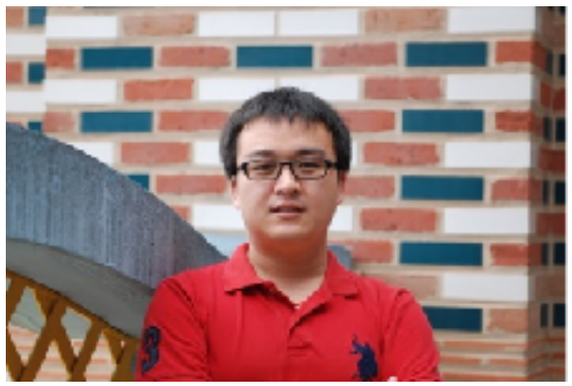
CCTLib: Pinpointing Software Inefficiencies with Fine-grained Program Monitoring

Milind Chabbi

Shasha Wen

Xu Liu

Who Are We?



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Introduction

Importance of Code Efficiency

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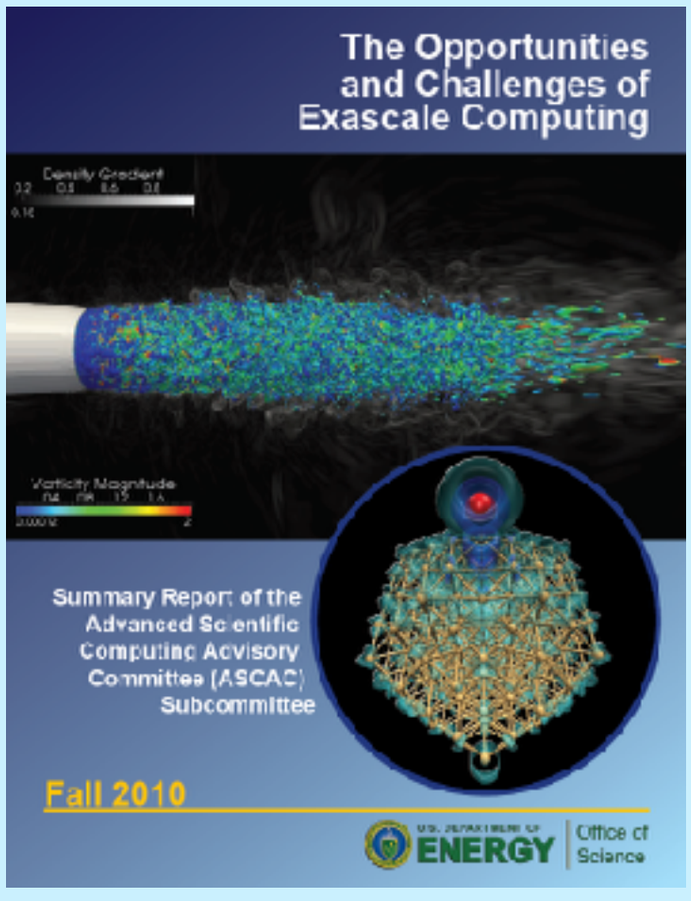

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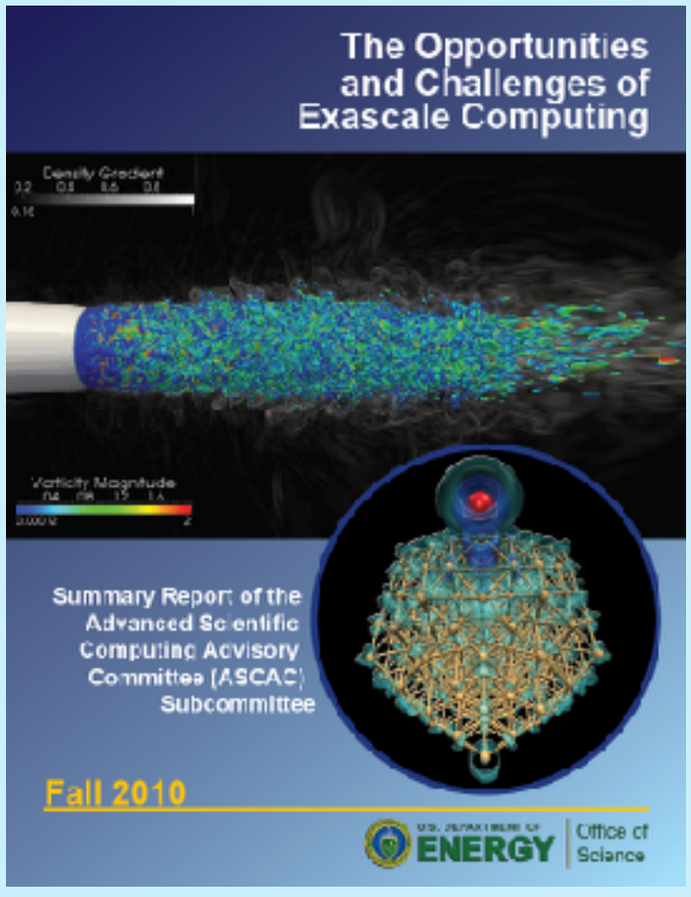

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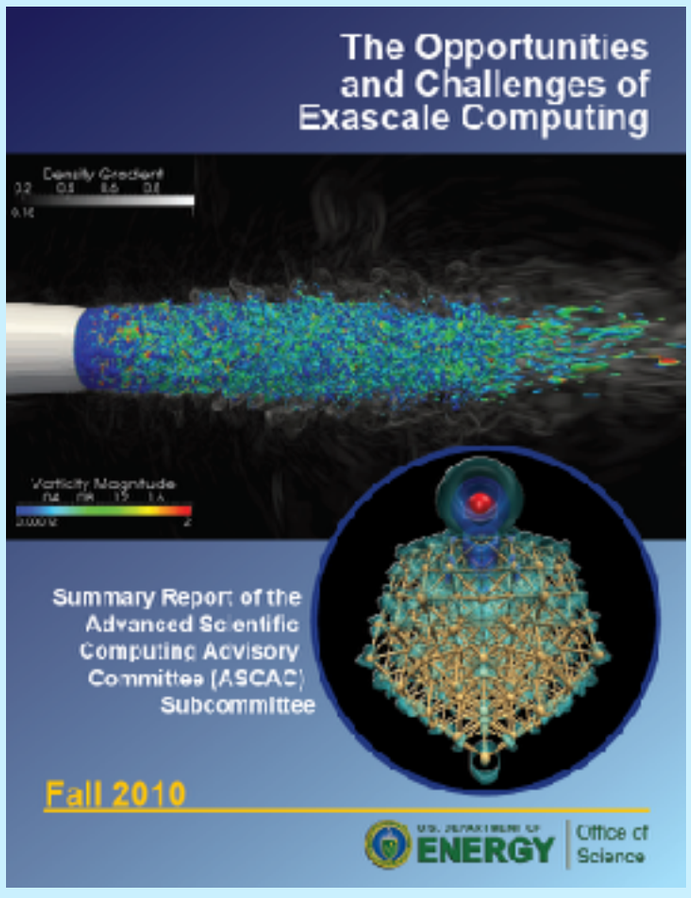

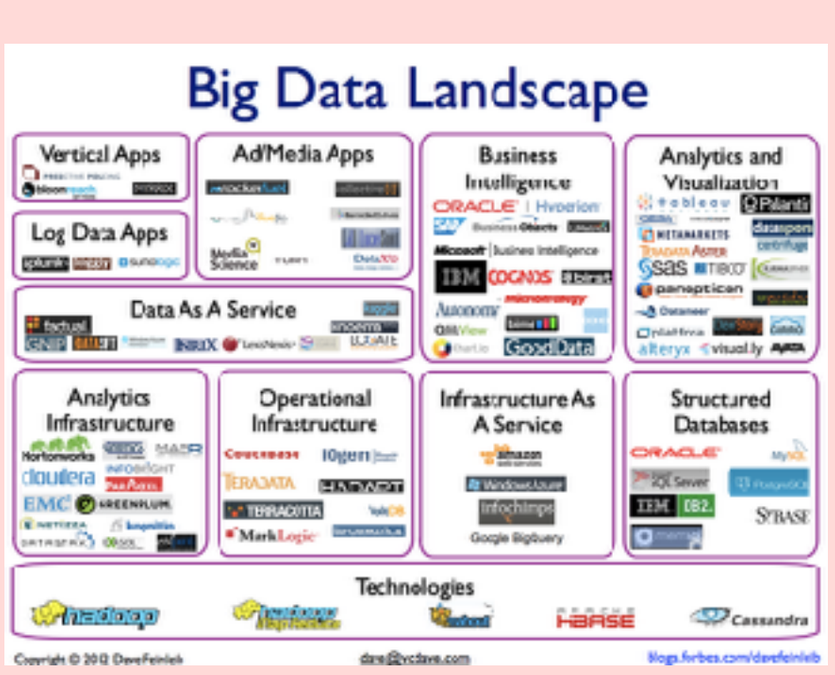

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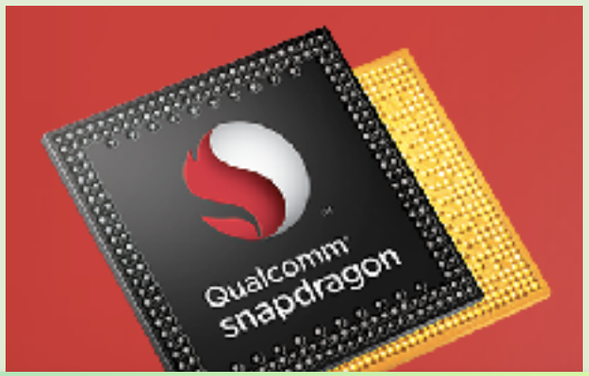
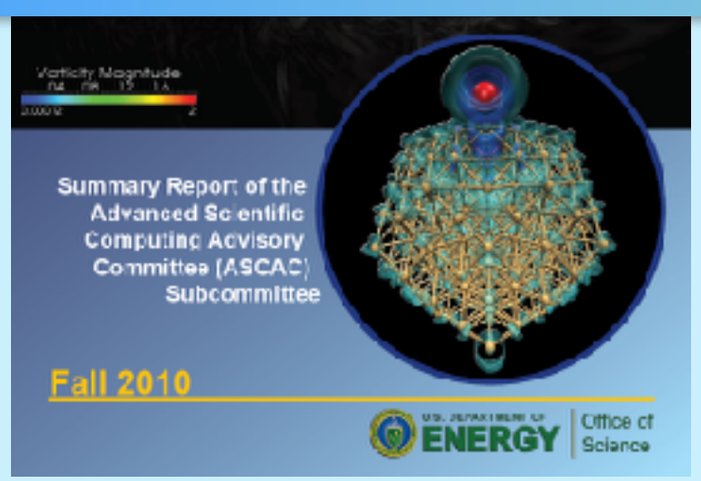


Programs need to be efficient at all scales



Sources of Performance Bottlenecks

- Code design
  - Algorithms
  - Data structures
- Programming practice
  - Aware of functionality but not performance
- Compiler optimization
  - Sometimes optimization may cause more harm than good
  - Code must be tailored to enable some optimization

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A tool set is necessary to pinpoint inefficiencies

Classical Performance Analysis

- Identify hot spots — high resource utilization
  - Time / CPU cycles
  - Cache misses on different levels
  - Floating point operations, SIMD
  - Derived metrics such as instruction per cycle (IPC)
- Improve code in hot spots
- Hot spot analysis is indispensable, but
  - Cannot tell if resources were **“well spent”**
  - Hot spots may be symptoms of performance problems
  - Need significant manual efforts to investigate root causes

From Resource Usage to Wastage

- Wasted data movement
  - Redundant memory accesses
    - Redundant stores: write same values to a memory location
  - Useless memory accesses
    - Dead stores: stored value got overwritten without use

- Wasted arithmetic computation
  - Symbolic equivalent computation
    - a=b+c; d=b+c
  - Result equivalent computation
    - a=b*b-c*c; d=(b+c)*(b-c)

- Unnecessary synchronization (locks and barriers)

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Need new profiling techniques
fine-grained profiling

HMMER: A Example for Resource Wastage

Unoptimized

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for (i = 1; i <= L; i++) {
  for (k = 1; k <= M; k++) {
      mc[k] = mpp[k-1] + tpmm[k-1];
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Declare as “restrict” pointers.
Can vectorize.

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> 16% running time improvement
> 40% with vectorization

Compilers Do NOT Eliminate All Inefficiencies

- Compilers have limitations with their static analysis
  - Aliasing and pointers
  - Limited optimization scopes: compilation units
  - Input-sensitive inefficiencies
  - Flow-sensitive inefficiencies

Coarse-grained Profilers Lack

- State-of-the-art coarse-grained profilers
  - Intel VTune
  - Rice HPCToolkit
  - Oracle Solaris Studio
  - ARM allinea

- Coarse-grained analysis
  - Sample instructions or events via hardware performance monitoring units (PMU)
    - One sample per 1M instructions
  - Do not track consecutive sequence of instructions or memory references —> cannot detect wasteful operations
  - Never capture semantic meaning of execution

Fine-grained Profiling

- Track each instruction
  - Operator
  - Operands
- Track each register
  - General registers
  - SIMD registers
- Track each memory location
  - Effective addresses
- Track each value in storage location
  - Value in registers
  - Value in memory
- One step closer to reconstructing the semantic meaning (or lack there of) in execution

HMMER Example

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2  add 0x0(%r13,%rax,4),%ecx #mpp[k-1]+tpmm[k-1]
3  mov %ecx, 0x4(%rdx)          #assign mc[k]
4  mov 0x18(%rsp),%rbx
5  mov (%r9,%rax,4),%r15d
6  add (%rbx,%rax,4),%r15d    #dpp[k-1]+tpdm[k-1]
7  mov   0x20(%rsp),%rbx
8  cmp   %ecx,%r15d           #%ecx is mc[k]
9  cmovge %r15d, %ecx
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dead store

Call Path Profiling for Fine-grained Analysis

- Associate problematic instructions with their call paths
  - ✦ Expose more semantic information about the instructions
  - ✦ Understand context-sensitive performance issues

- If no call path collected for fine-grained analysis
  - ✦ Do not provide root causes of the problem
  - ✦ Do not guide source code optimization

An Example: SPEC bwaves

A pair of redundant computation

movsdq 0x8(%rdi,%r10,8), %xmm0:__mul:<no src>

**************REDUNDANT WITH *************

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CCTLib: a framework that collects calling context for fine-grained profilers

CCTLib Overview

- Functionality
  - ✦ Can capture call path for each dynamic instruction
  - ✦ Can capture the data object read/written by each memory access
    - ✳ Heap data objects: call paths to the allocations
    - ✳ Static data objects: names from symbol table
- Programmability
  - ✦ APIs provide request-based service for clients
- Overhead
  - ✦ Moderate overhead in both runtime and space

CCTLib Software

- git clone https://github.com/CCTLib/cctlib.git
  - Supported on x86_64 linux, gcc > 4.8.2
  - Pin 3.0 not yet supported.
- cd cctlib
- sh build.sh

```
PIN ROOT is NOT set!
+ echo   (1) Download Pin from the WWW and automatically set PIN_ROOT?
  (2) Enter PIN_ROOT in the commandline?
  (any key) Exit?
  (1) Download Pin from the WWW and automatically set PIN_ROOT?
  (2) Enter PIN_ROOT in the commandline?
  (any key) Exit?
```

- Choose (1)
- Successful installation will end with this message

```
**********************************************************
********** ALL TESTS PASSED **********
**********************************************************
```

CCTLib Software

- Distributed under MIT license

- Contact

  cctlib-forum@lists.wm.edu

Scale of Call Paths

	Description	Original program running for 10 minutes
Debuggers	On each break point	**$< 10^3$**
Performance analysis tools	On each sample (1 sample/ms)	**6×10^5**
Fine-grained instrumentation tools	On each instruction (2GHz CPU)	**1.2×10^{12}**

Challenges in Ubiquitous Call Path Collection

1. Overhead (space)
2. Overhead (time)
3. Overhead (parallel scaling)

Store History of Contexts Compactly

Problem:

Deluge of call paths

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<u>Problem:</u>

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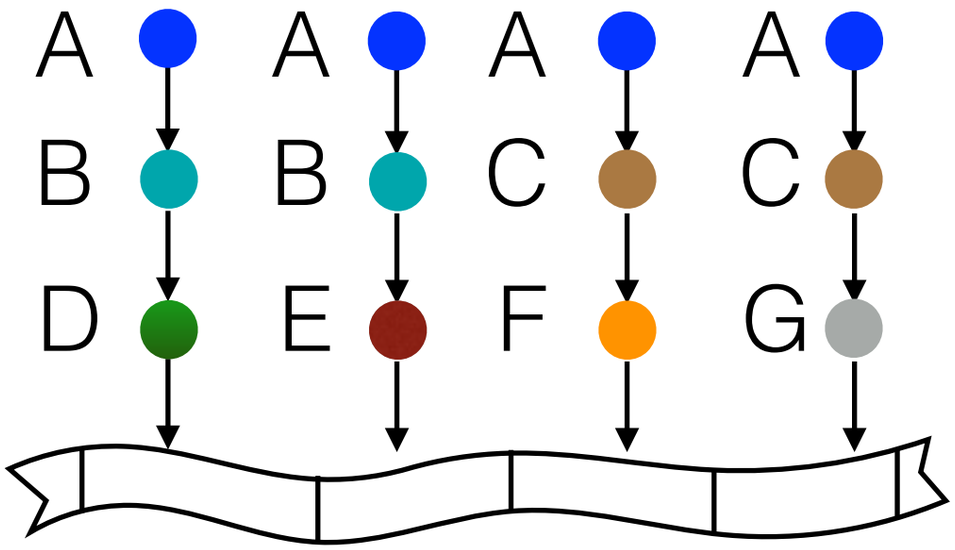

