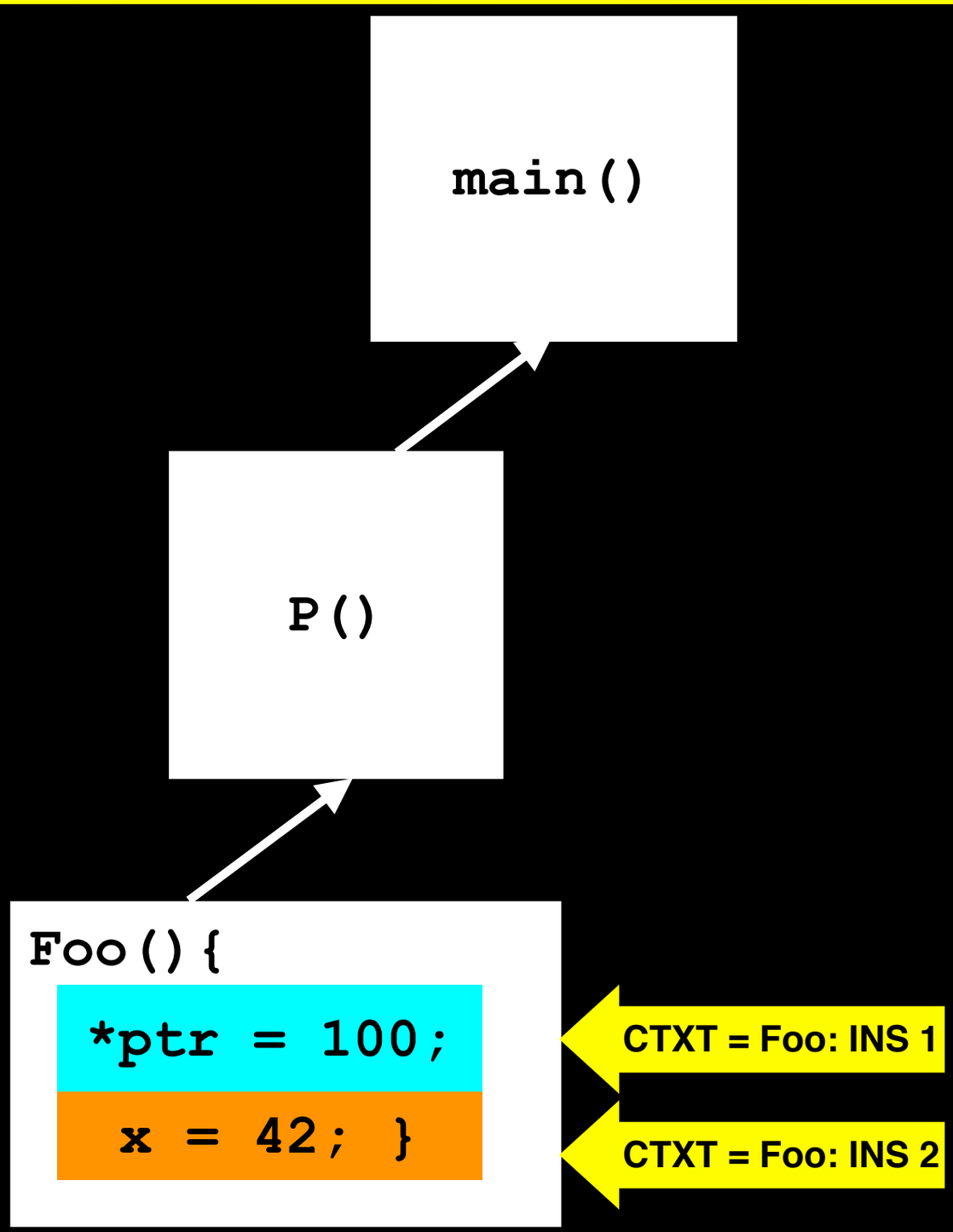

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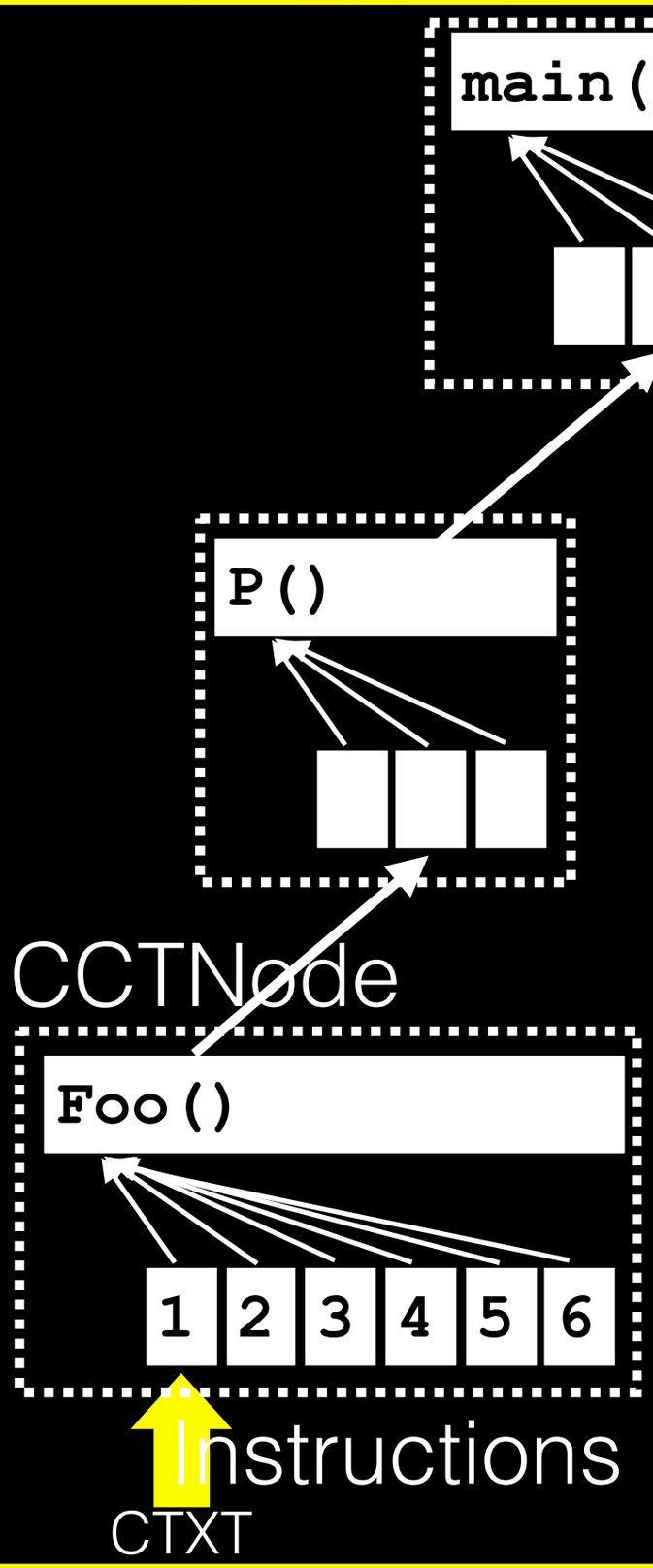

A CCT node represents a *Pin trace*

- CCTLib maintains *node* → *Pin trace* mapping
- Each slot in a node represents an instruction in a *Pin trace*

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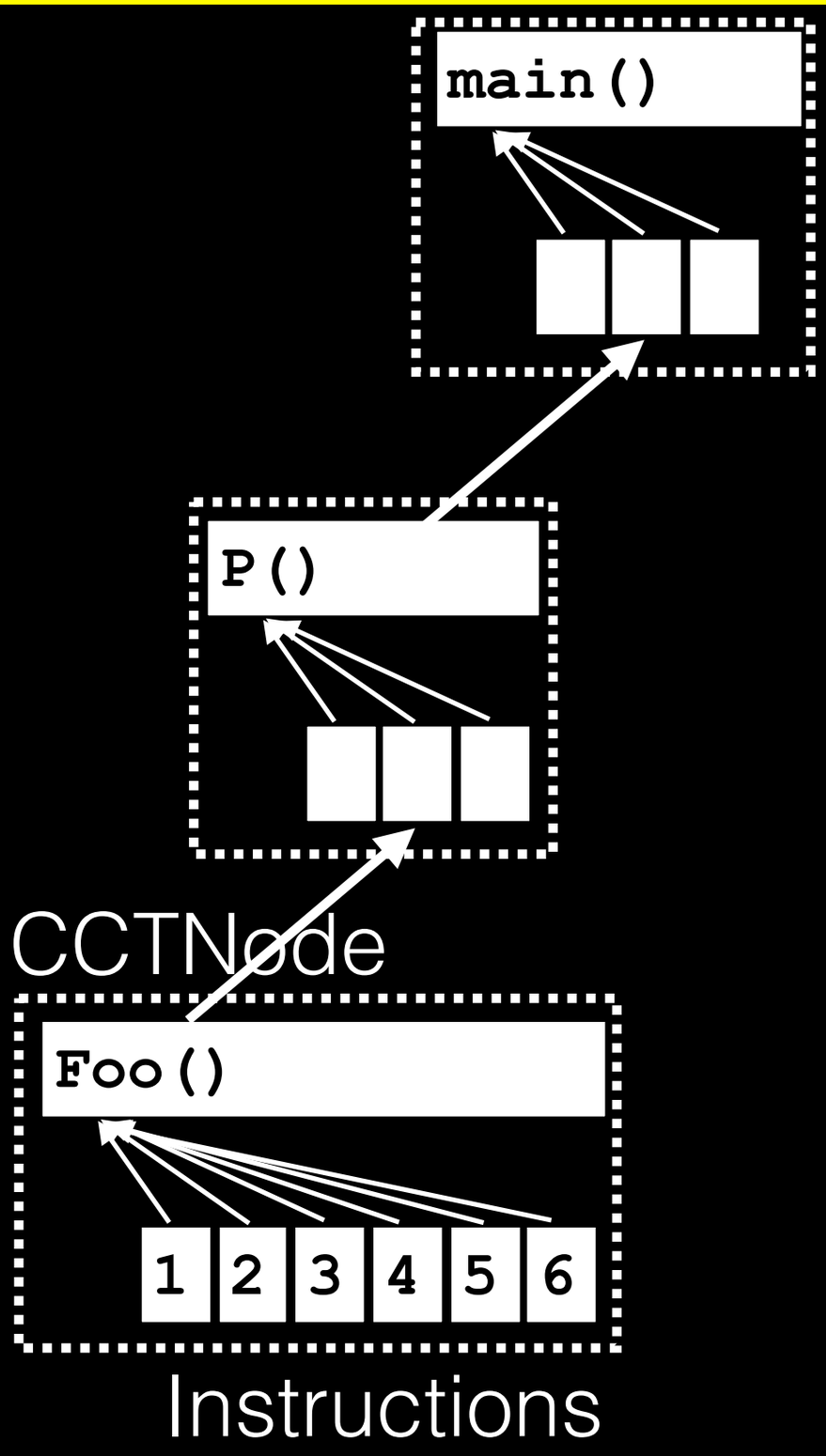

- Problem: Mapping *IP* to *Slot* at runtime
  - ✦ Variable size x86 instructions
  - ✦ Non-sequential control flow
- Solution:
  - ✦ Pin's *trace-instrumentation* to hardwire *Slot#* as argument to context query routine for an *IP*
- Result:
  - ✦ Constant time to query CTXT

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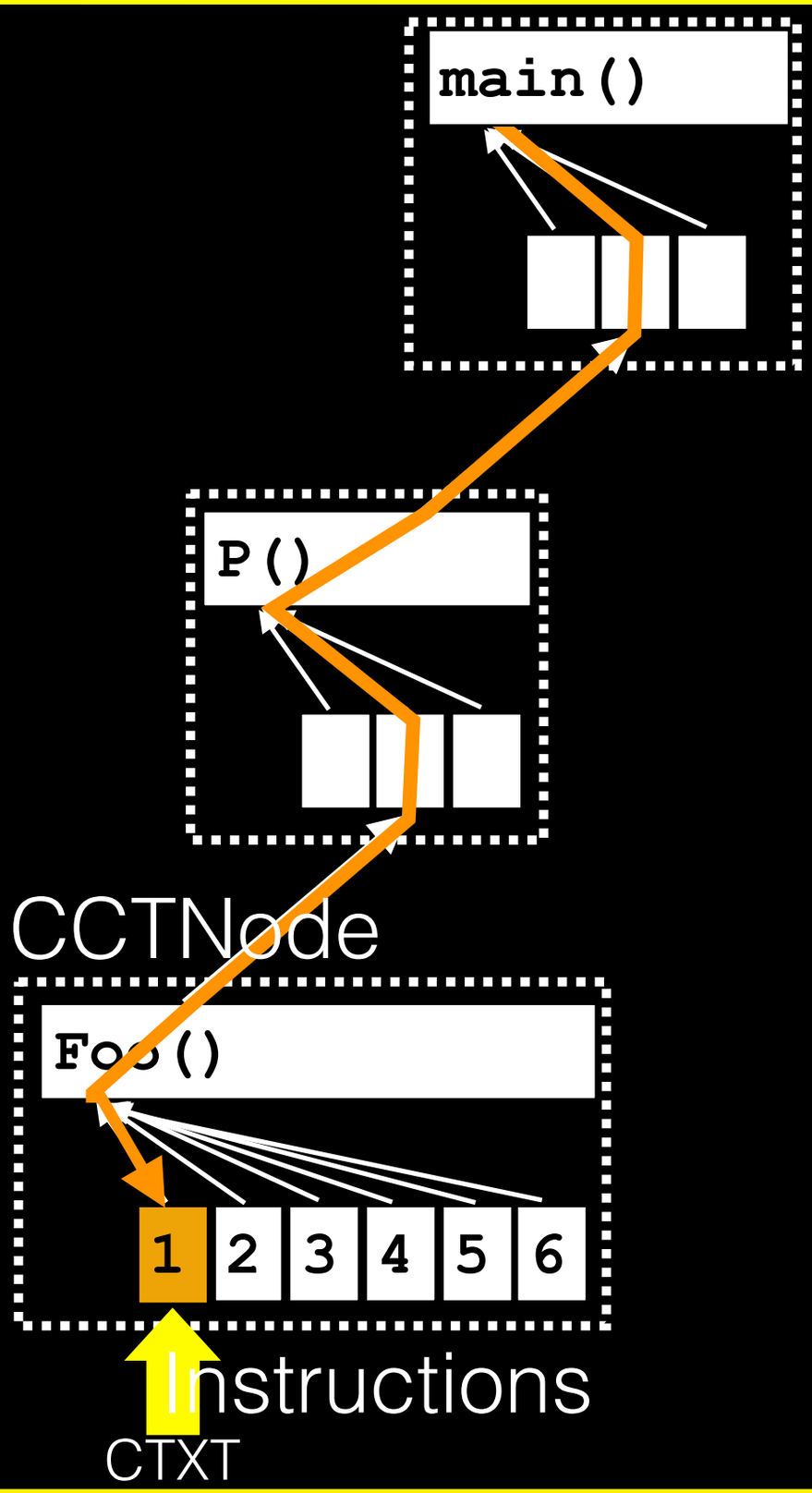

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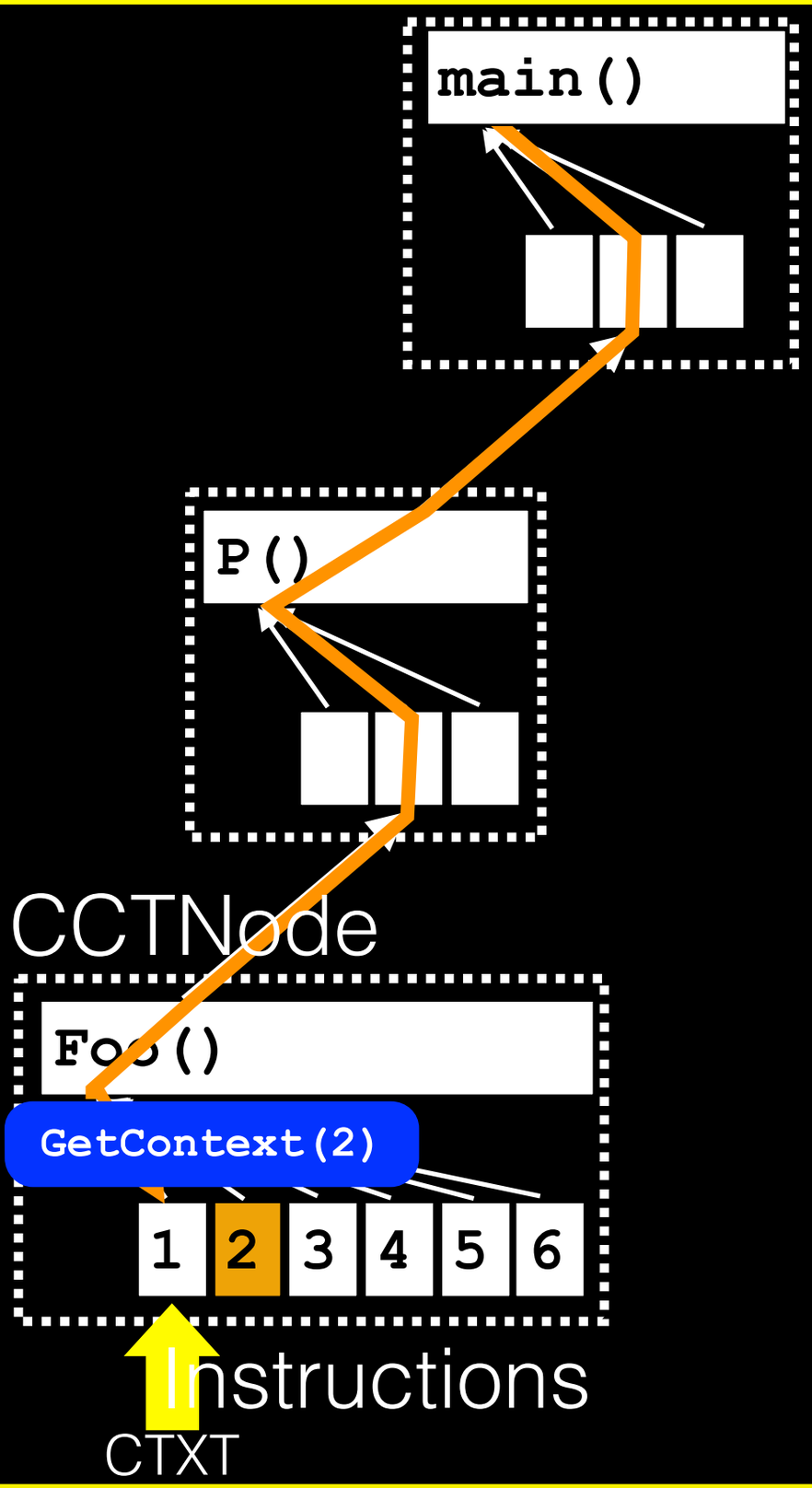