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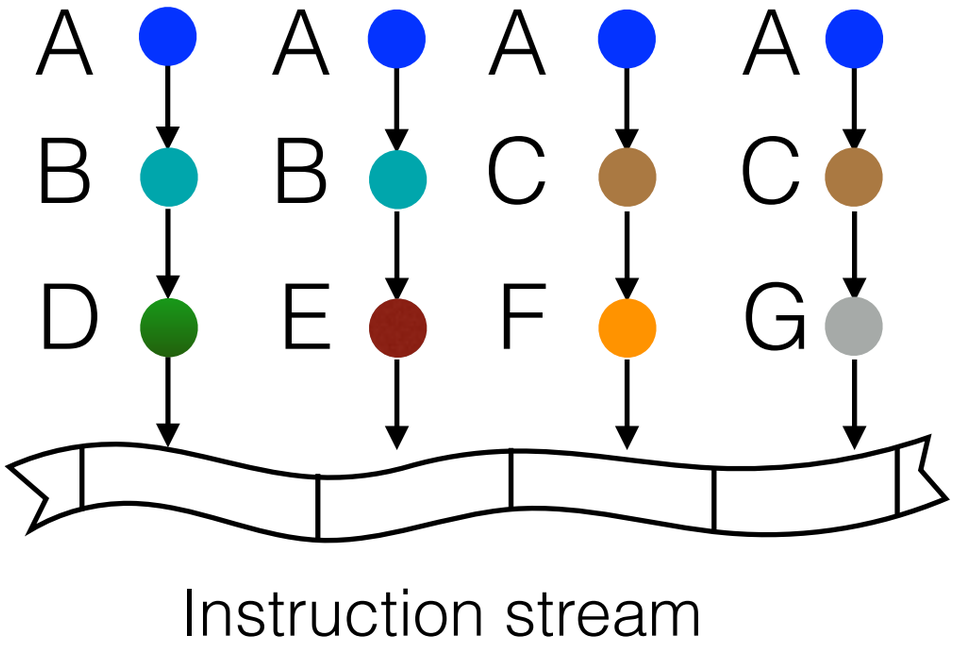
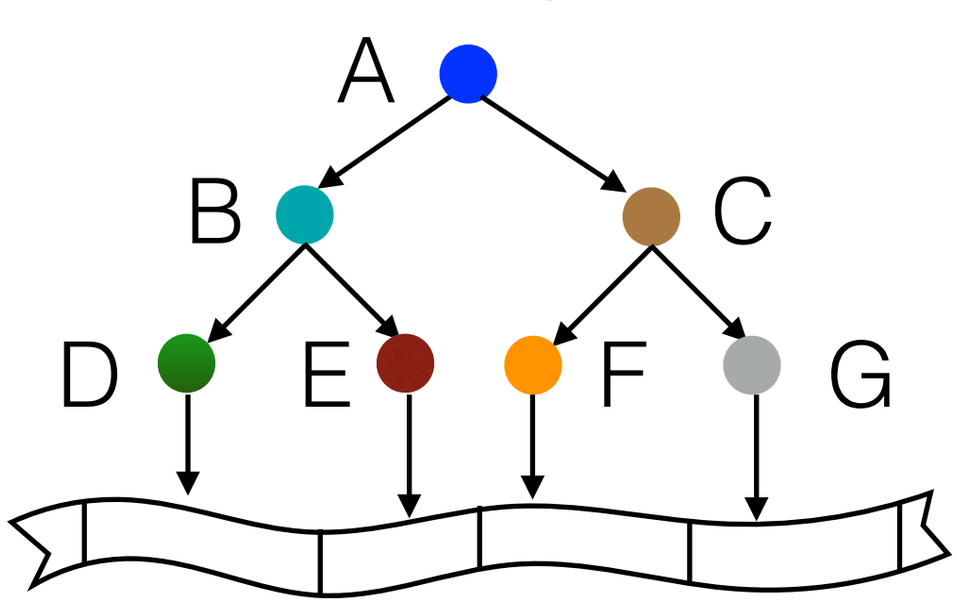


Solution

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

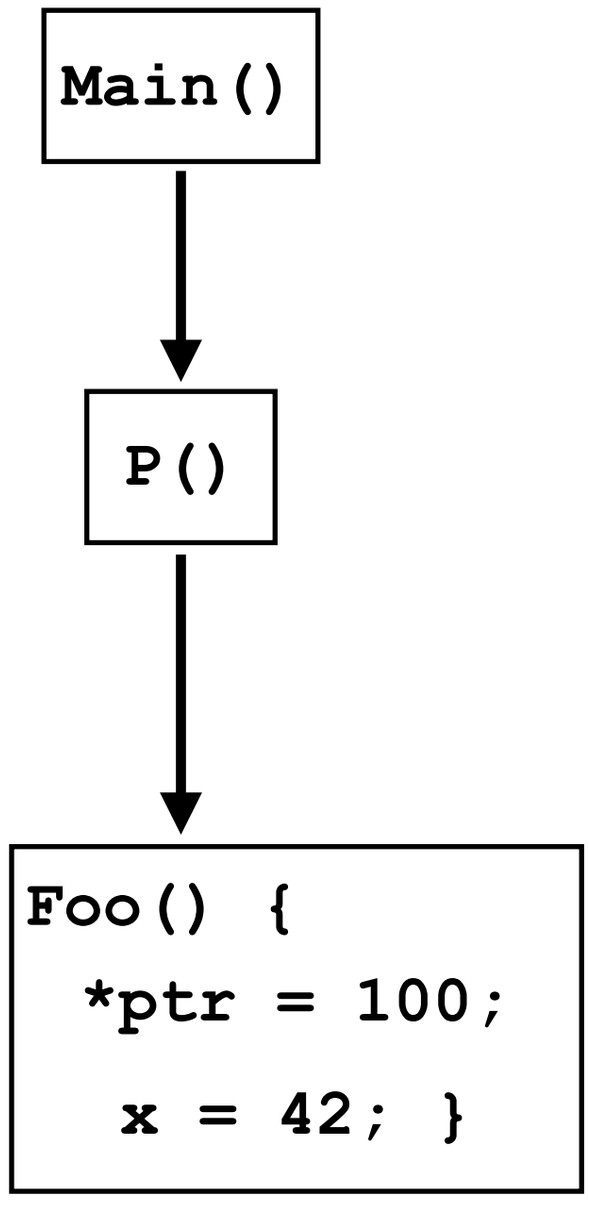


Exploiting Hardware Performance Counters with Flow and Context Sensitive Profiling: Ammons et al. PLDI'97

Shadow Stack to Avoid Unwinding Overhead

Problem:
Unwinding overhead

Solution:
Reverse the process. Eagerly build a replica/shadow stack on-the-fly.



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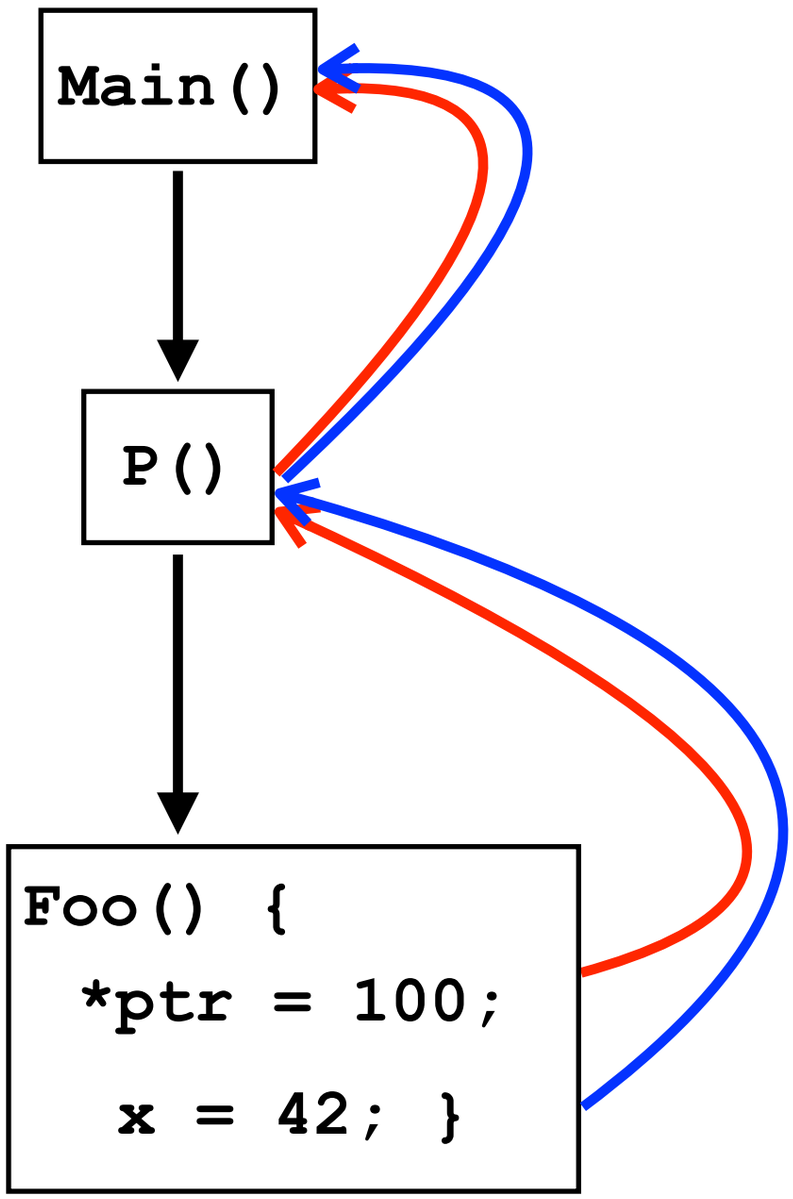

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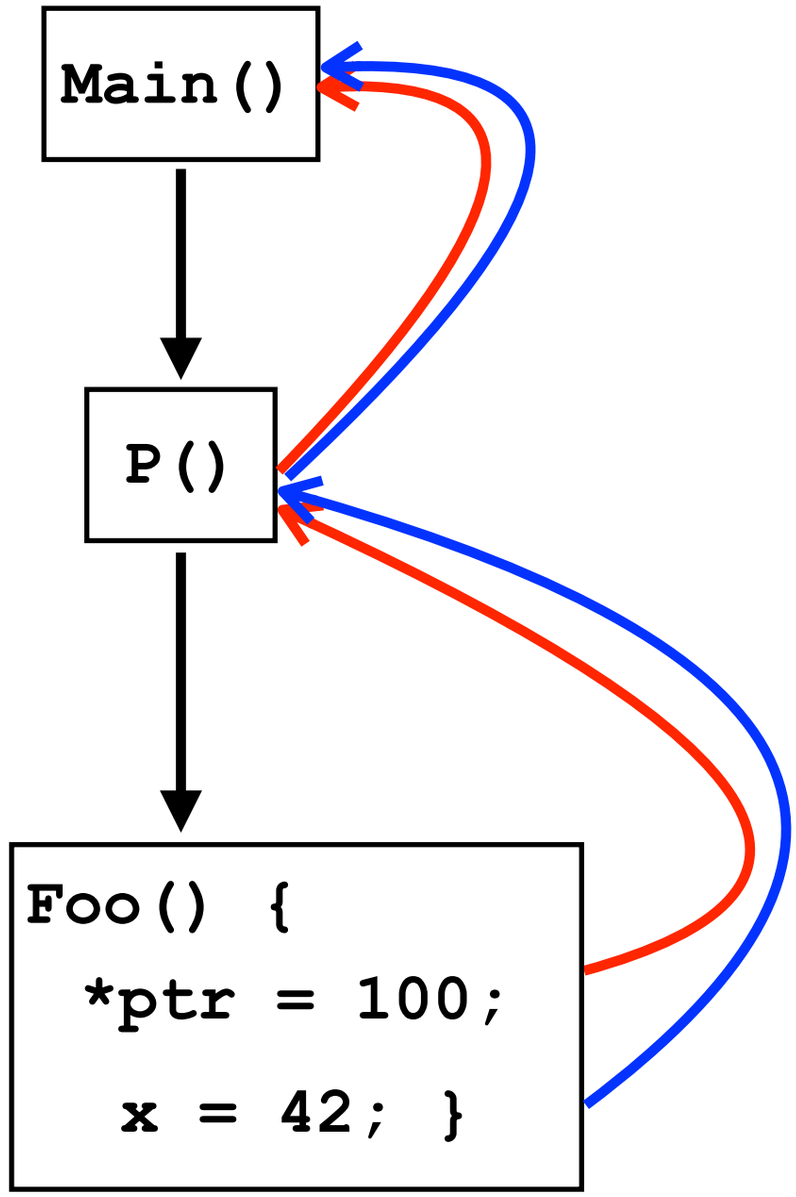

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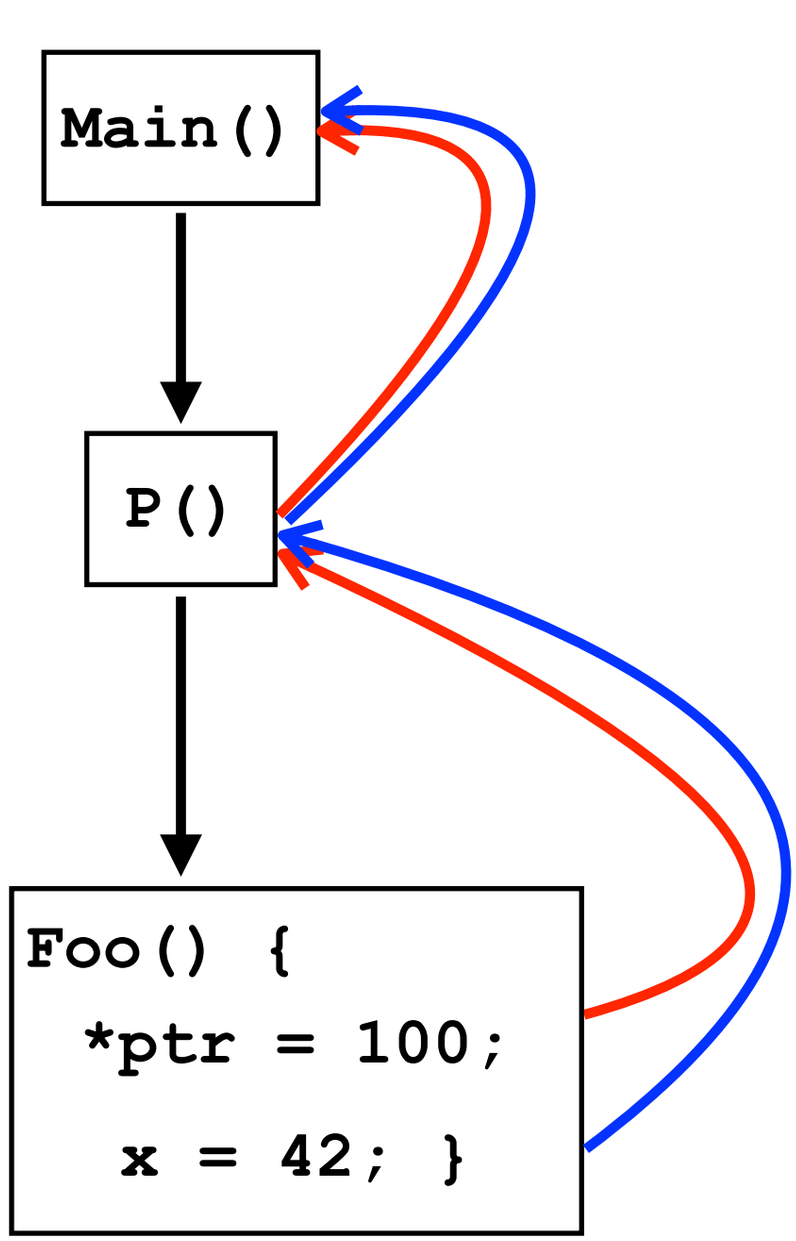

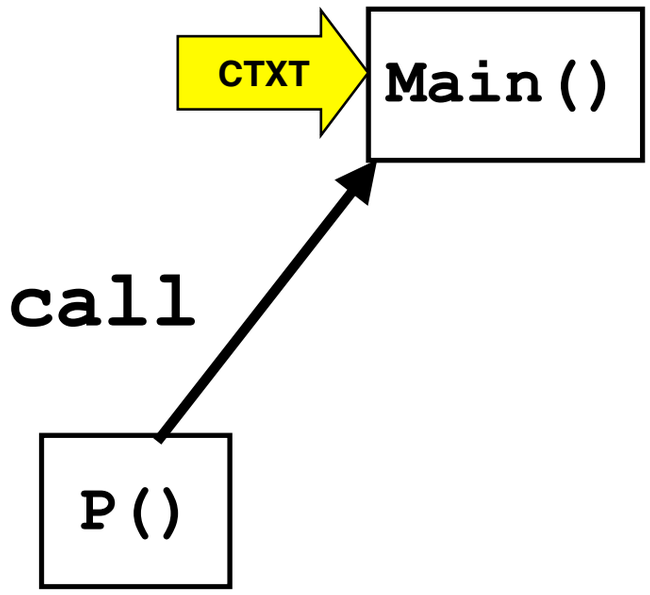

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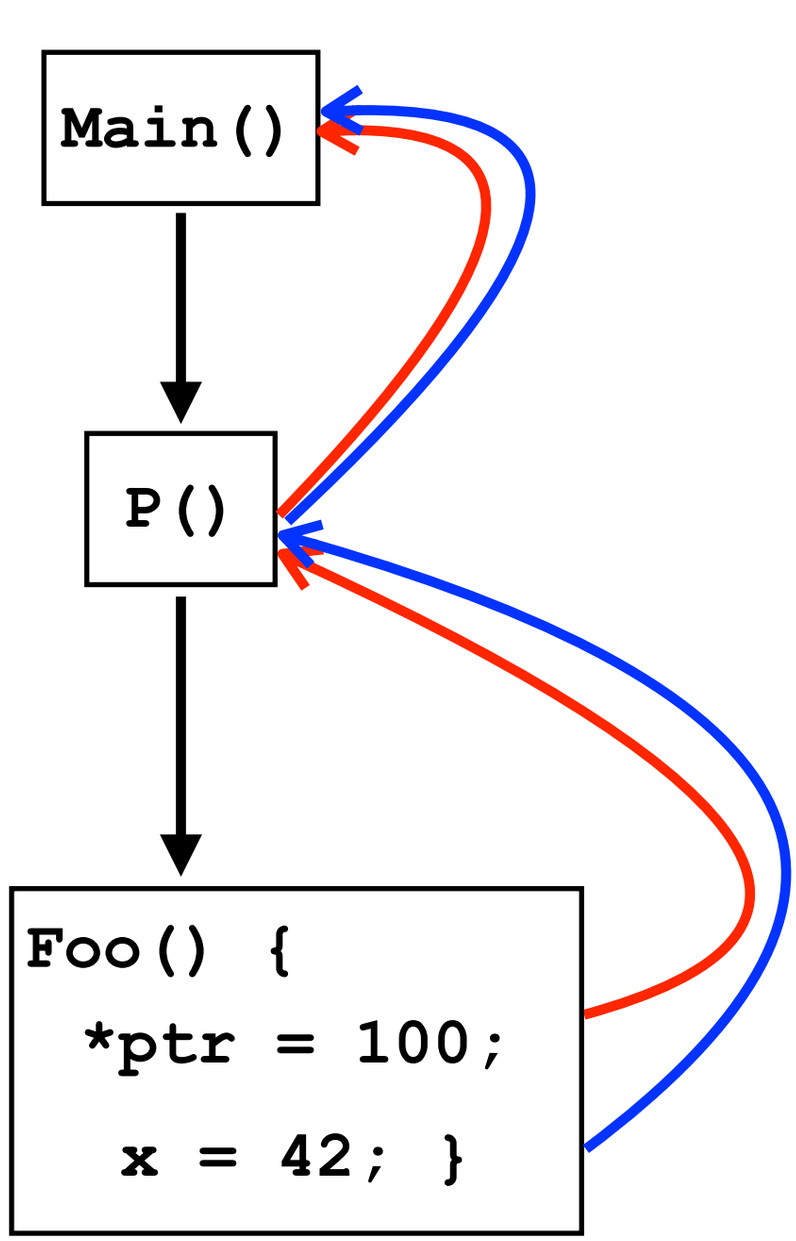

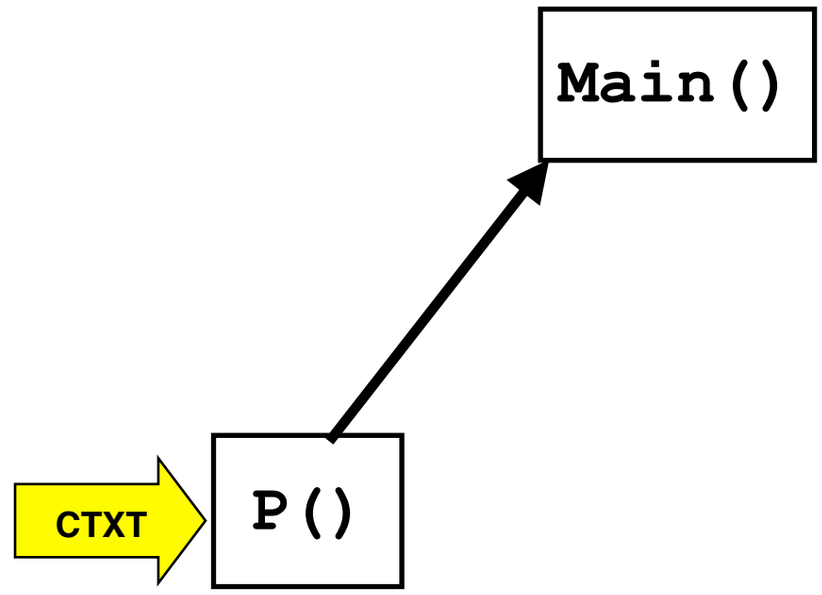

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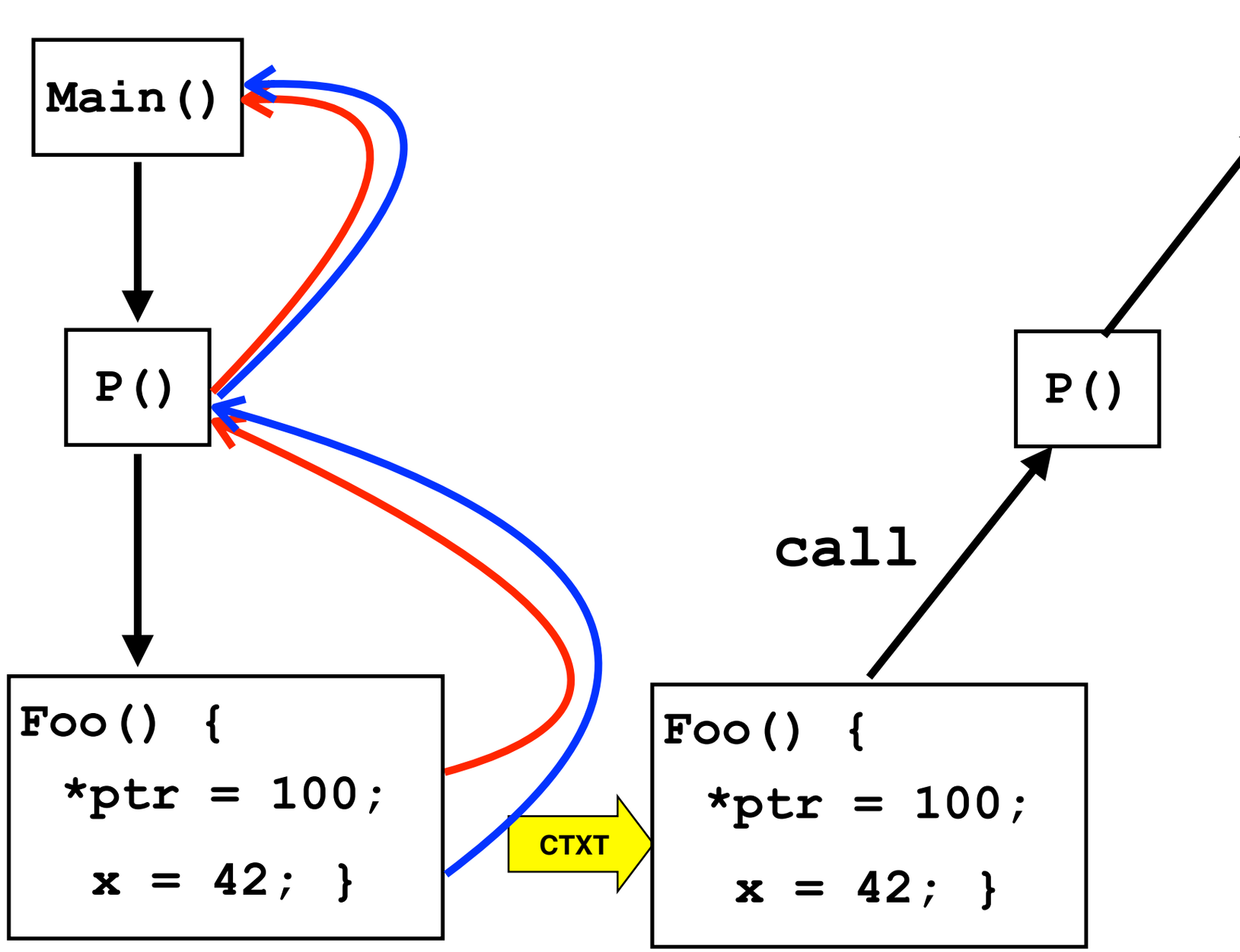

Tools can obtain pointer to the current context via CTXT **in <u>constant time</u>**

Shadow Stack to Avoid Unwinding Overhead

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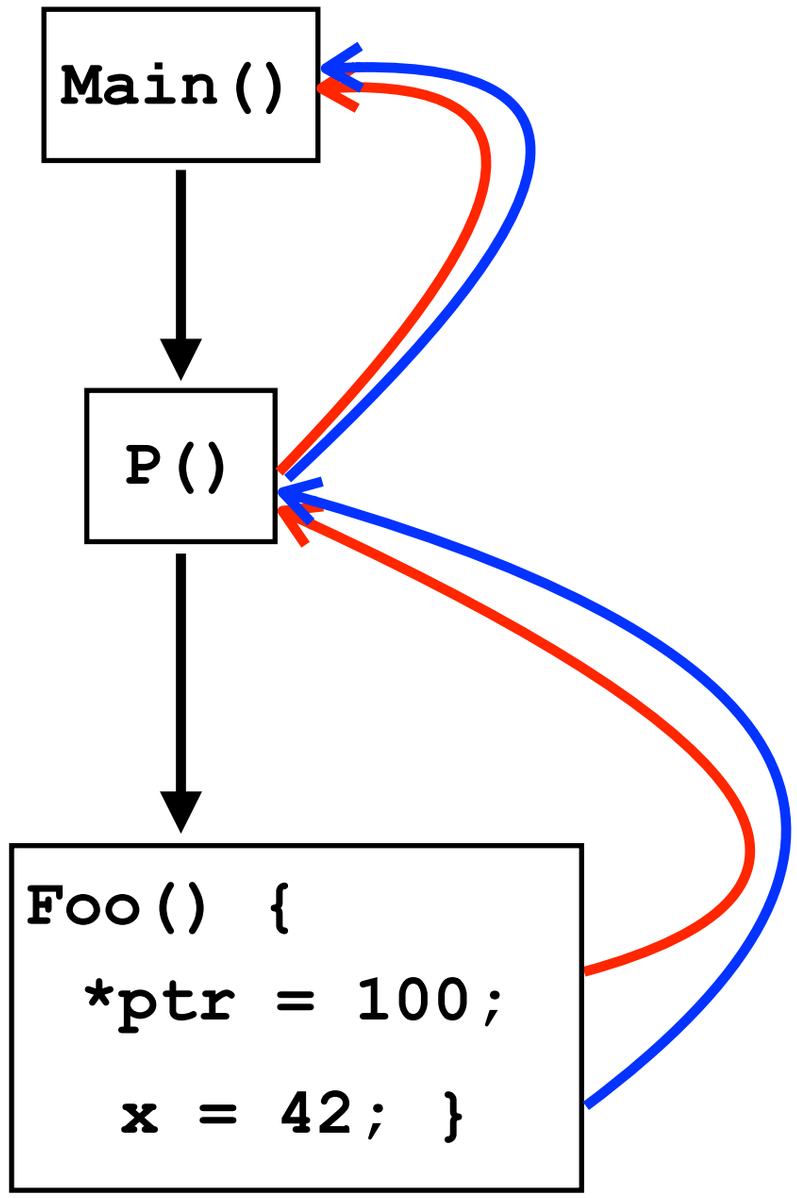