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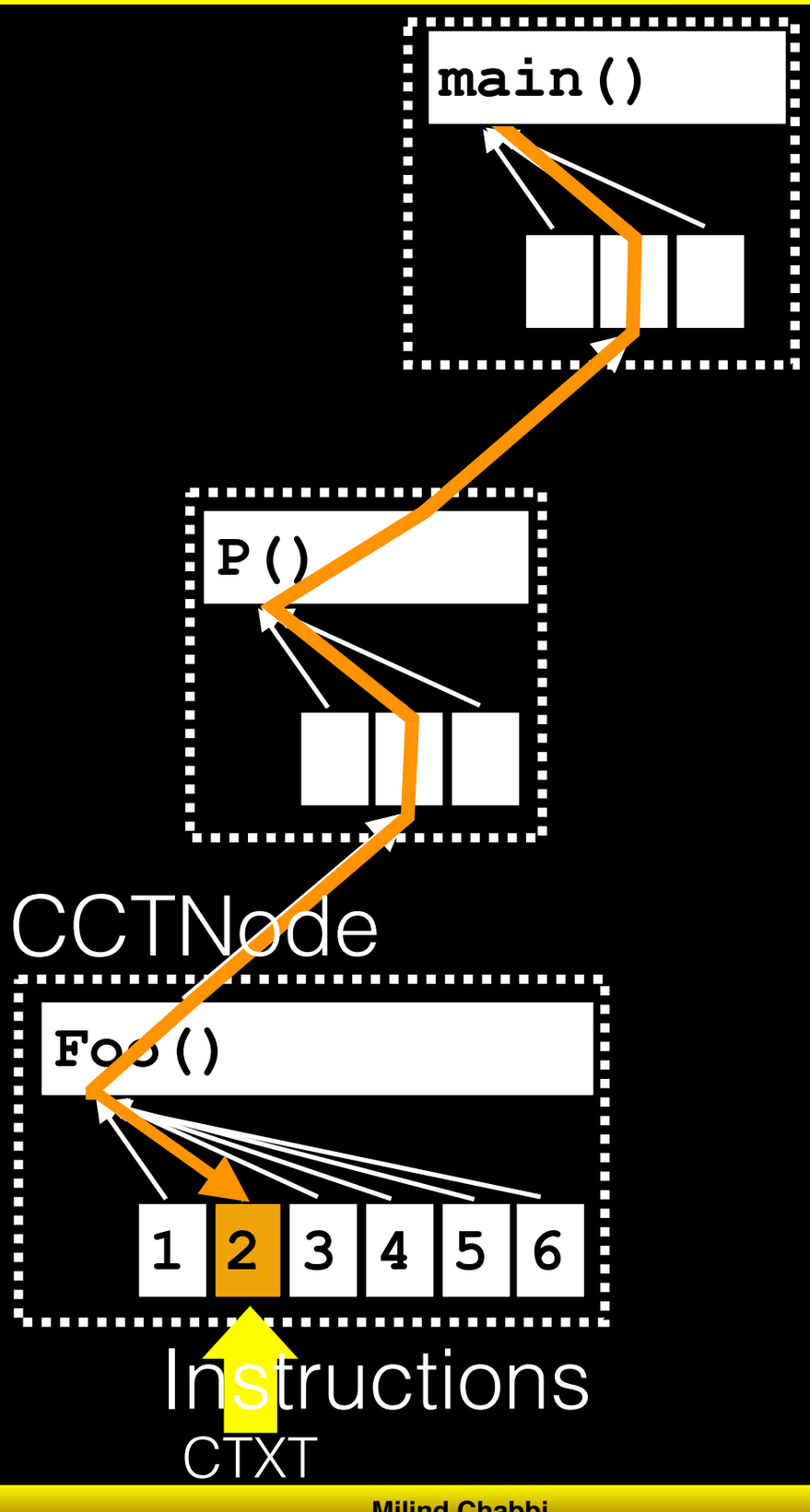

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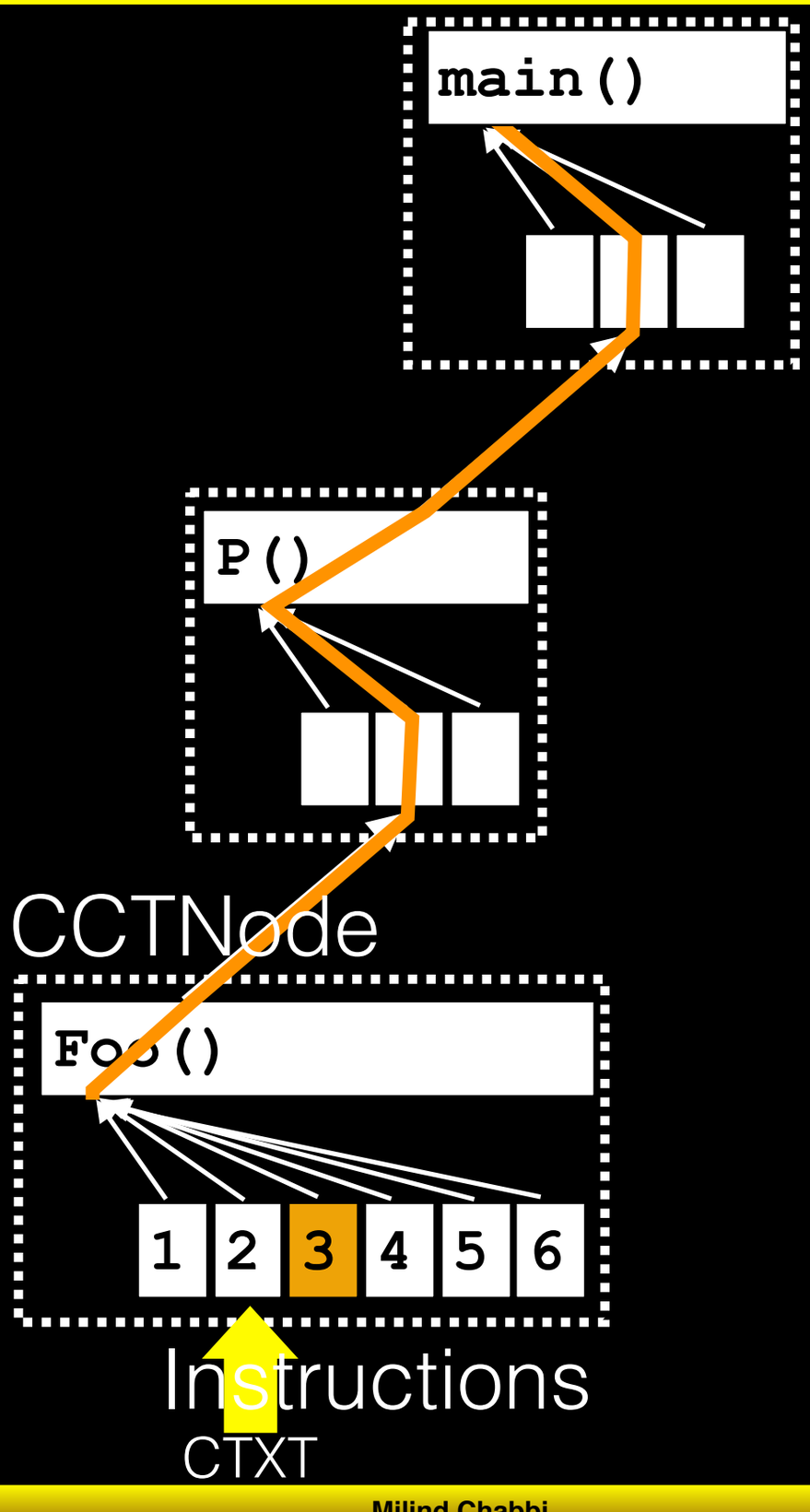