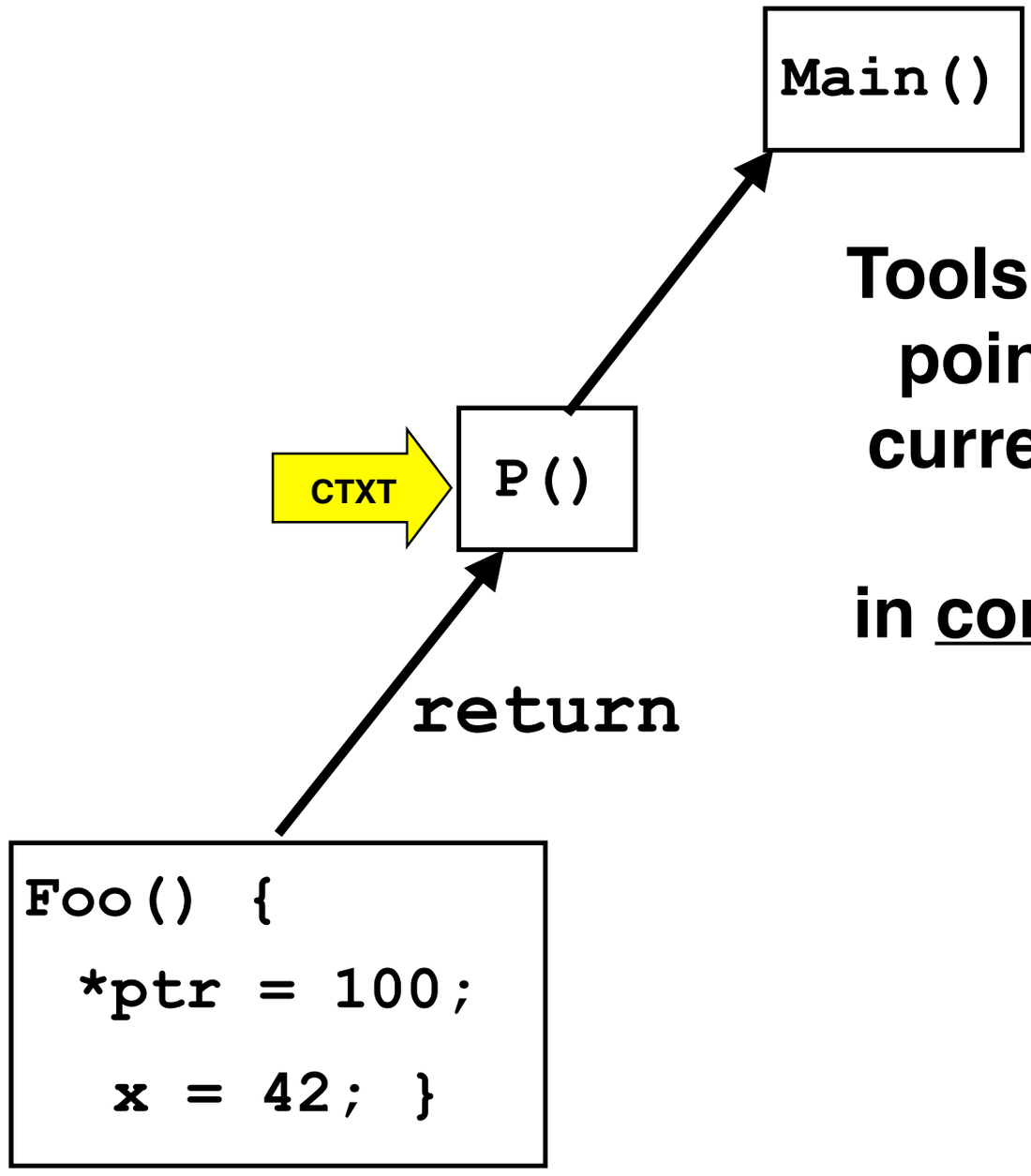

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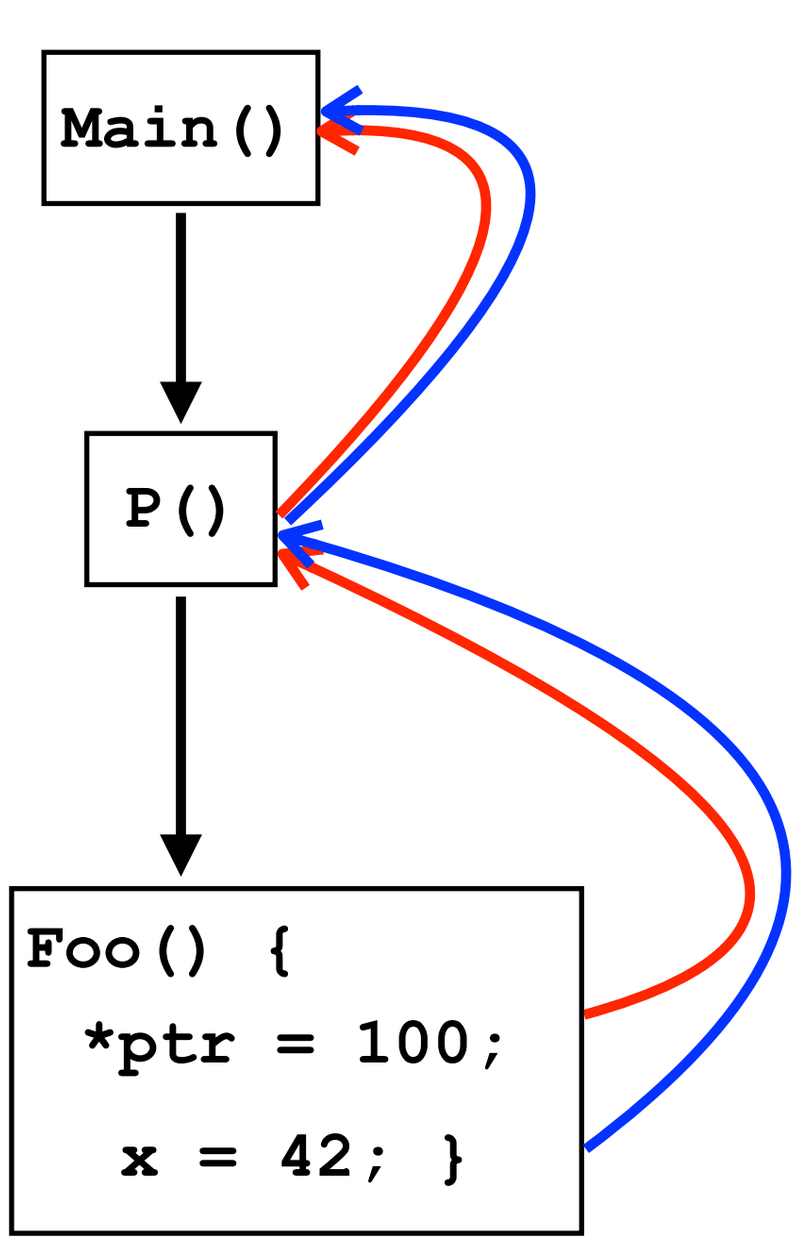
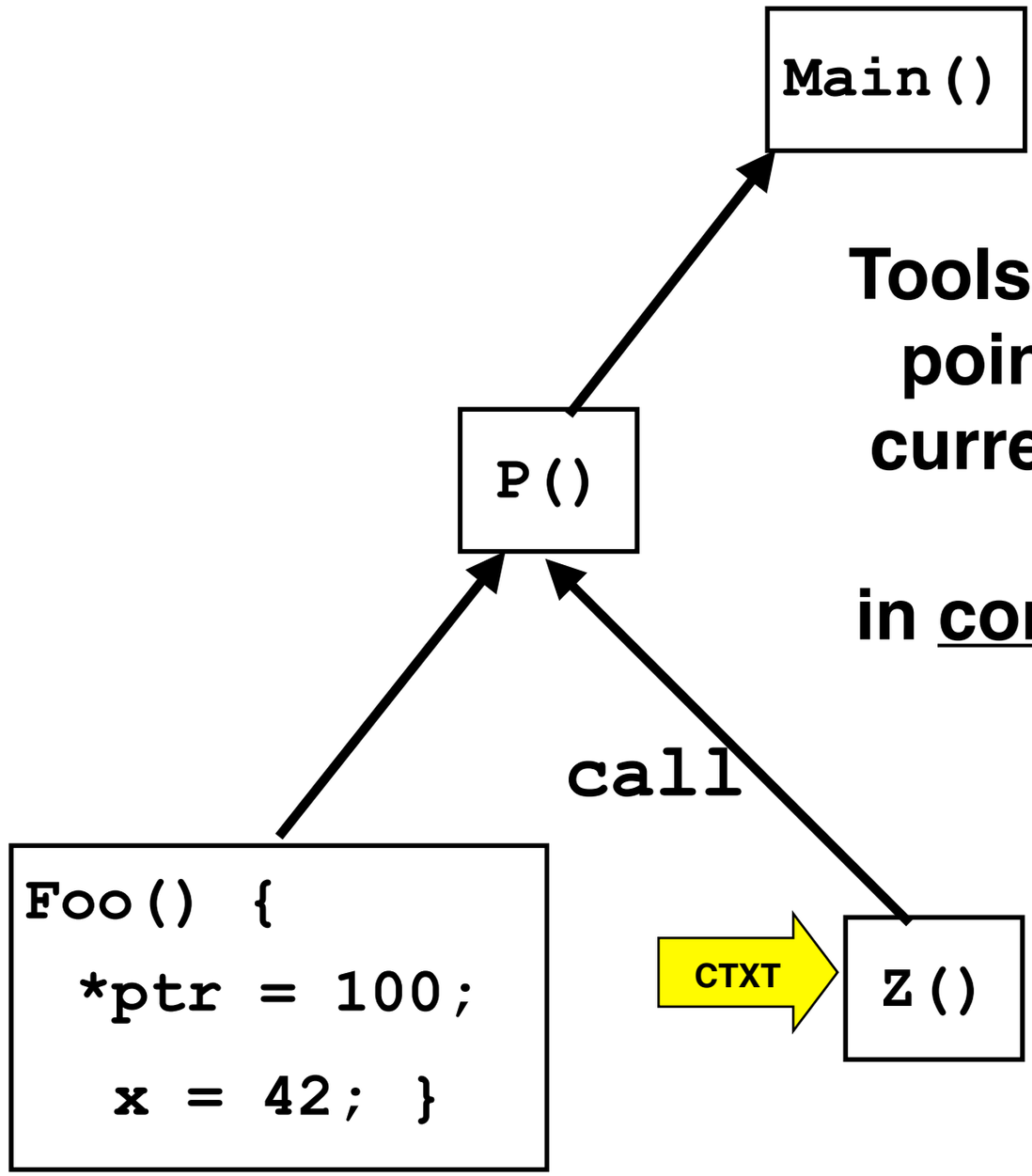
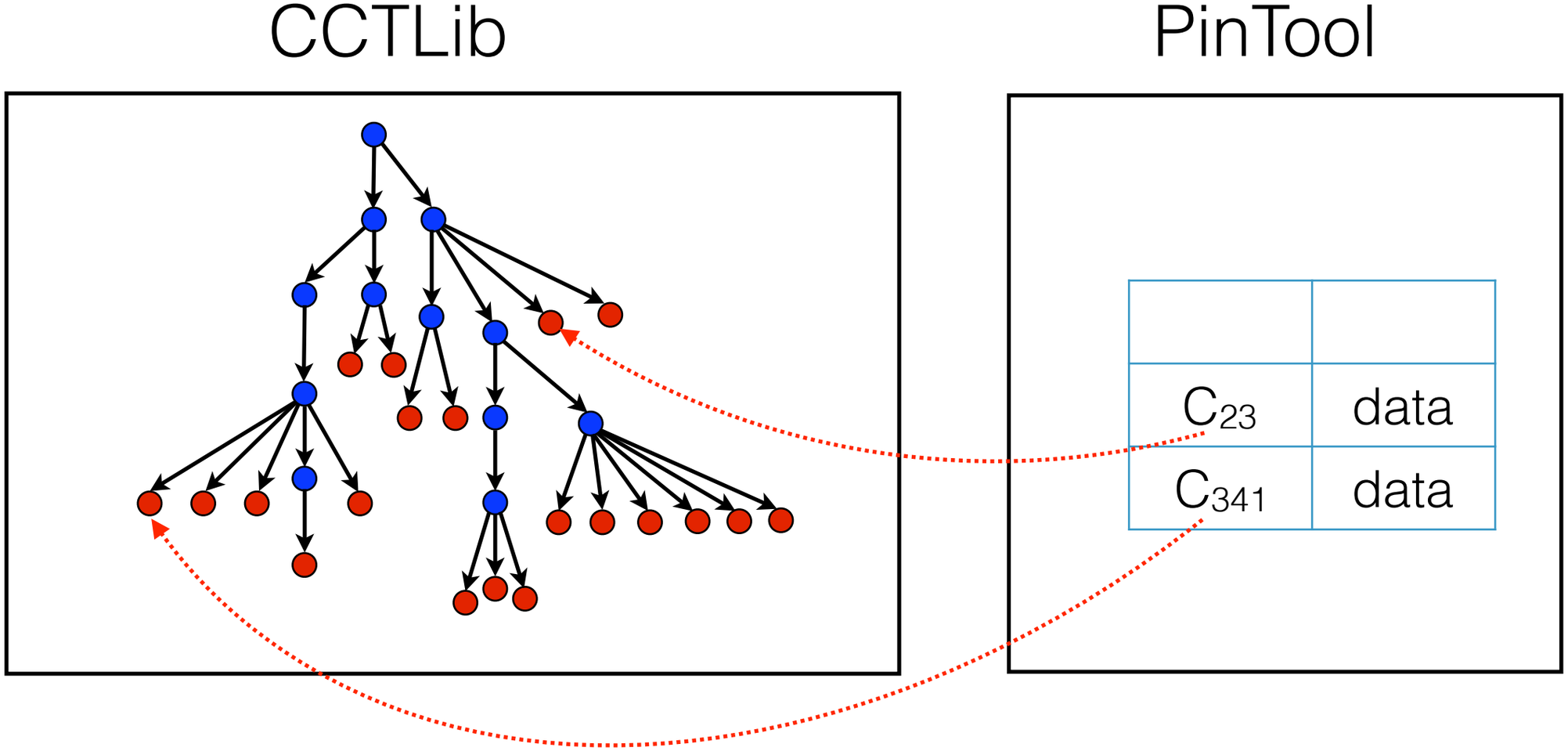




Tools can obtain pointer to the current context via CTXT in constant time

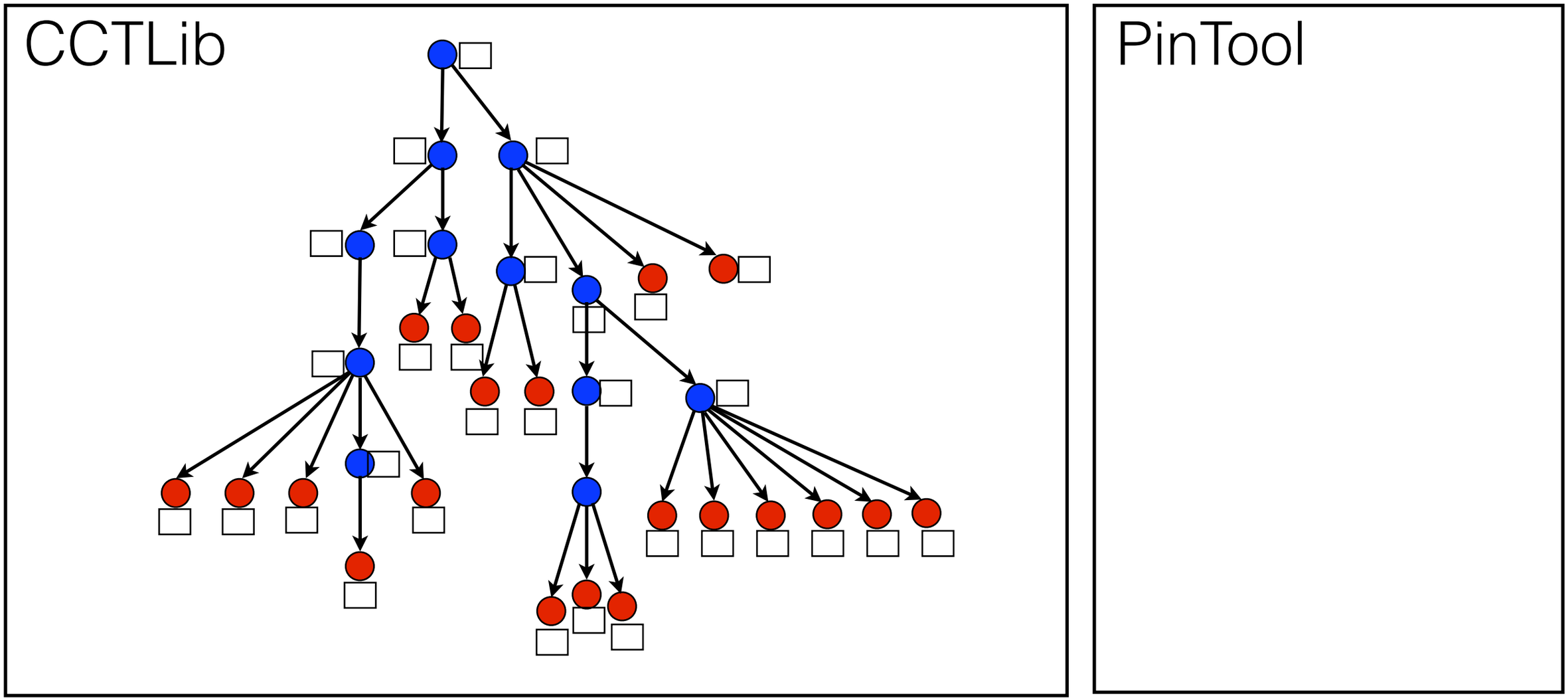
Two Ways to Use CCTLib By Pin Tools

- Option 1: Store context handles (ContextHandle_t) within the Pin tool and access the context (traverse full call chain) as needed



Two Ways to Use CCTLib By Pin Tools

- Option 2: Associate a user-defined “metric” with each `ContextHandle_t` and store it in the calling context tree. Perform a tree traversal as needed.



Associating Address to Data Objects

- Static objects
  - ✦ Record all `<AddressRange, VariableName>` tuples in a map

- Dynamic allocations
  - ✦ Instrument all allocation/free routines
  - ✦ Maintain `<AddressRange, ContextId>` 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

Context To DOT

Execution-wide calling context tree for
NWChem—a six-million line computational chemistry code

```
/* Description:
            Dumps all CCTs into DOT files for visualization.
*/
    void DottifyAllCCTs();
```

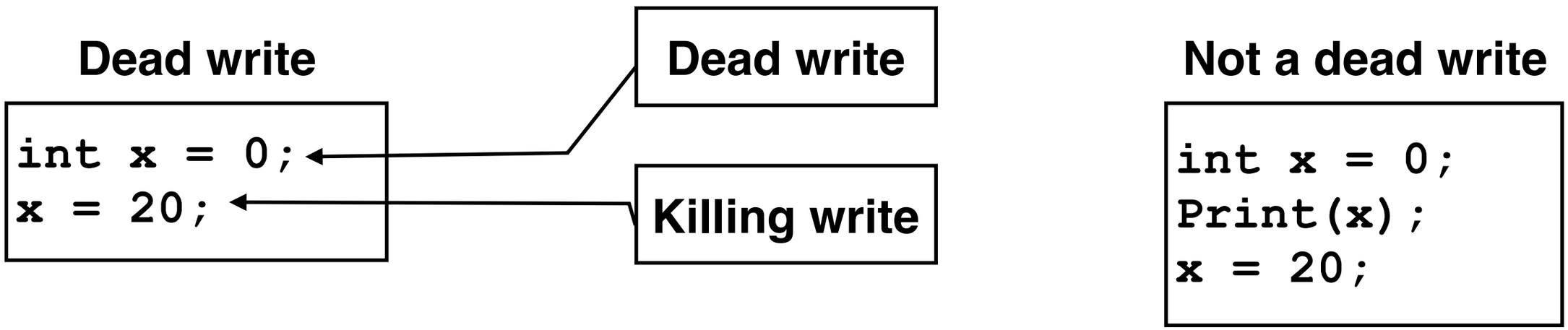
CCTLib Client Tools

- DeadSpy: Pinpoining dead stores in a program
  - ✦ Detects dead writes in an execution
- RedSpy: Pinpointing silent stores in a program
  - ✦ Detects redundant data movement in an execution
- RVN: Runtime Value Numbering
  - ✦ Detects useless computations in an execution
- Metric client
  - ✦ Captures hot paths
- Footprint client
  - ✦ Computes context-sensitive memory footprint of a data object

Pinpointing Useless Memory Accesses

- Accessing memory is expensive on modern architectures
  - Multiple levels of hierarchy
  - Cores share cache
  - Limited bandwidth per core
- Unnecessary writes
  - Cause unnecessary capacity miss and coherence traffic —> affects resource shared system
  - Wear out NVM-based or disk-based memory

Dead write: Two writes happen to the same memory location without an intervening read



Dead Writes: Example

Riemann solver kernel
3-level nested loop
20% execution time

```
do k
 do j
  do i
   Wgdnv(i, j, k, 0) = …
   Wgdnv(i, j, k, inorm) = …
   Wgdnv(i, j, k, 4) = …
   if (spout.le.0.0d0) then
    Wgdnv(i, j, k, 0) = …
    Wgdnv(i, j, k, inorm) = …
    Wgdnv(i, j, k, 4) = …
   endif
   if (spin.gt.0.0d0) then
    Wgdnv(i, j, k, 0) = …
    Wgdnv(i, j, k, inorm) = …
    Wgdnv(i, j, k, 4) = …
   endif
```

- Chombo: AMR framework for solving PDEs
- Compilers can't eliminate all dead writes because of:
  - Aliasing / ambiguity
  - Aggregate variables
  - Function boundaries
  - Late binding
  - Partial deadness

Dead Writes: Example

Code lacked "design for performance"

```
do k
 do j
  do i
   Wgdnv(i, j, k, 0) = …
   Wgdnv(i, j, k, inorm) = …
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   if (spout.le.0.0d0) then
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    Wgdnv(i, j, k, 4) = …
   endif
   if (spin.gt.0.0d0) then
    Wgdnv(i, j, k, 0) = …
    Wgdnv(i, j, k, inorm) = …
    Wgdnv(i, j, k, 4) = …
   endif
```

Better code: Use else-if nesting

```
do k
 do j
  do i
   if (spin.gt.0.0d0) then
    Wgdnv(i, j, k, 0) = …
    Wgdnv(i, j, k, inorm) = …
    Wgdnv(i, j, k, 4) = …
   elif (spout.le.0.0d0) then
    Wgdnv(i, j, k, 0) = …
    Wgdnv(i, j, k, inorm) = …
    Wgdnv(i, j, k, 4) = …
   else
    Wgdnv(i, j, k, 0) = …
    Wgdnv(i, j, k, inorm) = …
    Wgdnv(i, j, k, 4) = …
   endif
```

Detection Scheme

- Monitor every load and store in a program
- Maintain state information for each memory byte referenced by the program
- Detect every dead write in an execution with an automaton

[CGO'12] "DeadSpy: A Tool to Pinpoint Program Inefficiencies"

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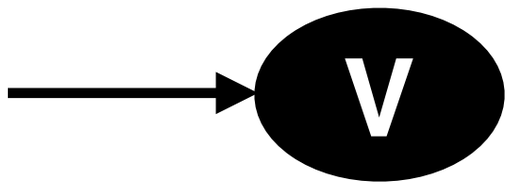

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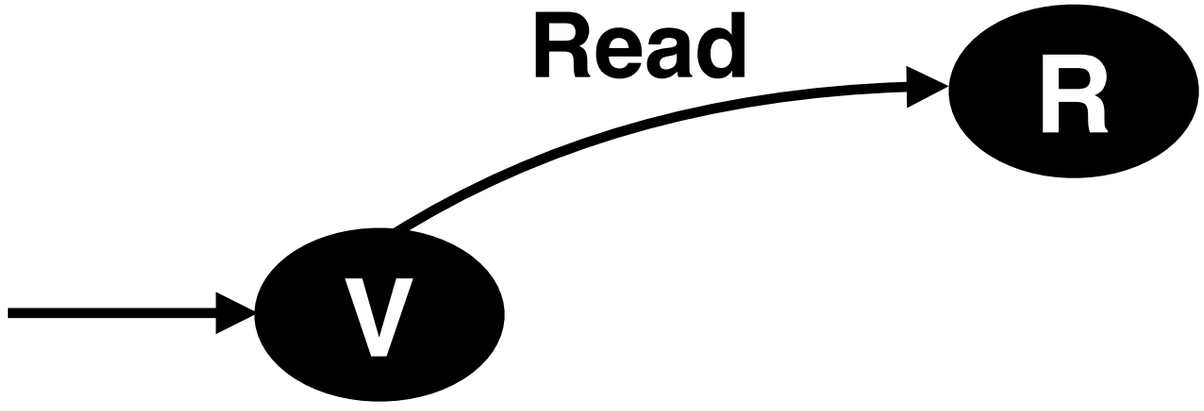

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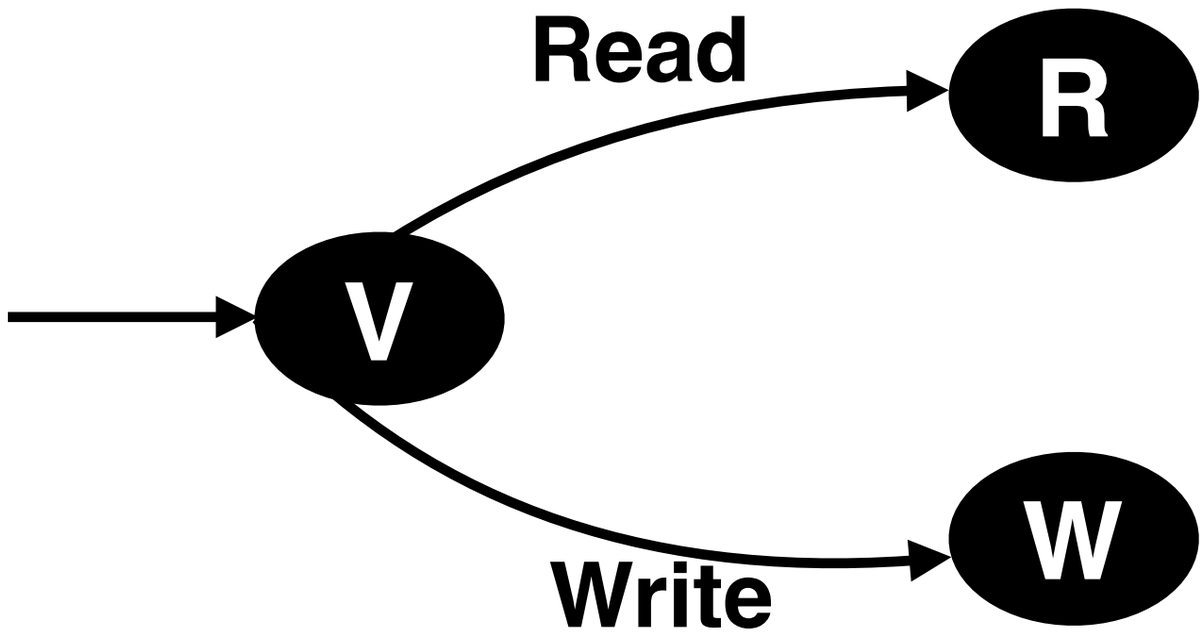