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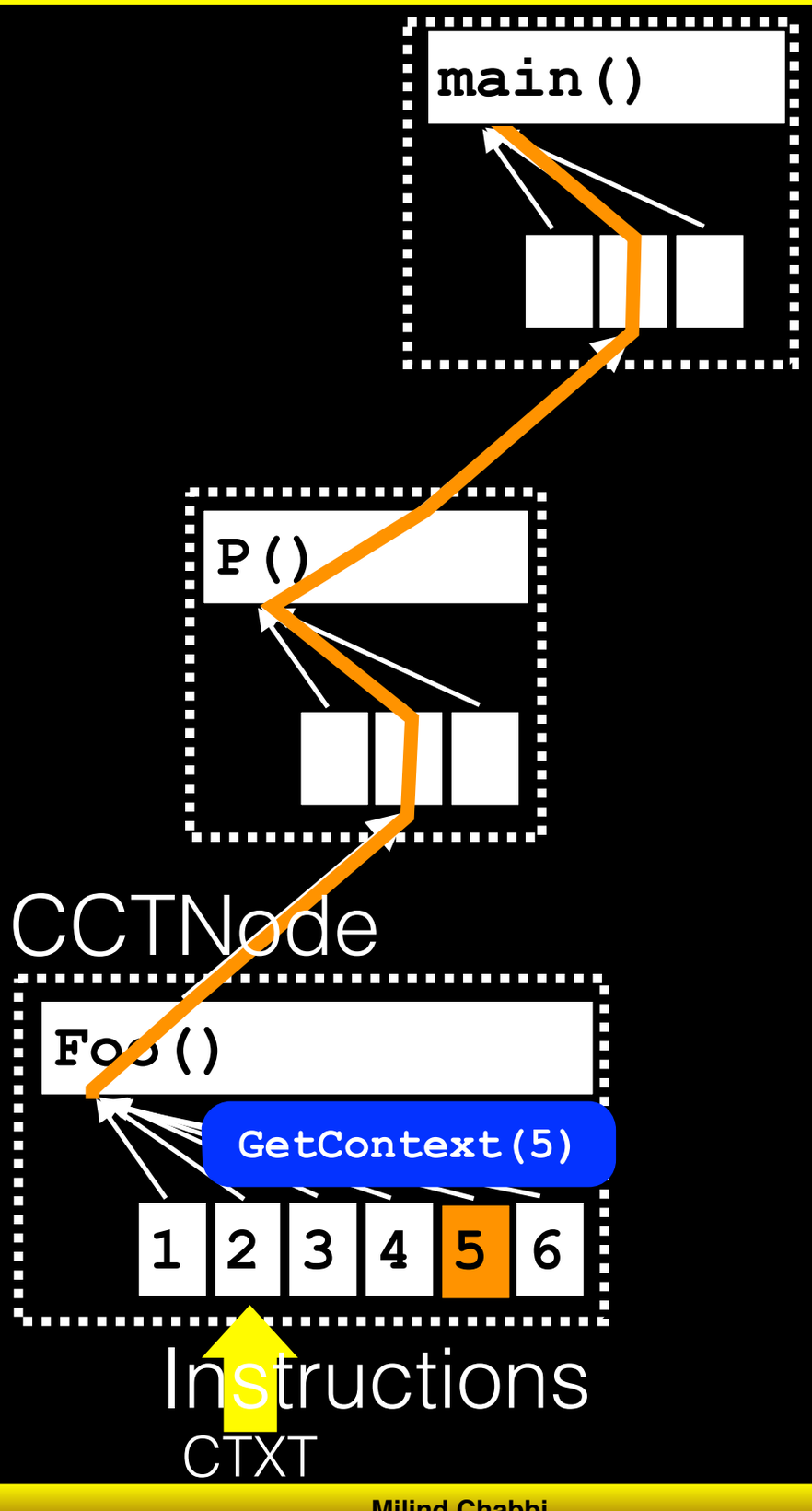

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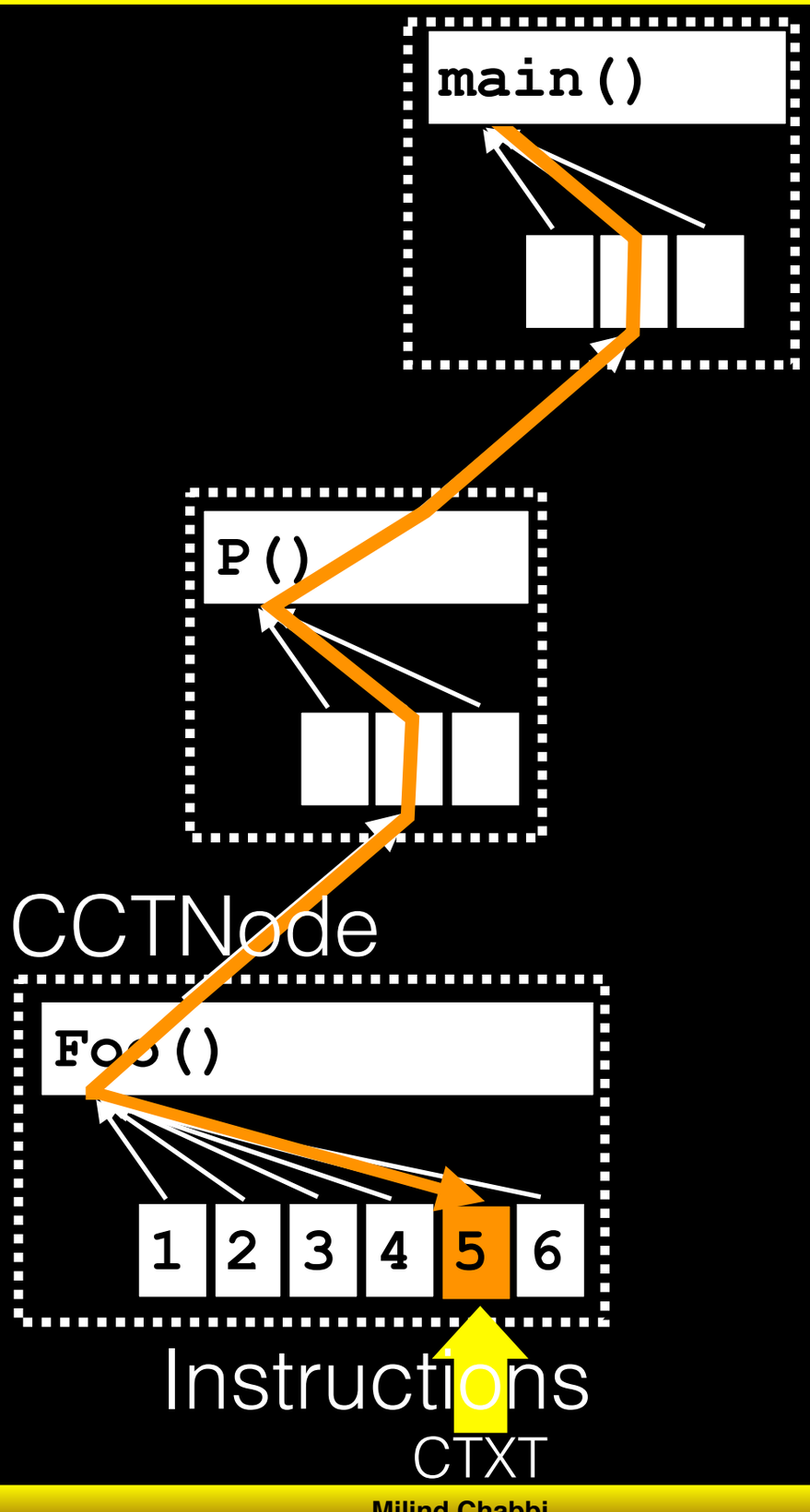

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Roadmap

CCTLib

- Ubiquitous call path collection
- Attributing costs to data objects
- Evaluation
- Conclusions

Data-Centric Attribution in CCTLib

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int MyArray[SZ];

int * Create(){
   return malloc(…);
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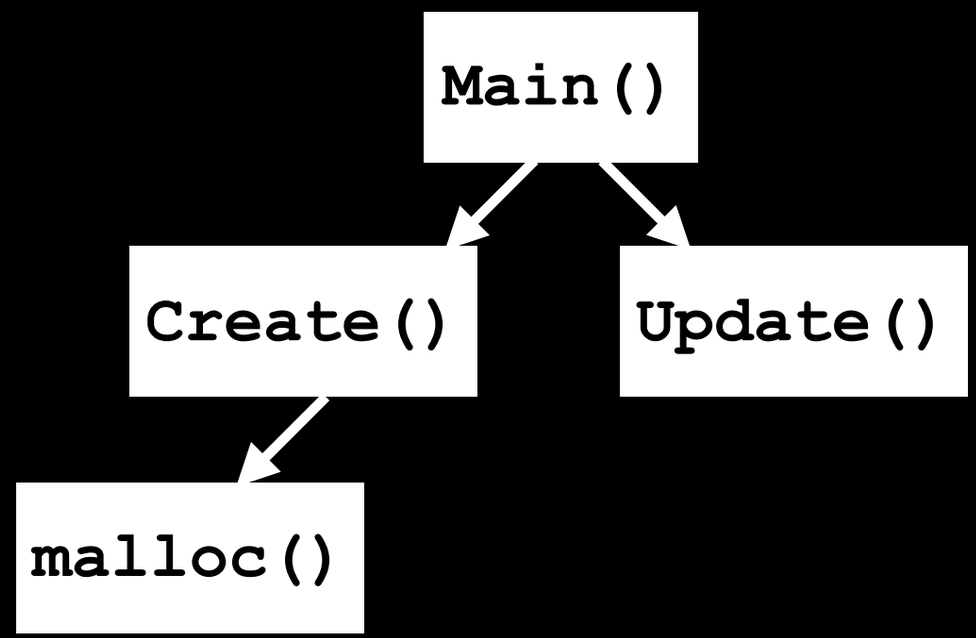

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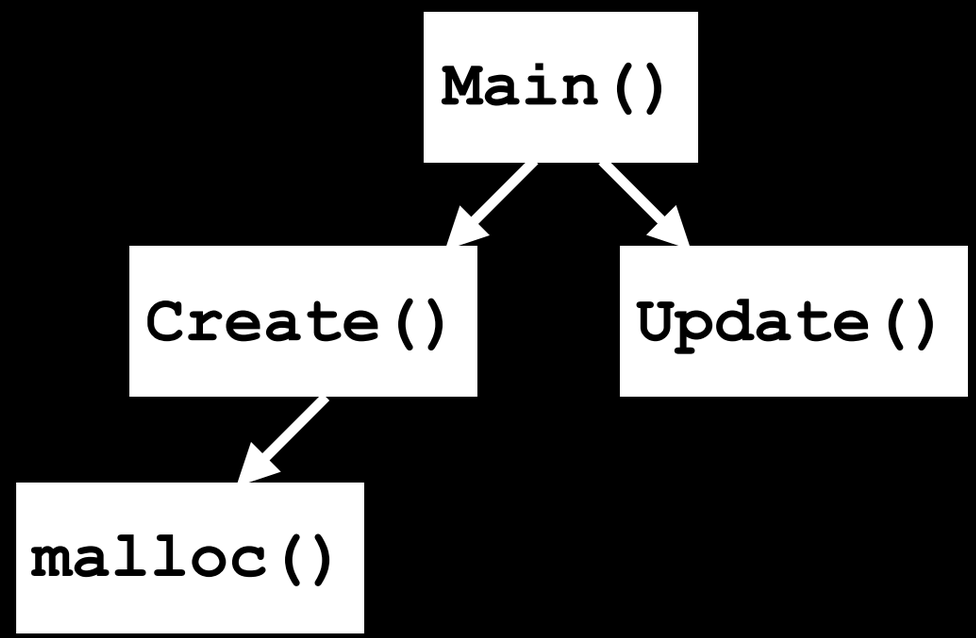

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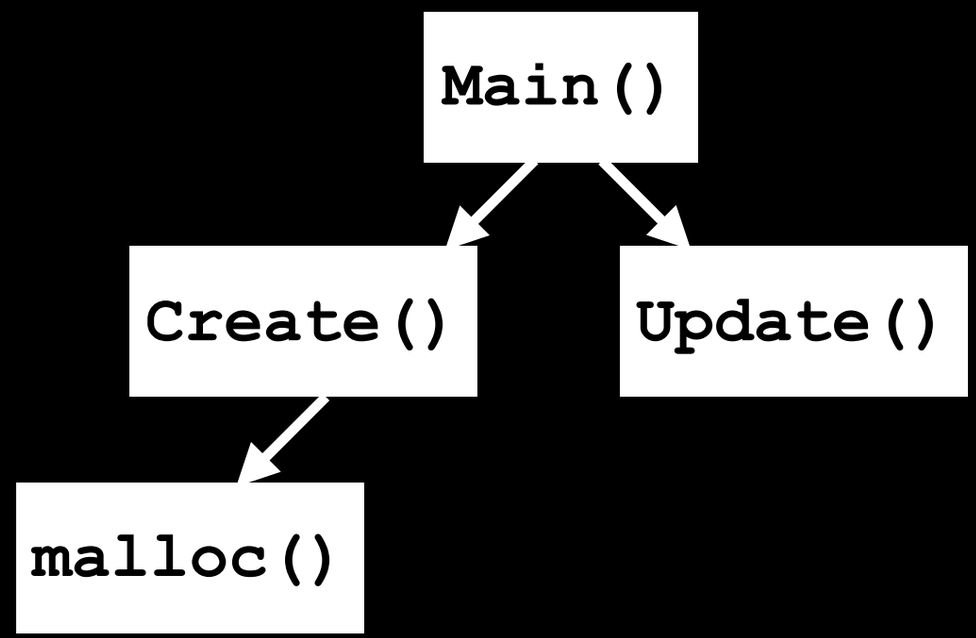

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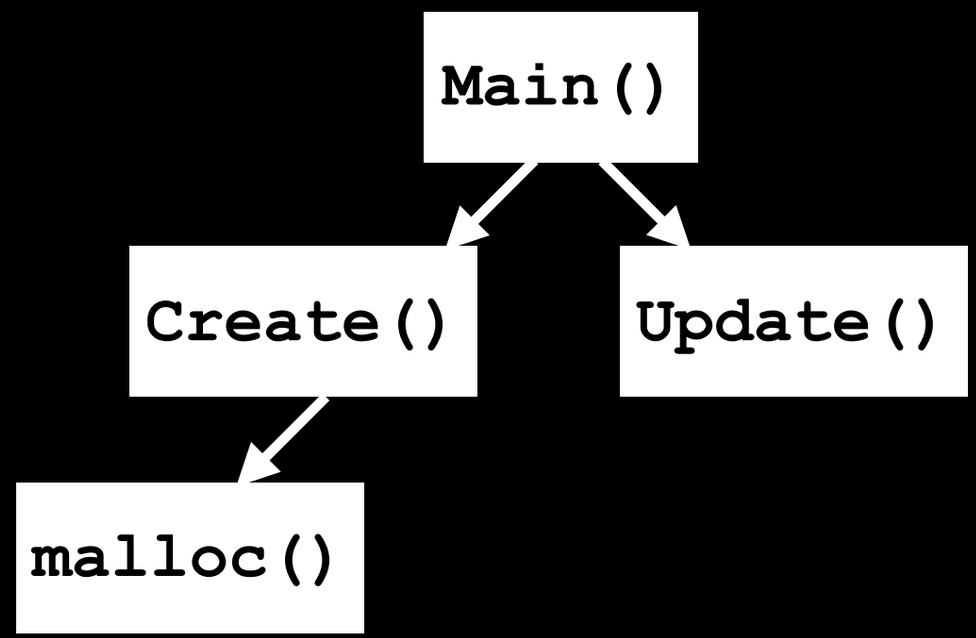

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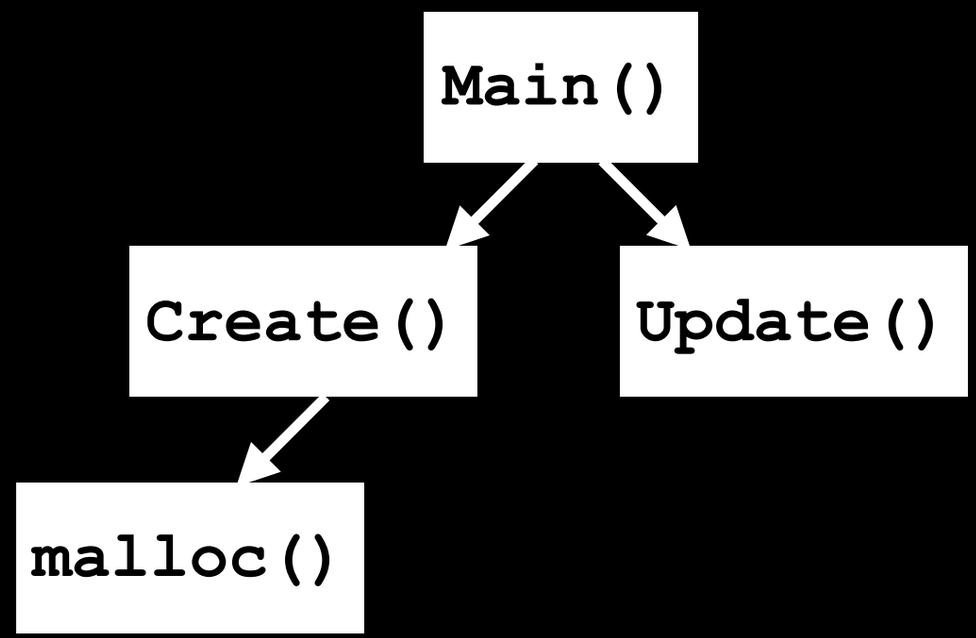