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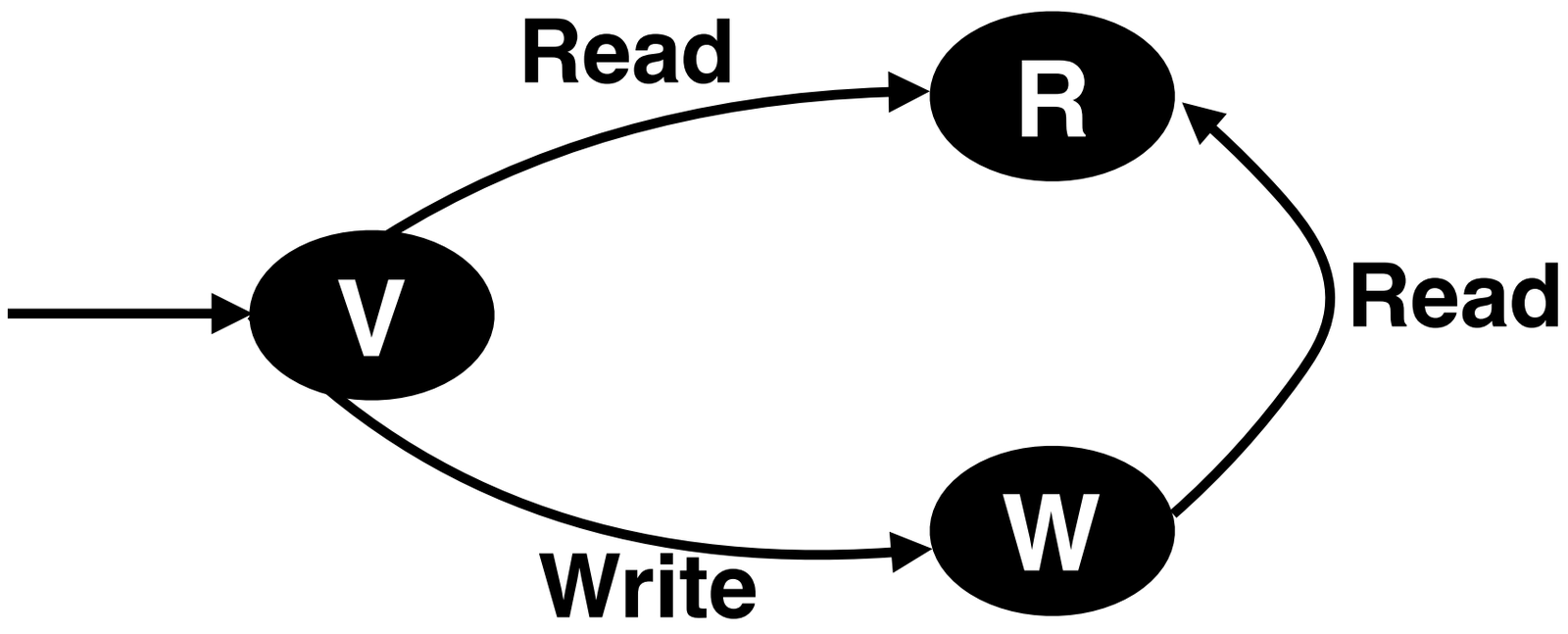

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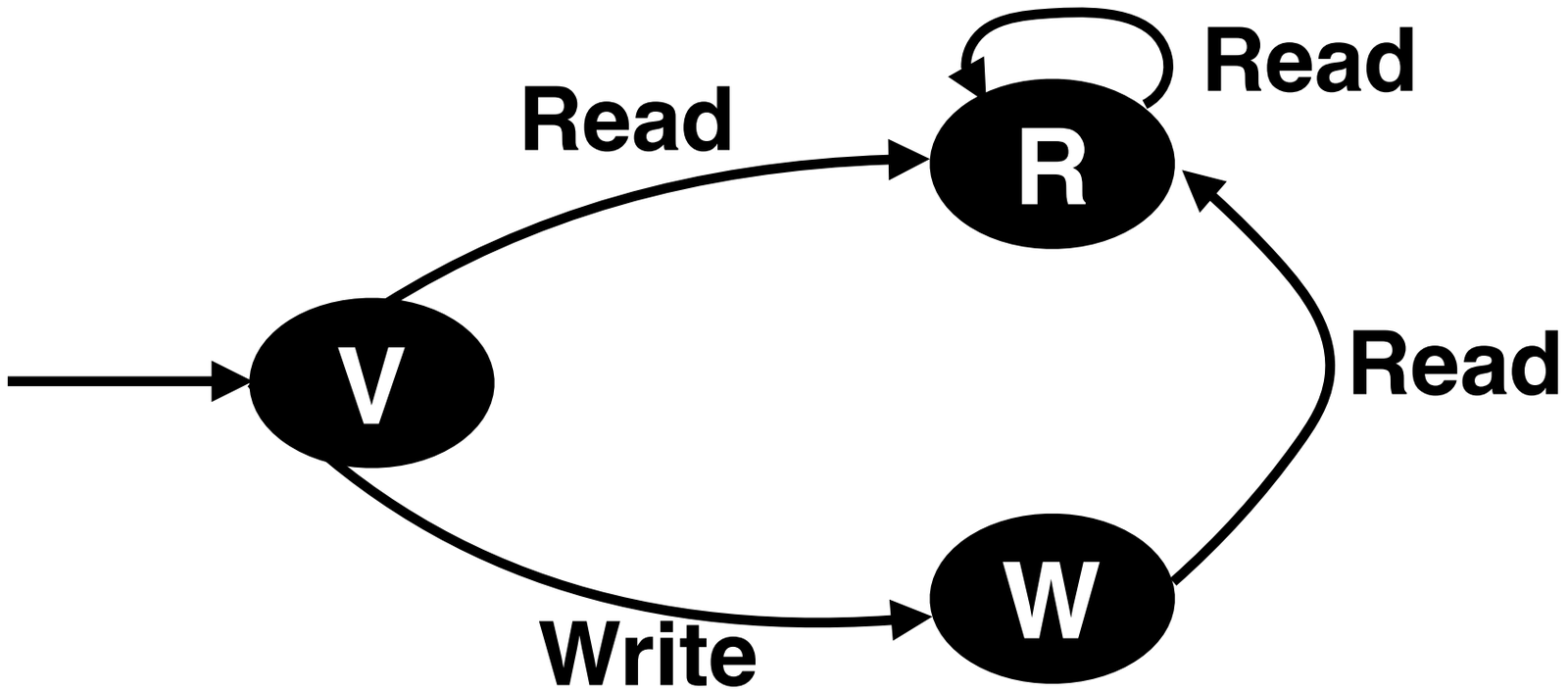

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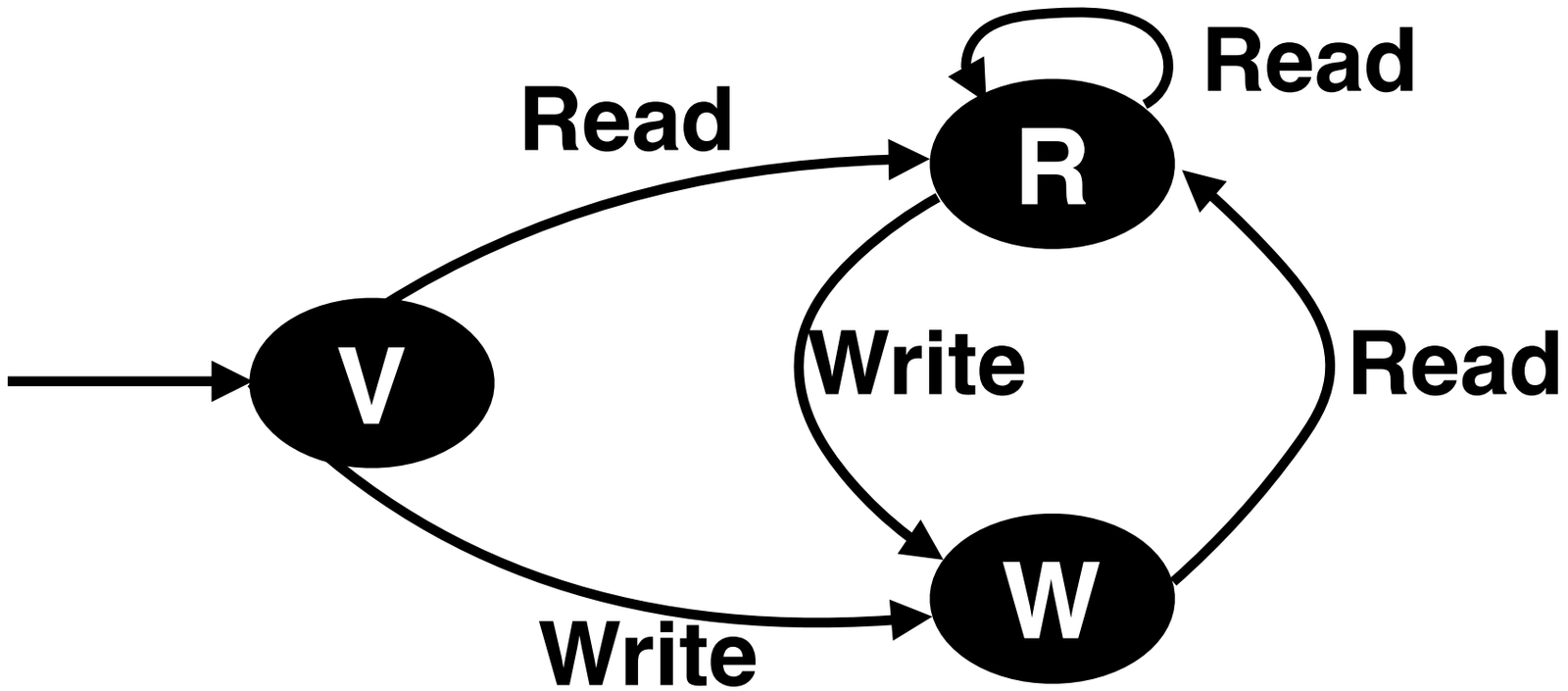

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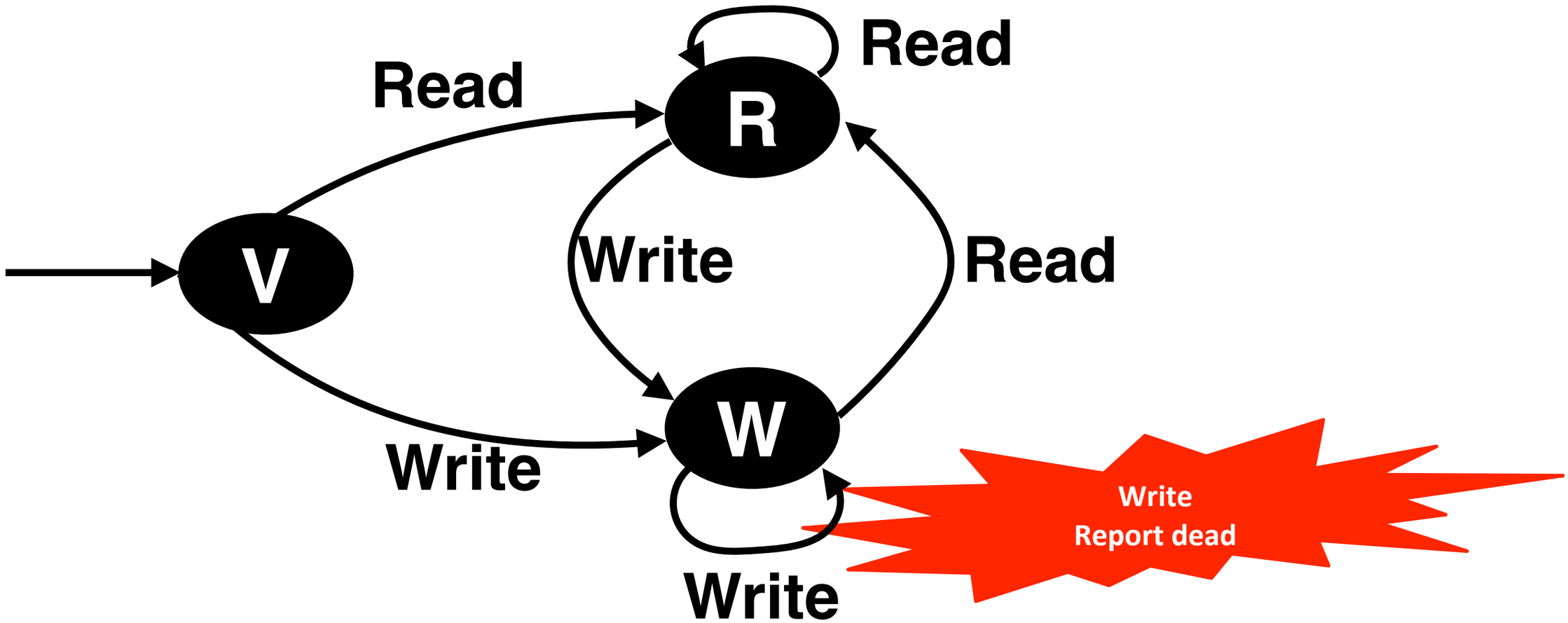
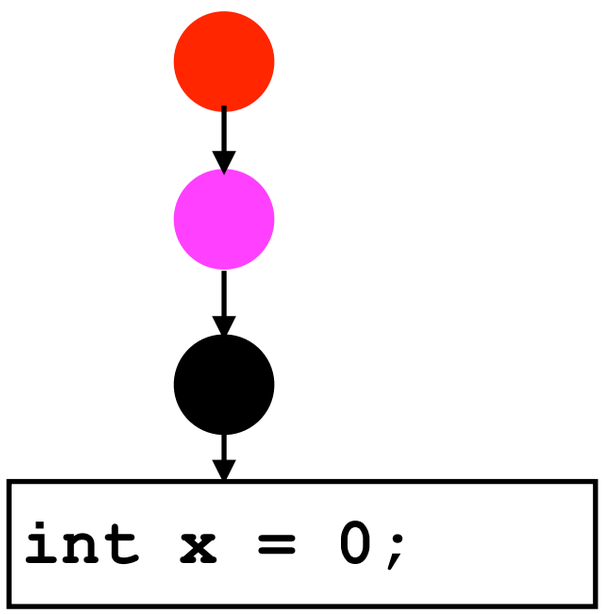


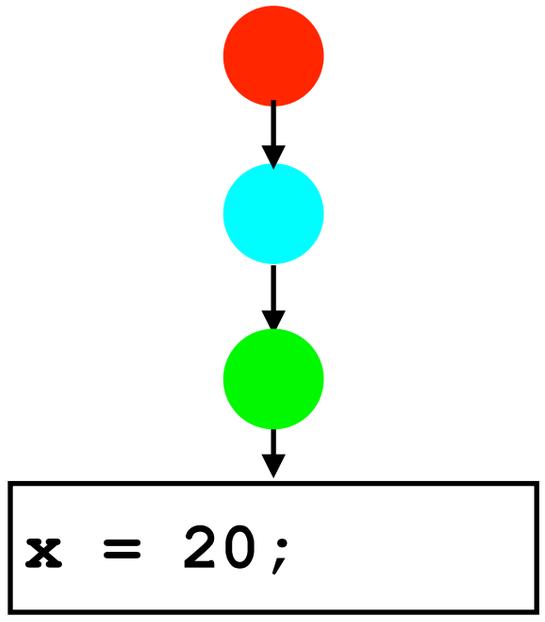
[CGO'12] "DeadSpy: A Tool to Pinpoint Program Inefficiencies"

DeadSpy: Measurement and Attribution

- Precise measurement
  - ✦ No false positives and no false negatives
- Precise attribution
  - ✦ Source-level feedback with calling context of dead and killing writes
  - ✦ On each dead write record <old-ctxt-handle, cur-ctxt-handle>



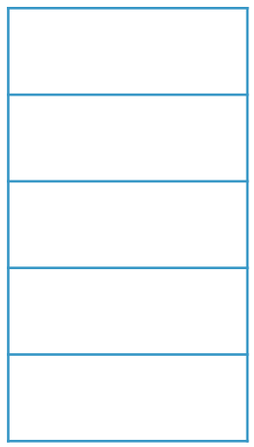
Dead write



Killing write

DeadSpy + CCTLib in Action

Memory



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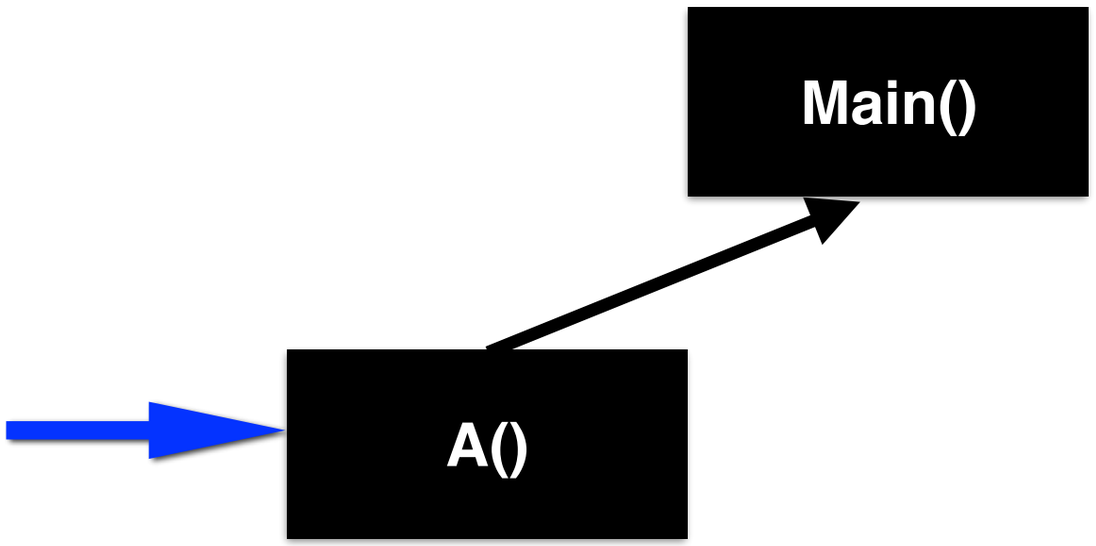