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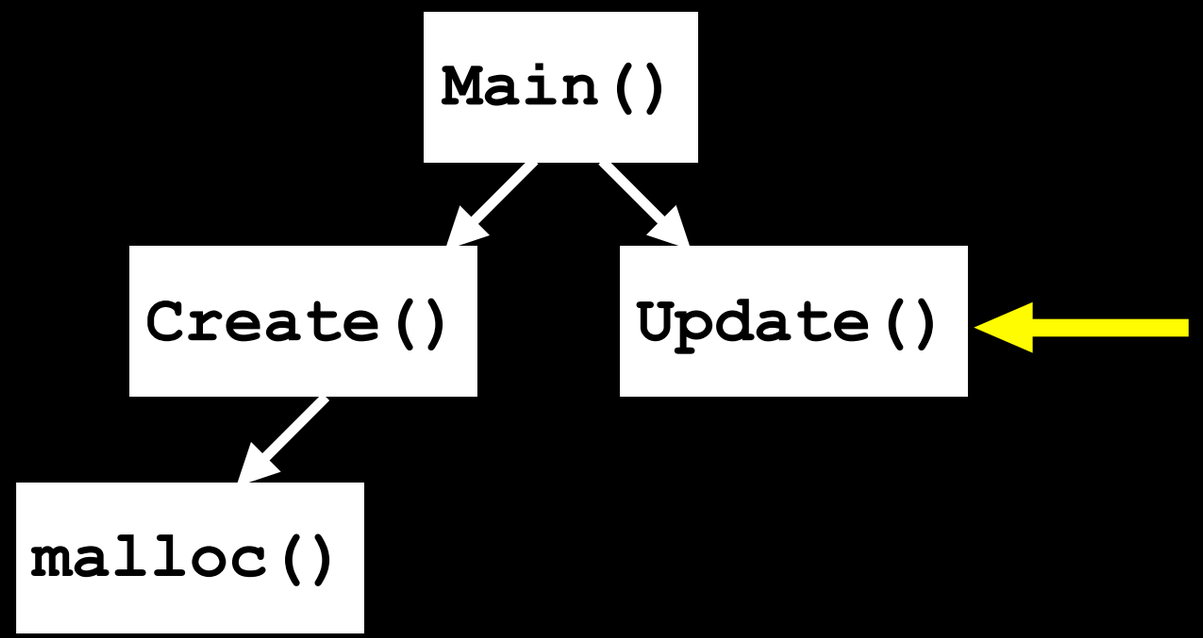

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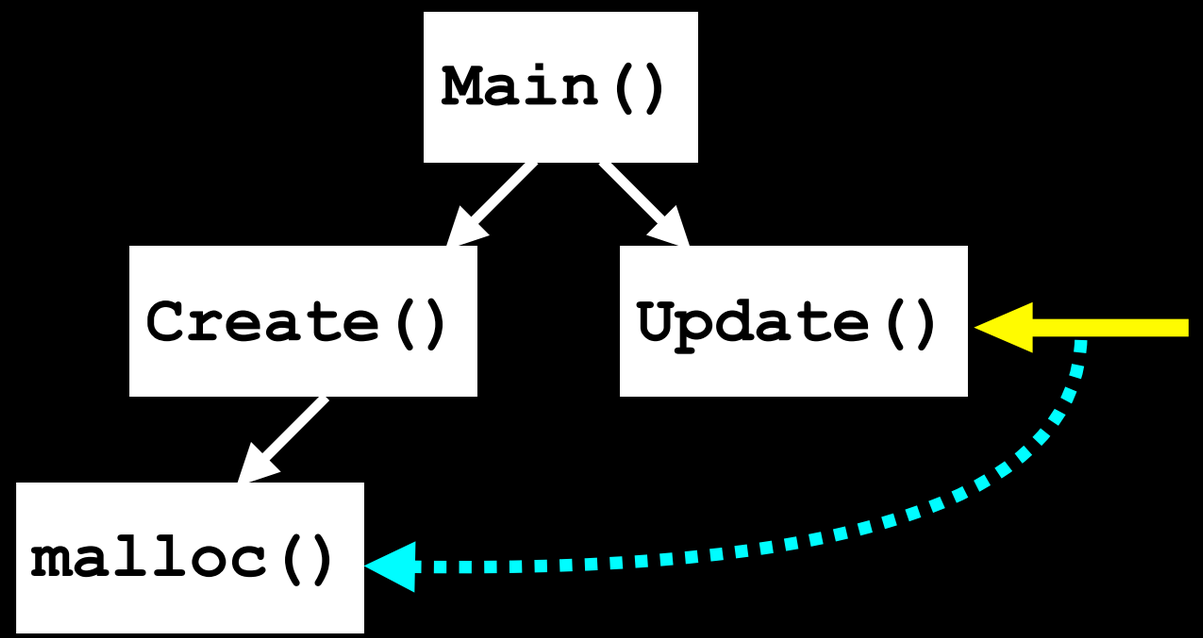

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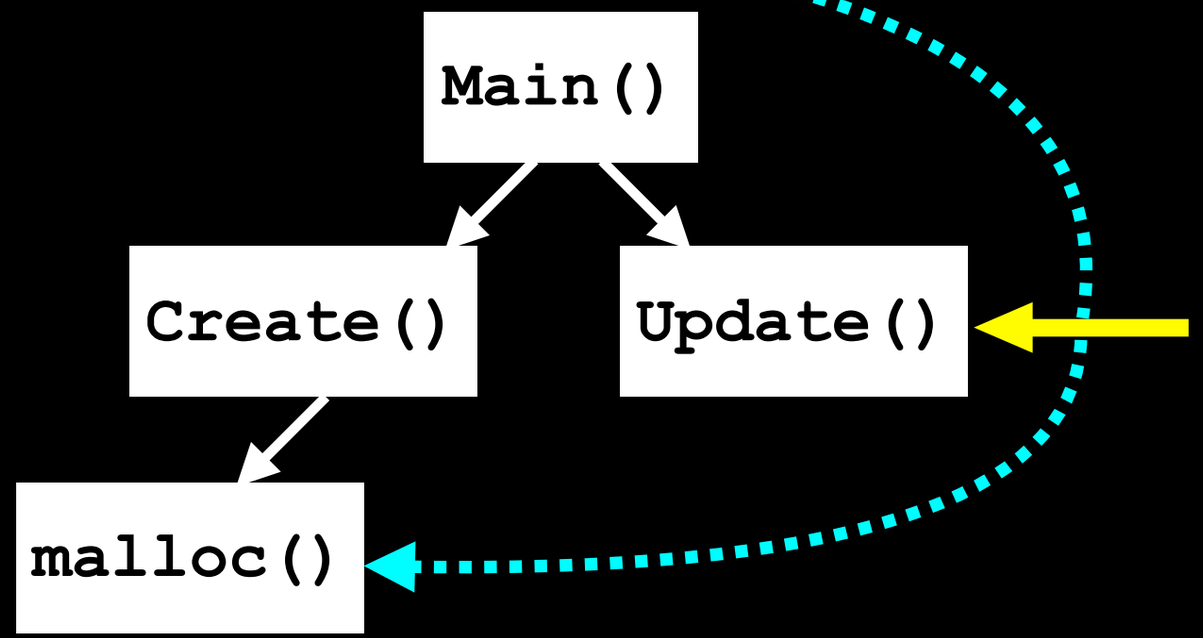

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Data-Centric Attribution

- How ?
  - ✦ Record all **<AddressRange, VariableName>** tuples in a map
  - ✦ Instrument all allocation/free routines and maintain **<AddressRange, CallPath>** tuples in the map
    - ✦ At each memory access: search the map for the address
- Problems
  - ✦ Searching the map on each access is expensive
  - ✦ Map needs to be concurrent for threaded programs

Data-Centric Attribution using a Balanced Tree

- Observation:
  - ✦ Updates to the map are infrequent
  - ✦ Lookups in the maps are frequent

- Solution #1: sorted map
  - ✦ Keep <AddressRange, Object> in a balanced binary tree
  - ✦ Low memory cost—O(N)
  - ✦ Moderate lookup cost—O(log N)
  - ✦ Concurrent access is handled by a novel replicated tree data structure

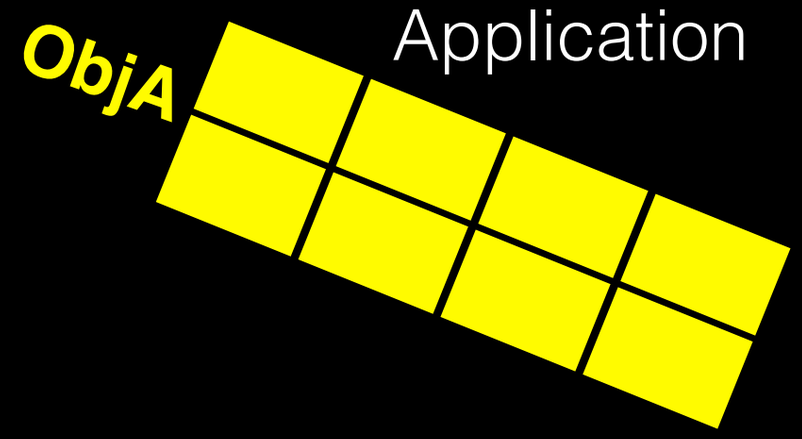
Data-Centric Attribution using Shadow Memory