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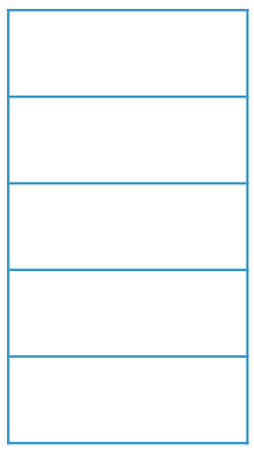

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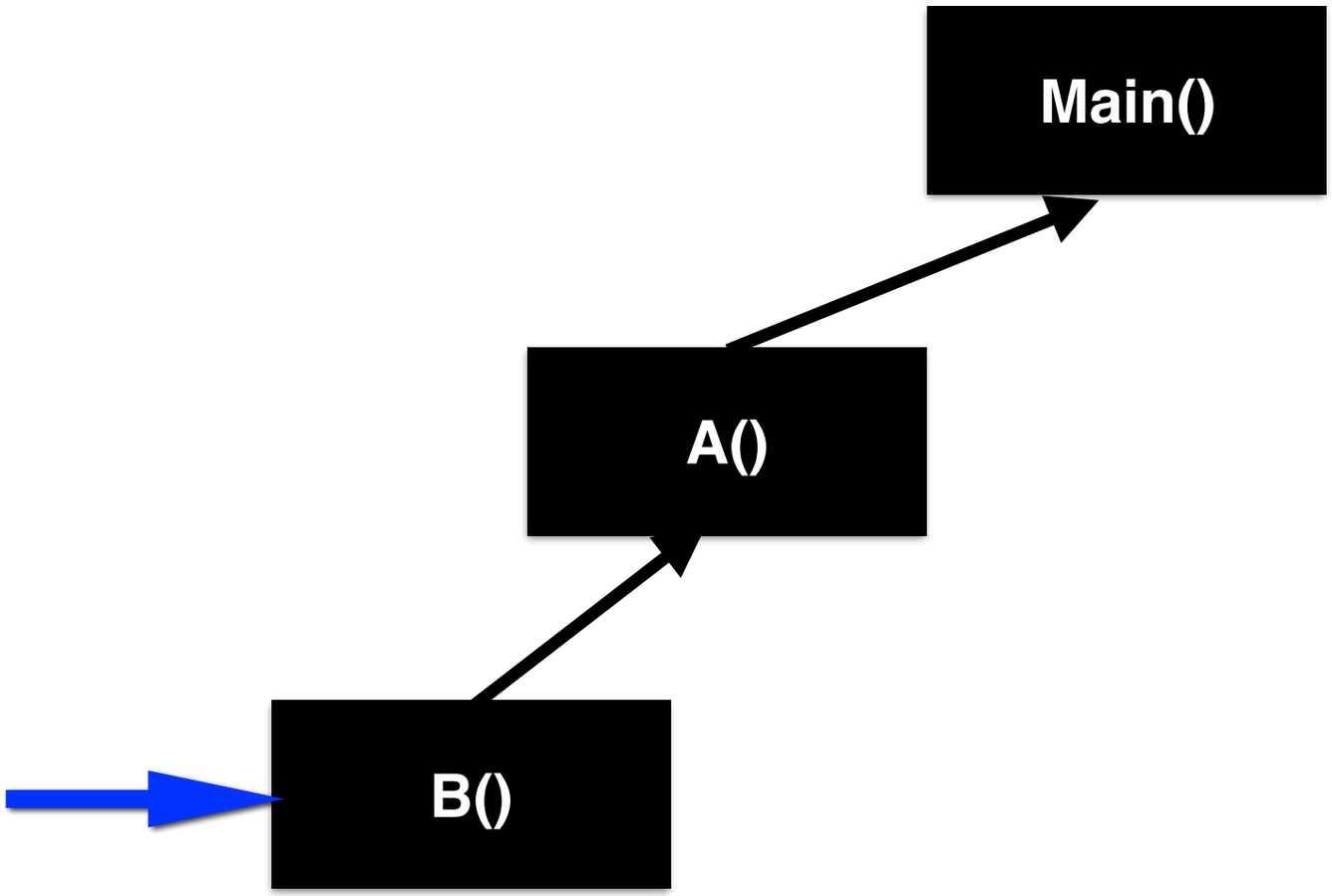

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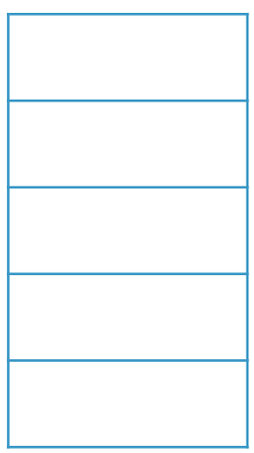

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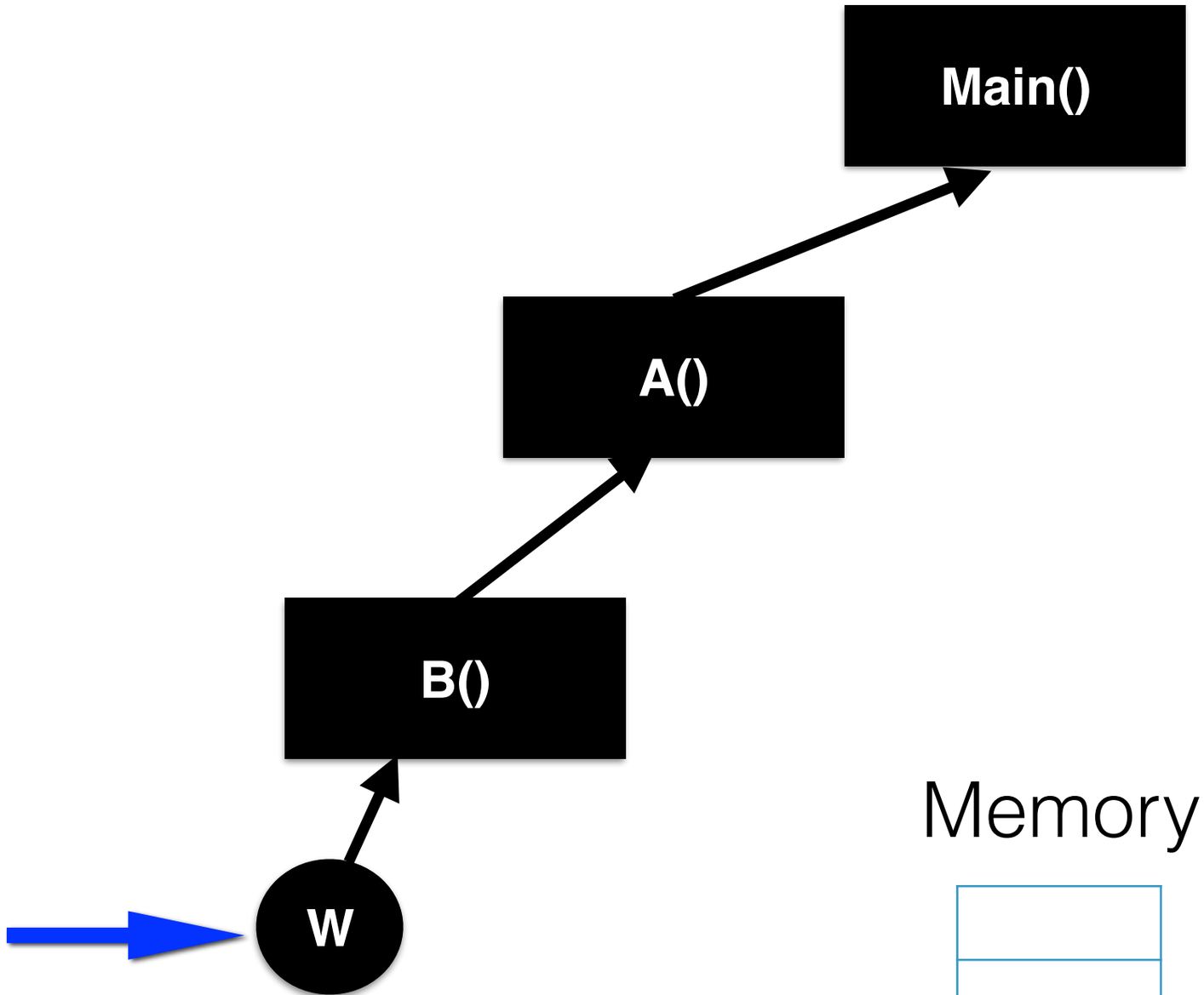

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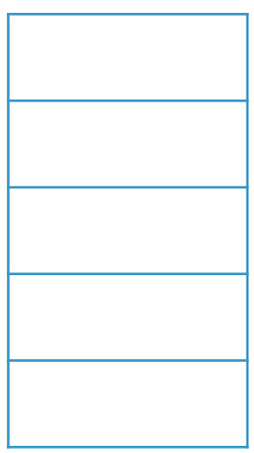

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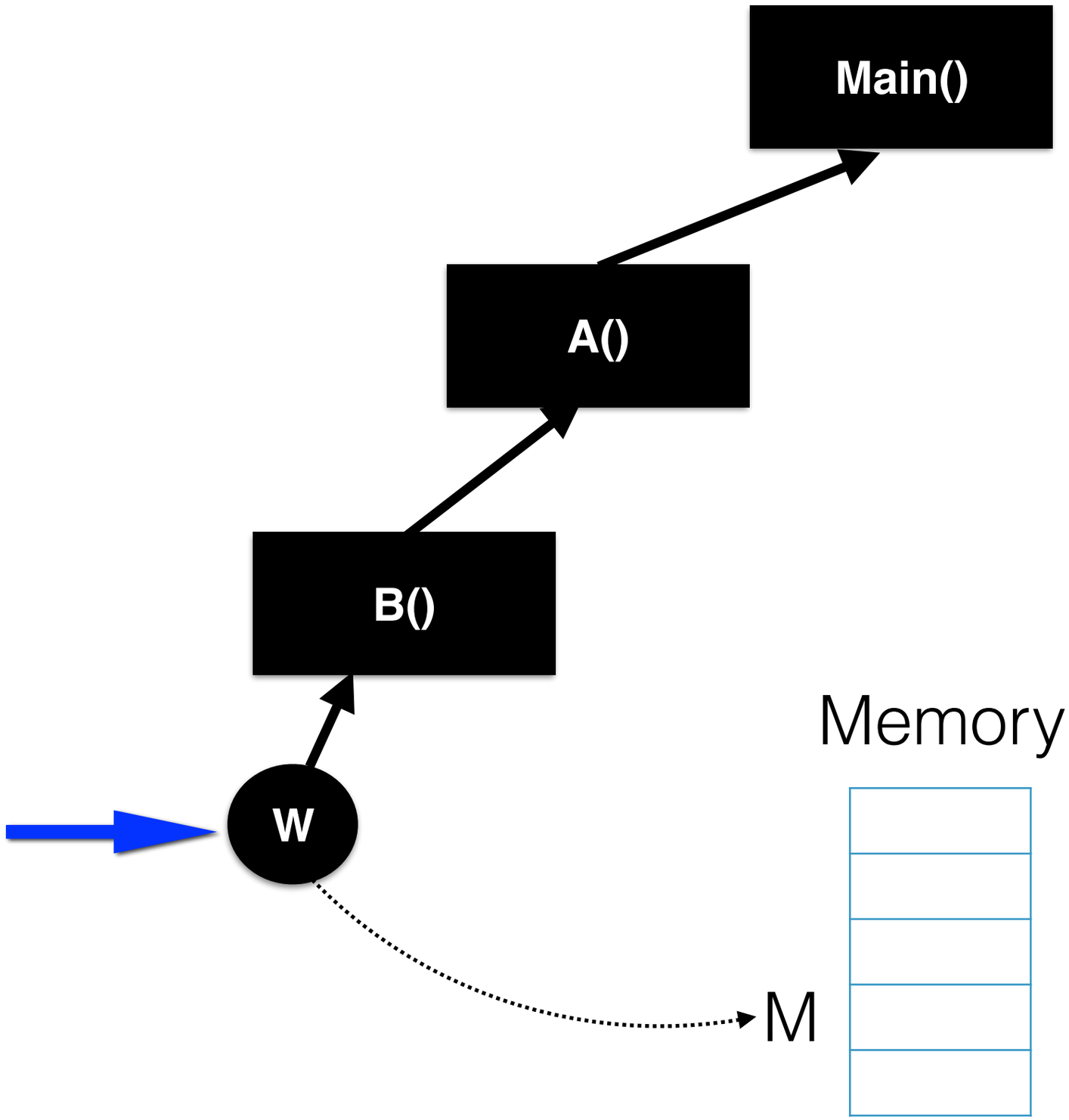

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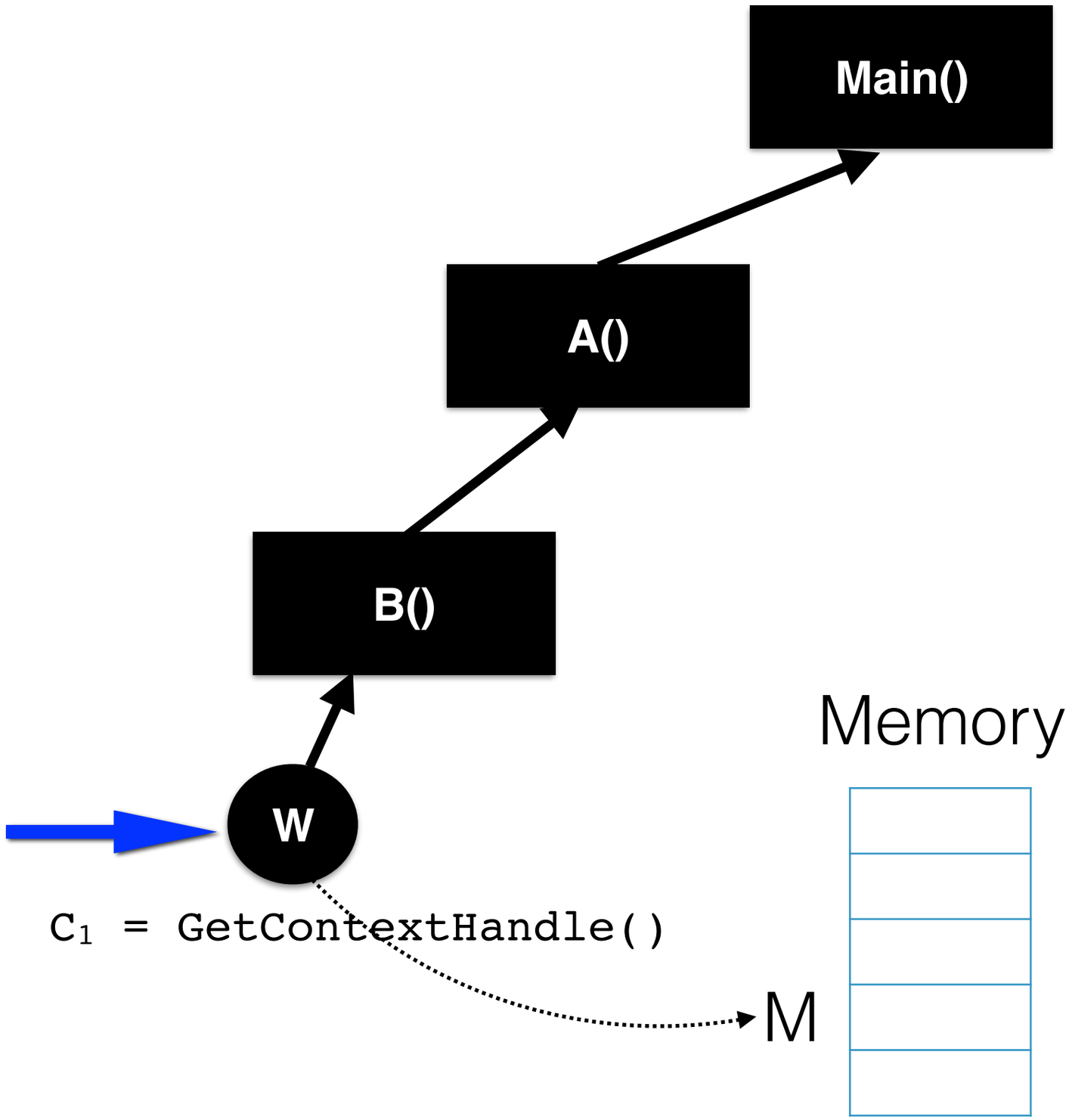

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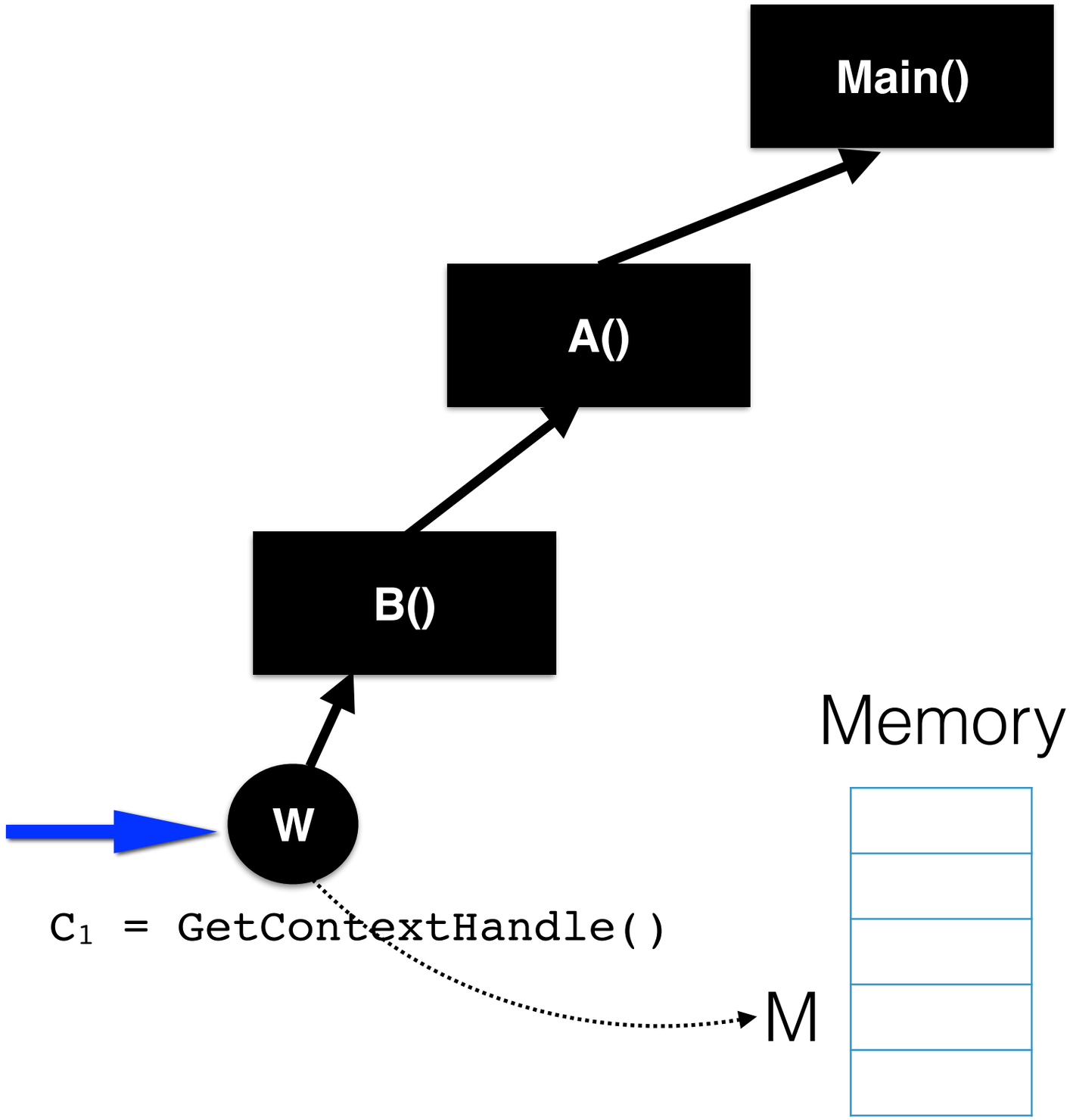

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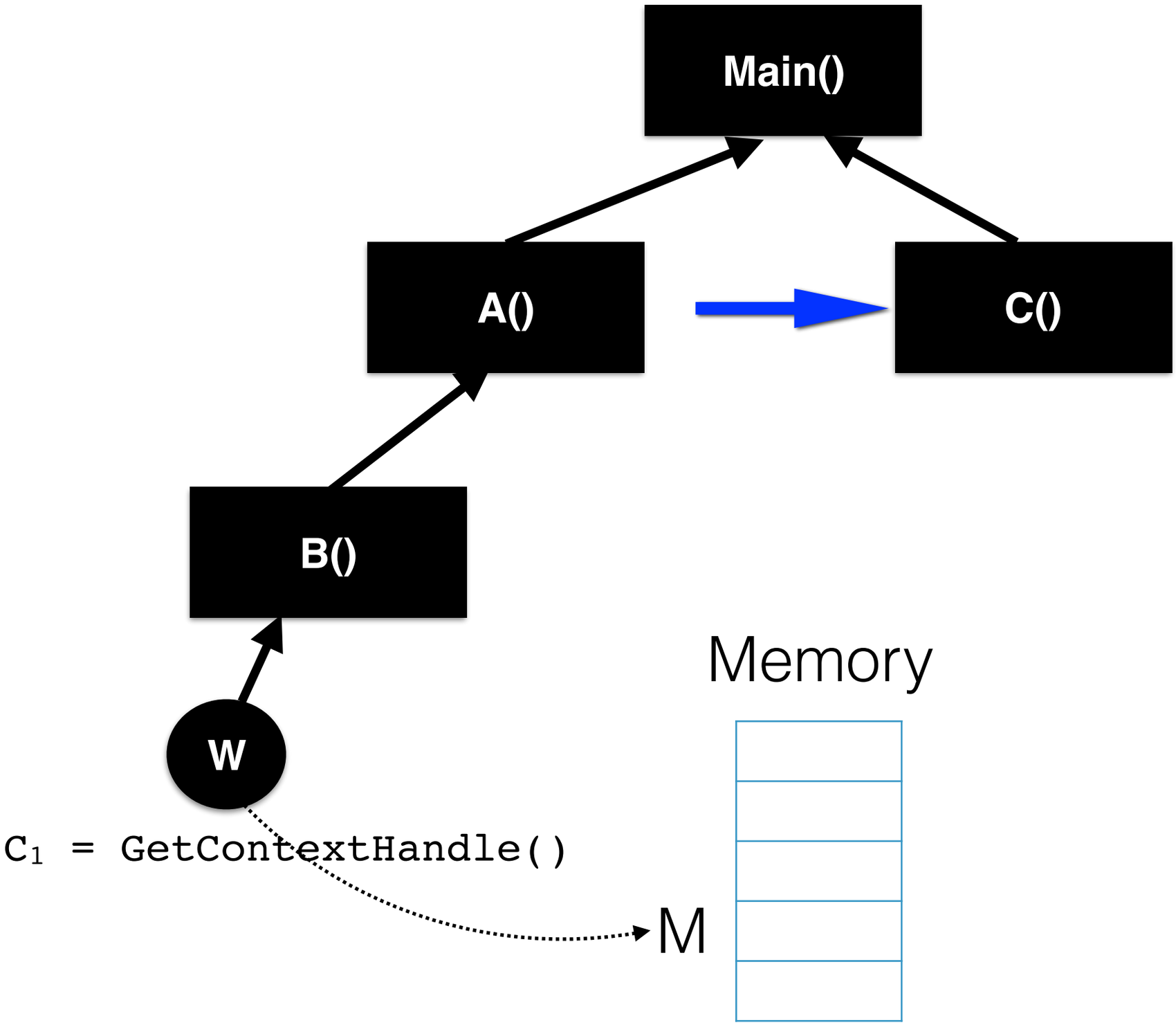

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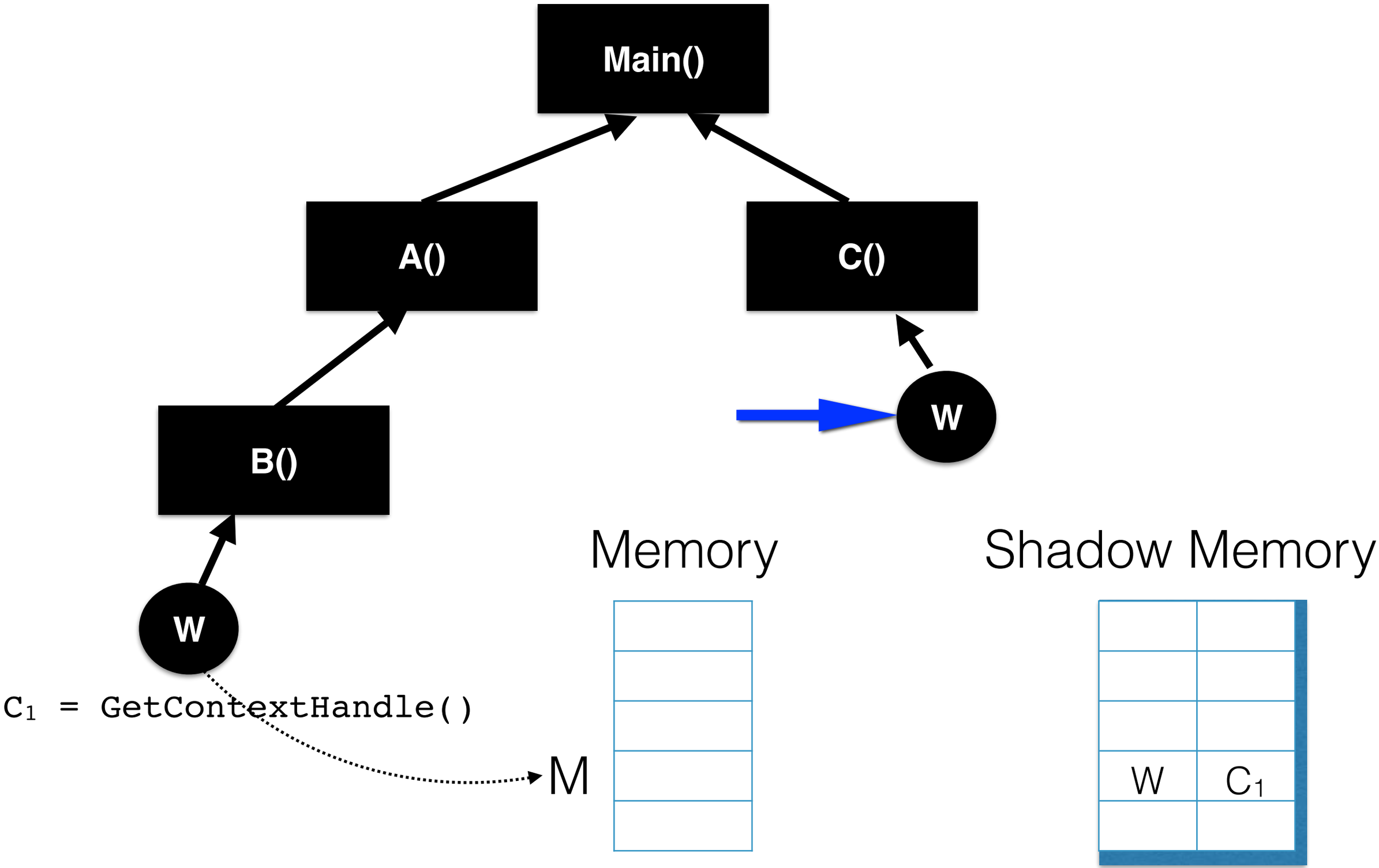

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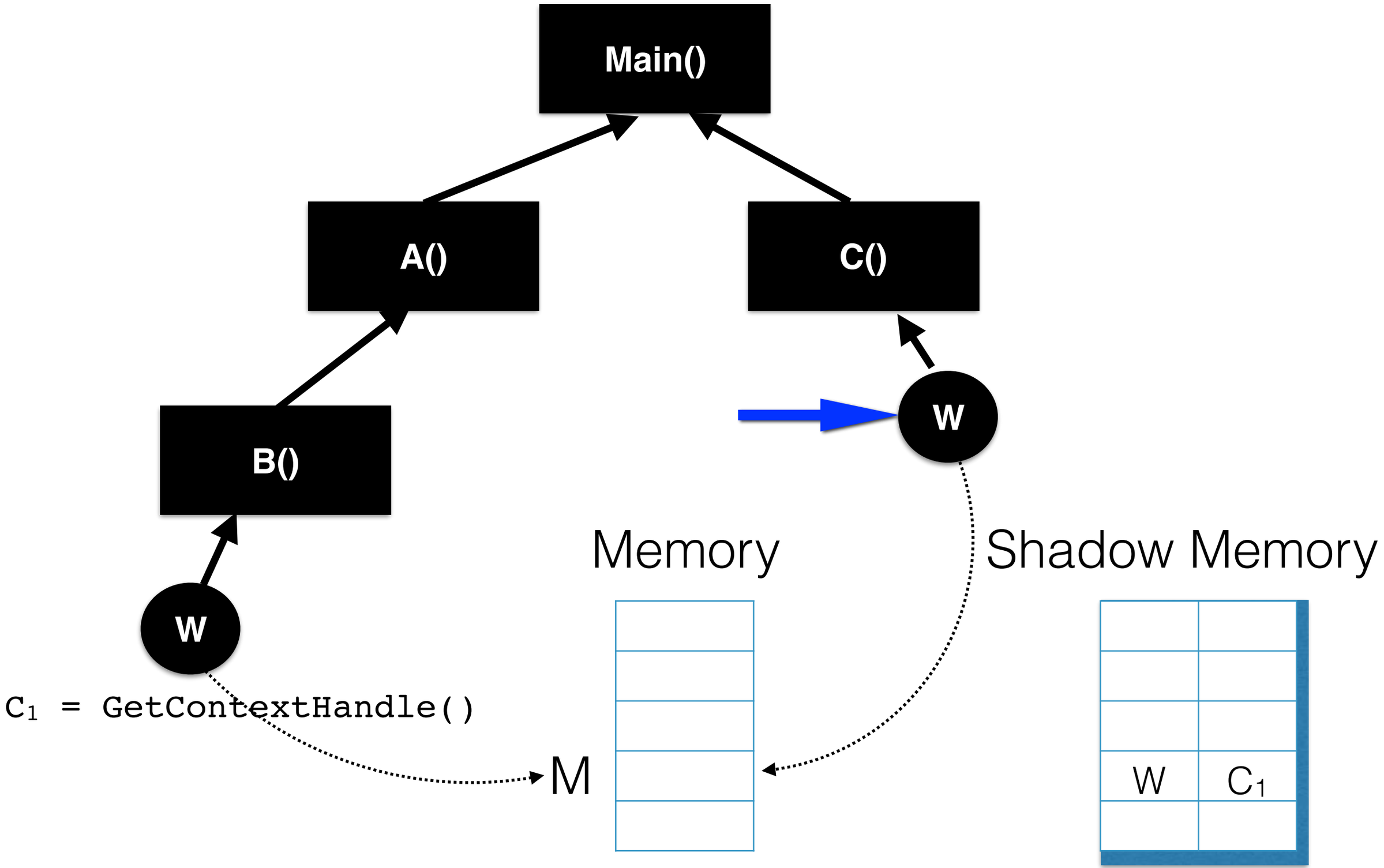

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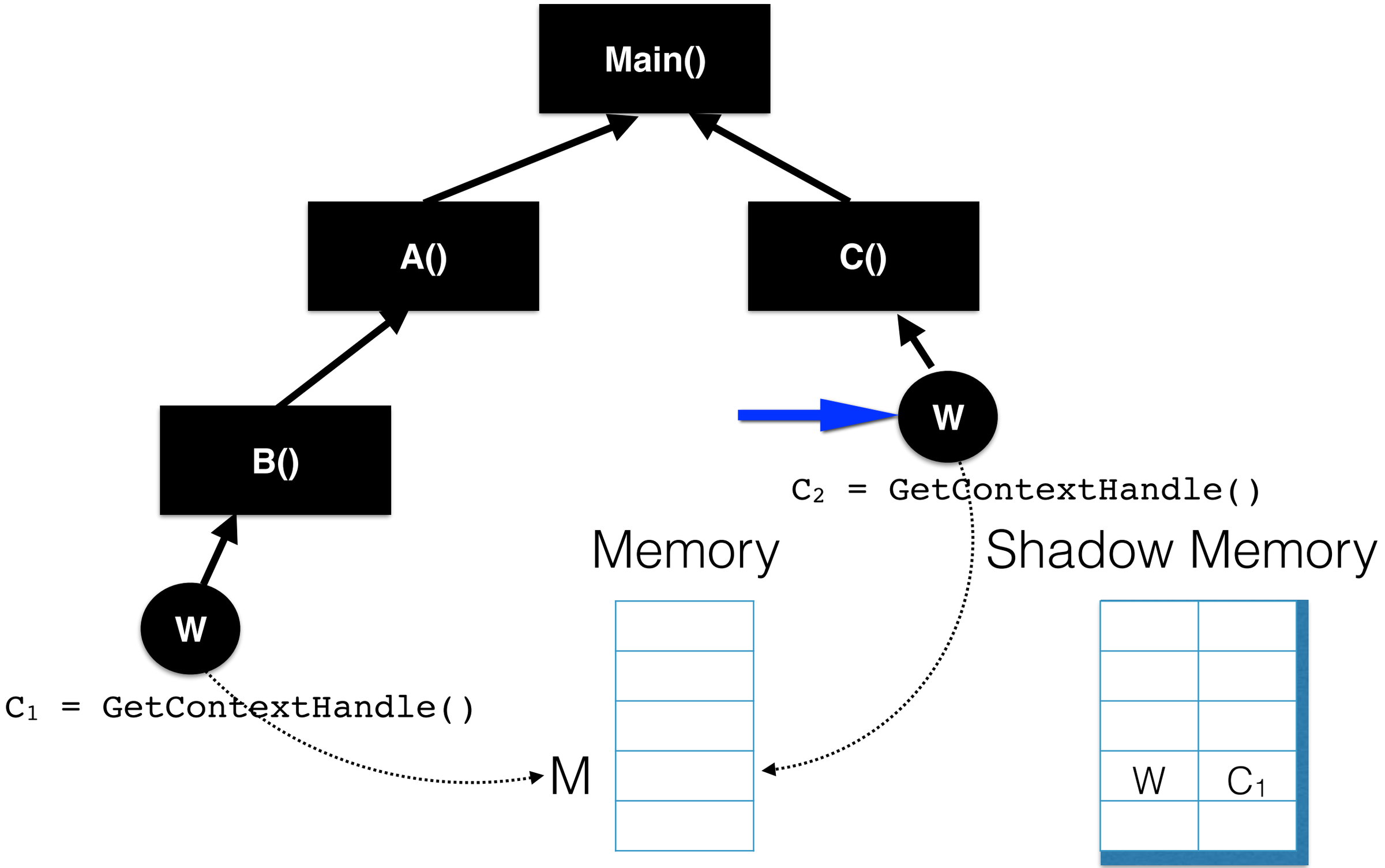
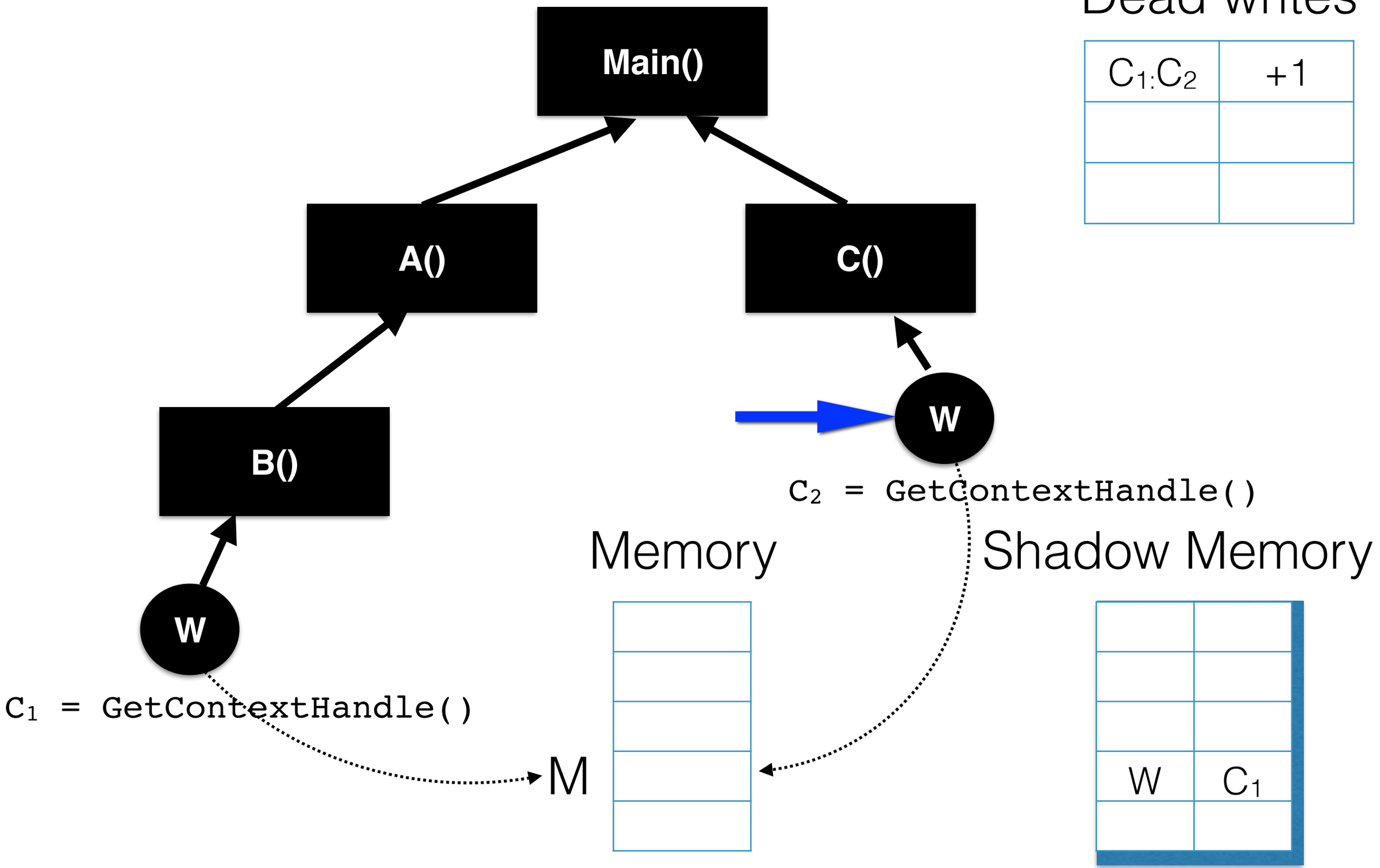