- Solution #2: shadow memory

Application CCTLib

Data-Centric Attribution using Shadow Memory

- Solution #2: shadow memory



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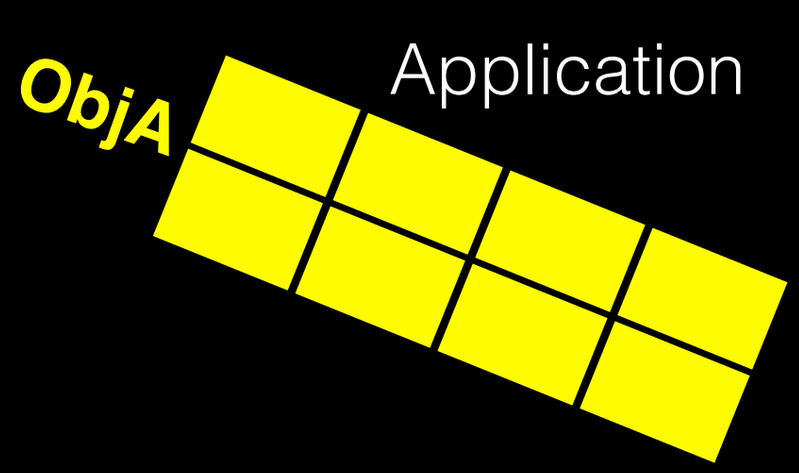

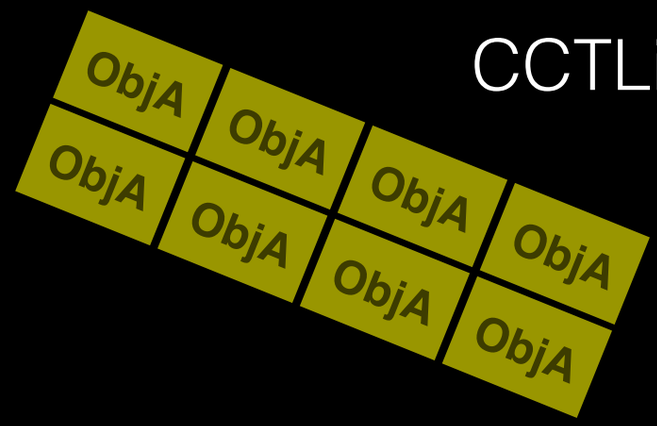

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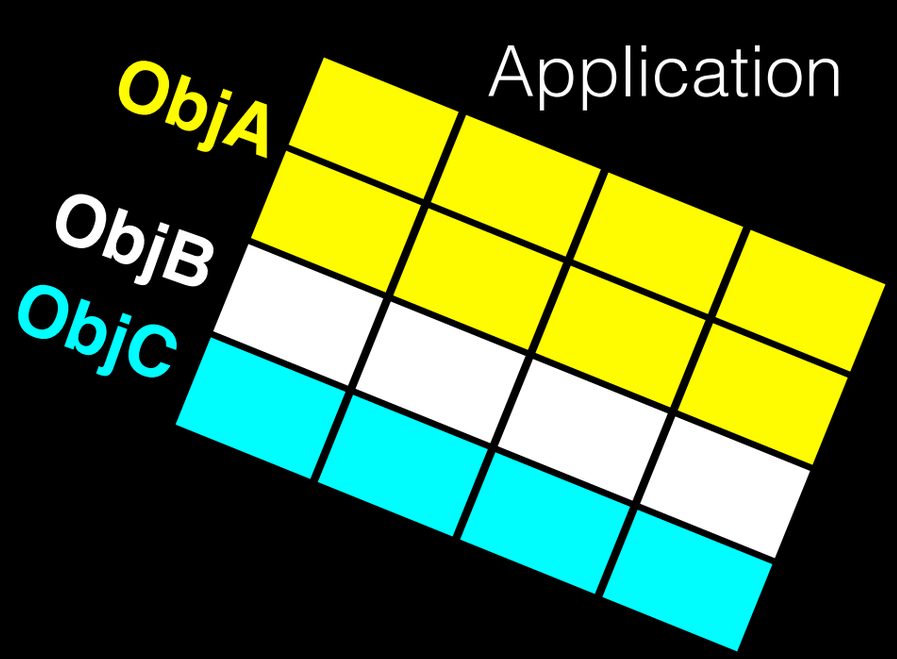

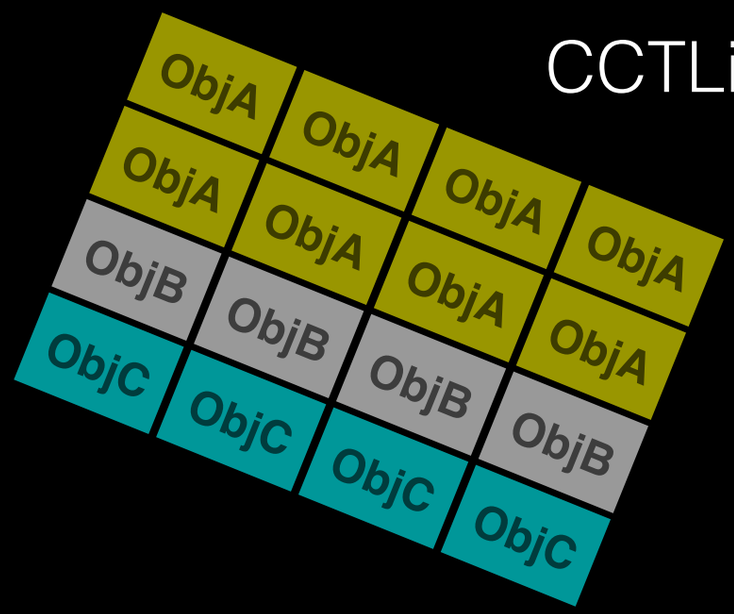

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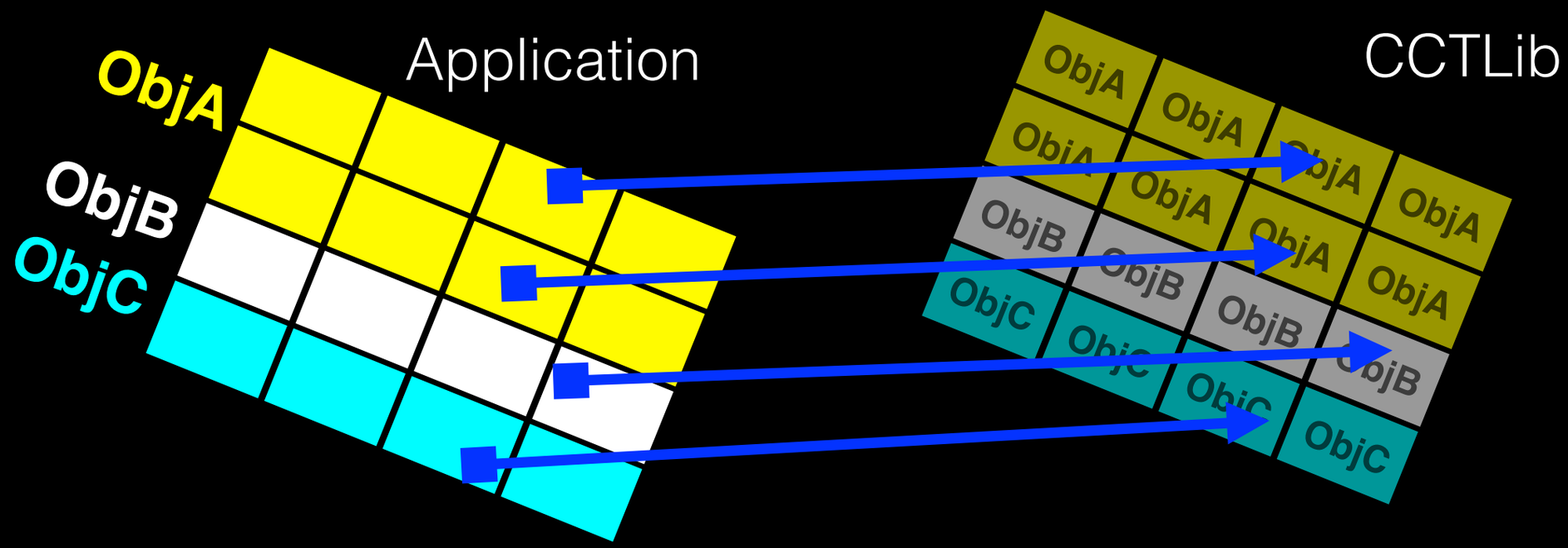

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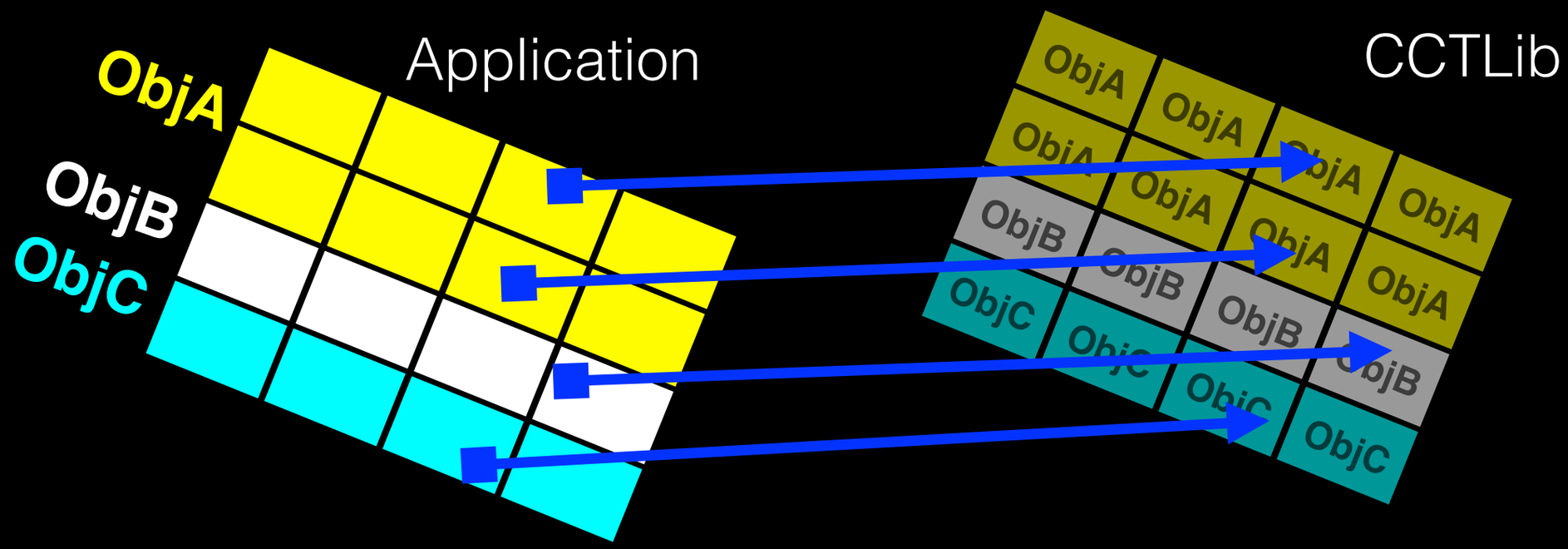

- For each memory cell, a shadow cell holds a handle for the memory cell's data object
  - ✦ Low lookup cost—O(1), high memory cost— $O(\sum_{i=1}^{N} sizeof(Obj(i)))$
  - ✦ Shadow memory supports concurrent access
- CCTLib supports both solutions, clients can choose

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Evaluation

Program	Running time in sec
astr	361
bzip2	161
gcc	70
h264ref	618
hmmer	446
libquantum	462
mcf	320
omnetpp	352
Xalan	295
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Experimental setup:

- 2.2GHz Intel Sandy Bridge
- 128GB DDR3
- GNU 4.4.6 tool chain

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Spec Int 2006 reference benchmark

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Hydrodynamics mini-app from LLNL
Frequent data allocation and de-allocations
Memory bound
Multithreaded, Poor scaling

Overhead Analysis

	Call path collection
Time overhead relative to original program (Null Pin tool)	**30x**
Time overhead relative to simple instruction counting Pin tool	**1.7x**
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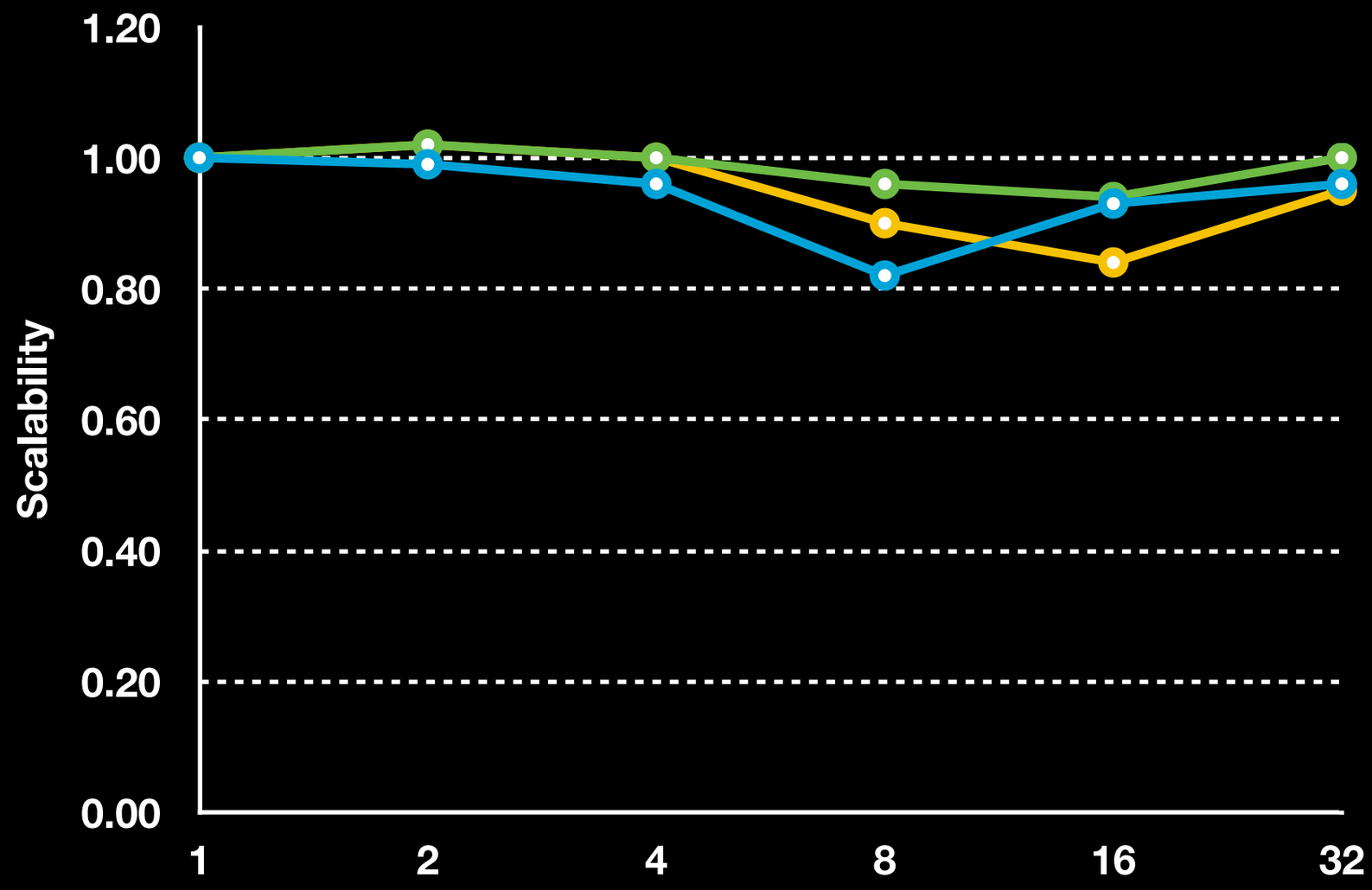
CCTLib Scales to Multiple Threads

CCTLib **overhead** of N threads: $\frac{E_{MON}(N)}{E_{ORIG}(N)}$

CCTLib **scalability** of N threads: $\frac{OVERHEAD(1)}{OVERHEAD(N)}$

Higher scalability is better, 1.0 is ideal

CCTLib scalability on LAMMPS



- Call path collection
- Data-centric attribution via Sorted maps
- Data-centric attribution via Shadow memoory

Conclusions

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- Ubiquitous calling context collection was previously considered prohibitively expensive
- Fine-grain attribution of metrics to calling contexts and data objects is practical
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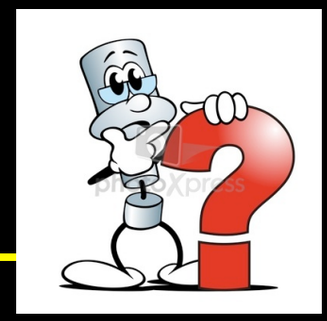

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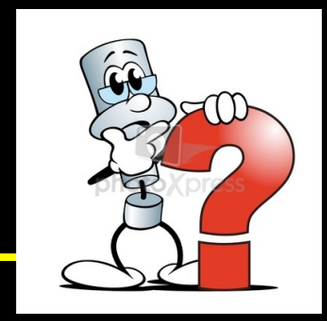

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http://code.google.com/p/cctlib/

Other Complications in Real Programs

- Complex control flow
  - ✦ Signal handling
  - ✦ Setjmp-Longjmp
  - ✦ C++ exceptions (try-catch)
- Thread creation and destruction
  - ✦ Maintaining parent-child relationships between threads
  - ✦ Scalability to large number of threads