DeadSpy + CCTLib in Action

Dead writes

C_1:C_2	+1



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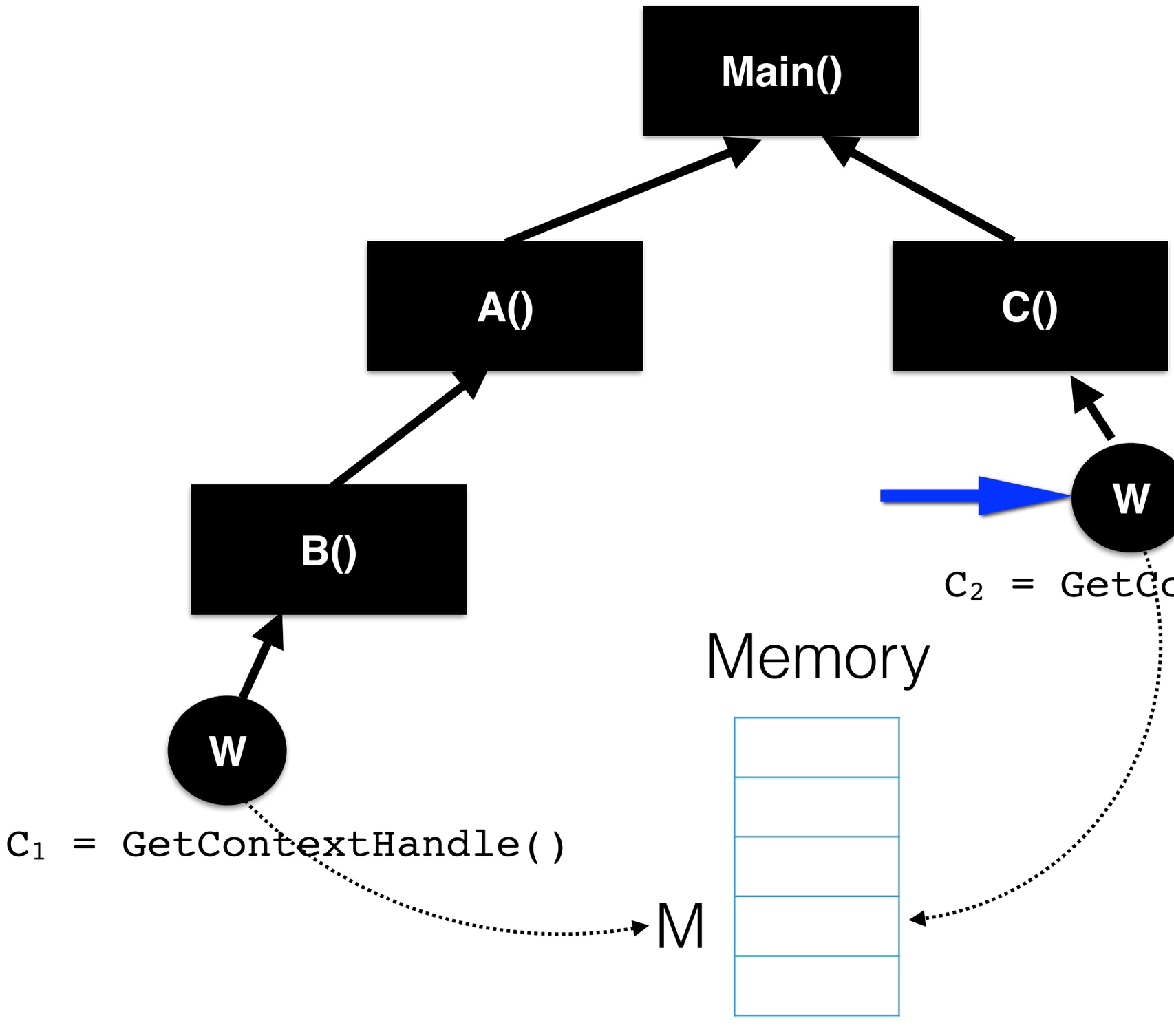
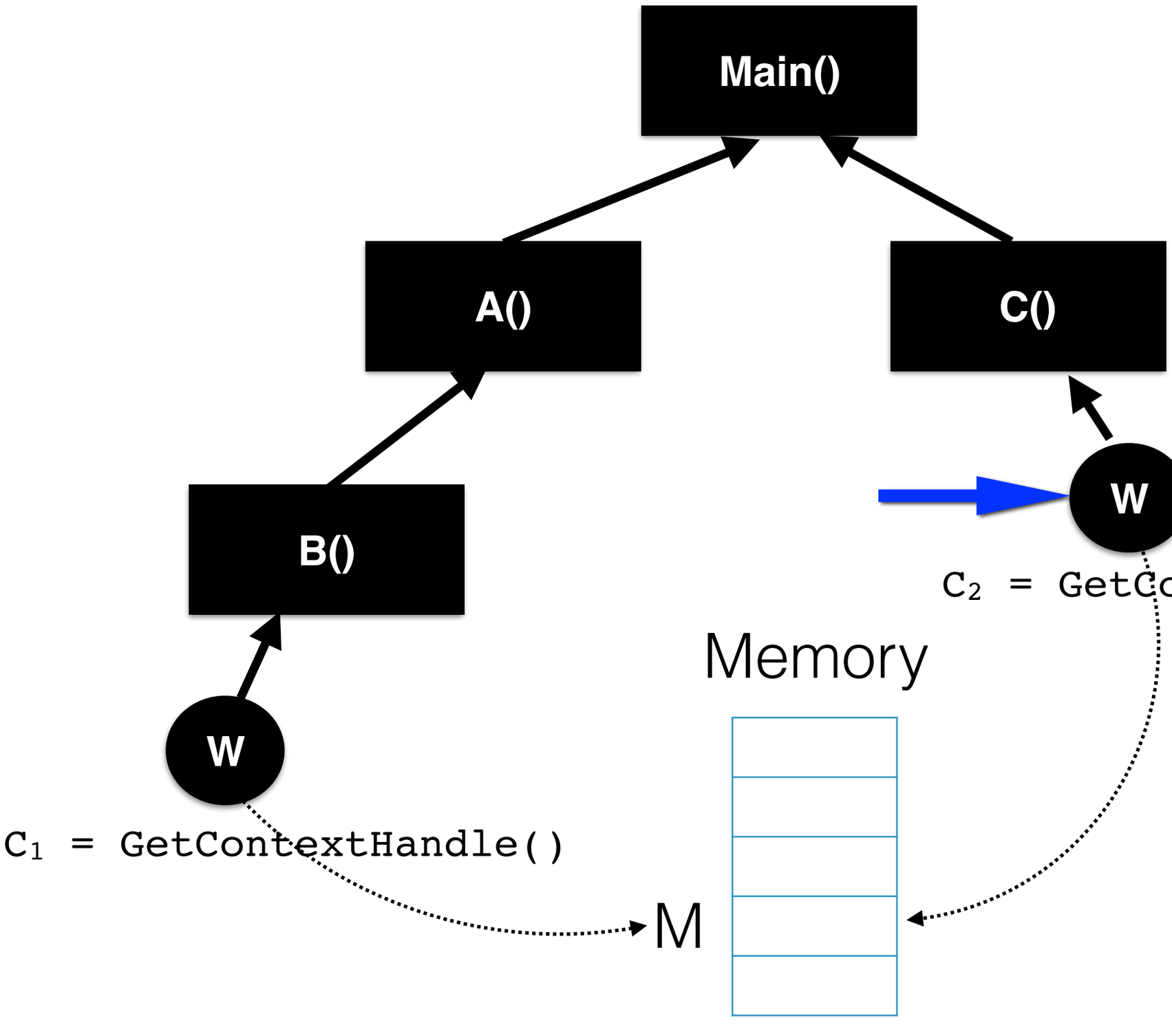


Dead writes

C_1:C_2	1234
C_3:C_{23}	959
C_2:C_{14}	546

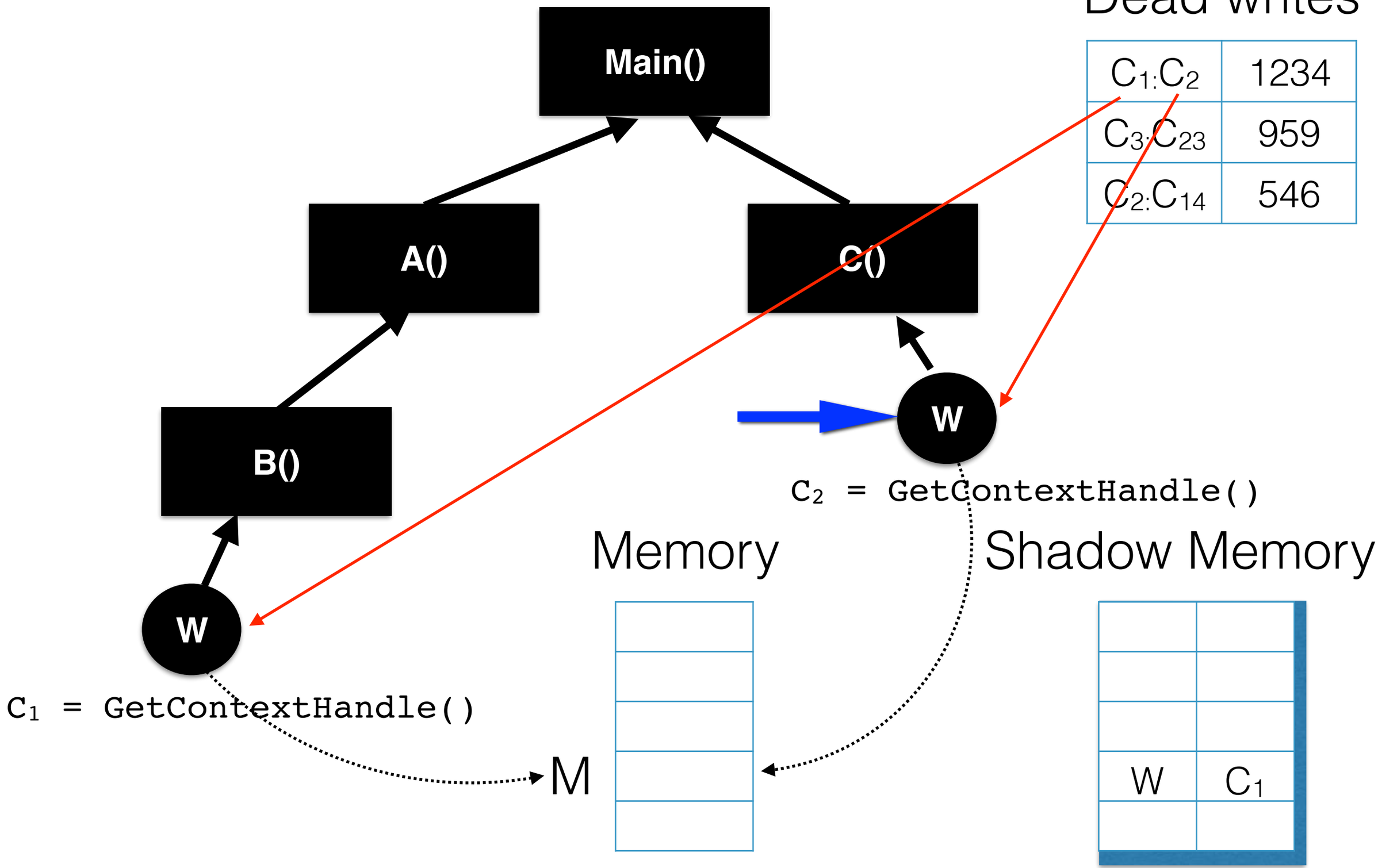
DeadSpy + CCTLib in Action



Dead writes

C_1:C_2	1234
C_3:C_{23}	959
C_2:C_{14}	546

DeadSpy + CCTLib in Action



Dead writes

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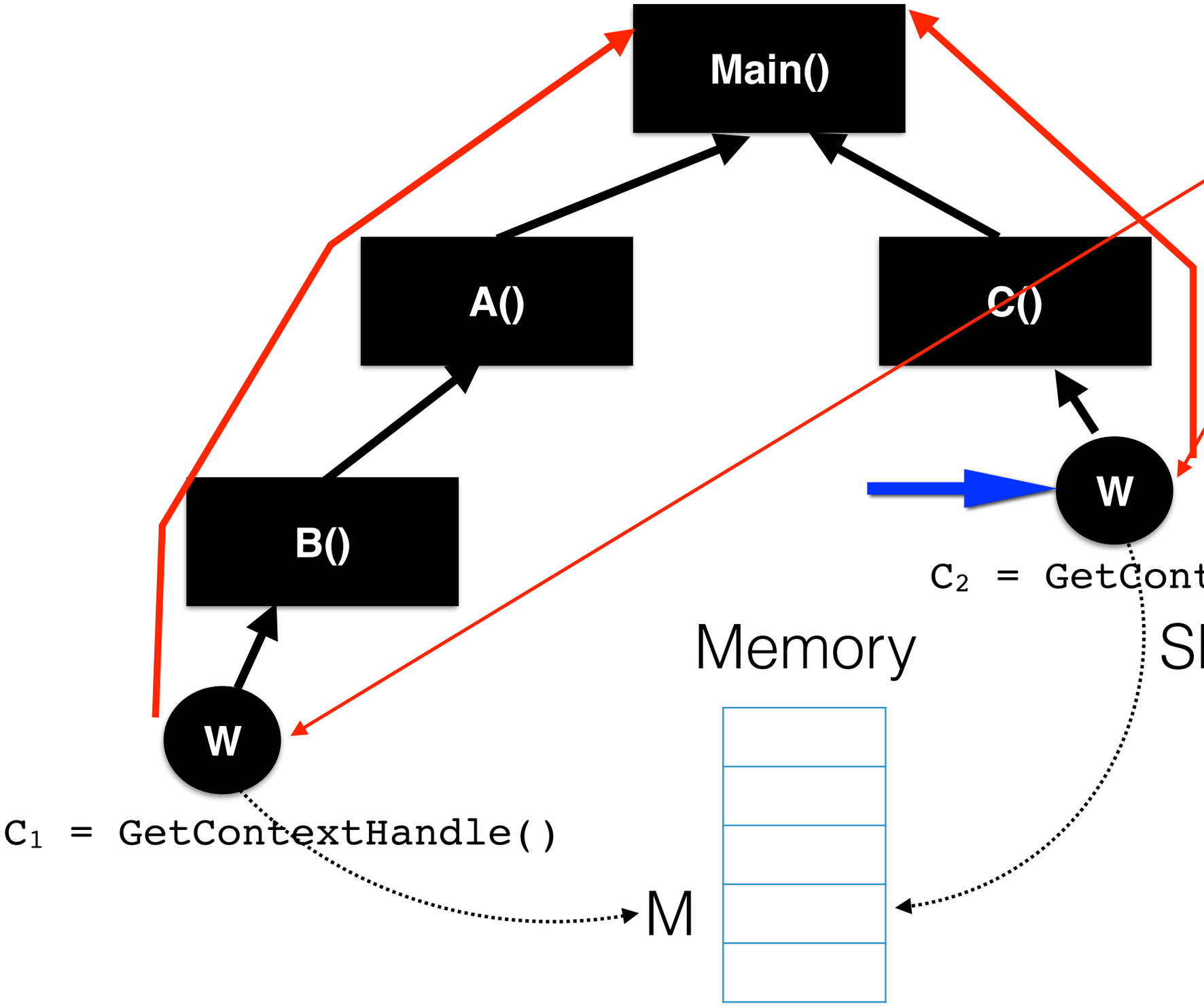

Dead writes

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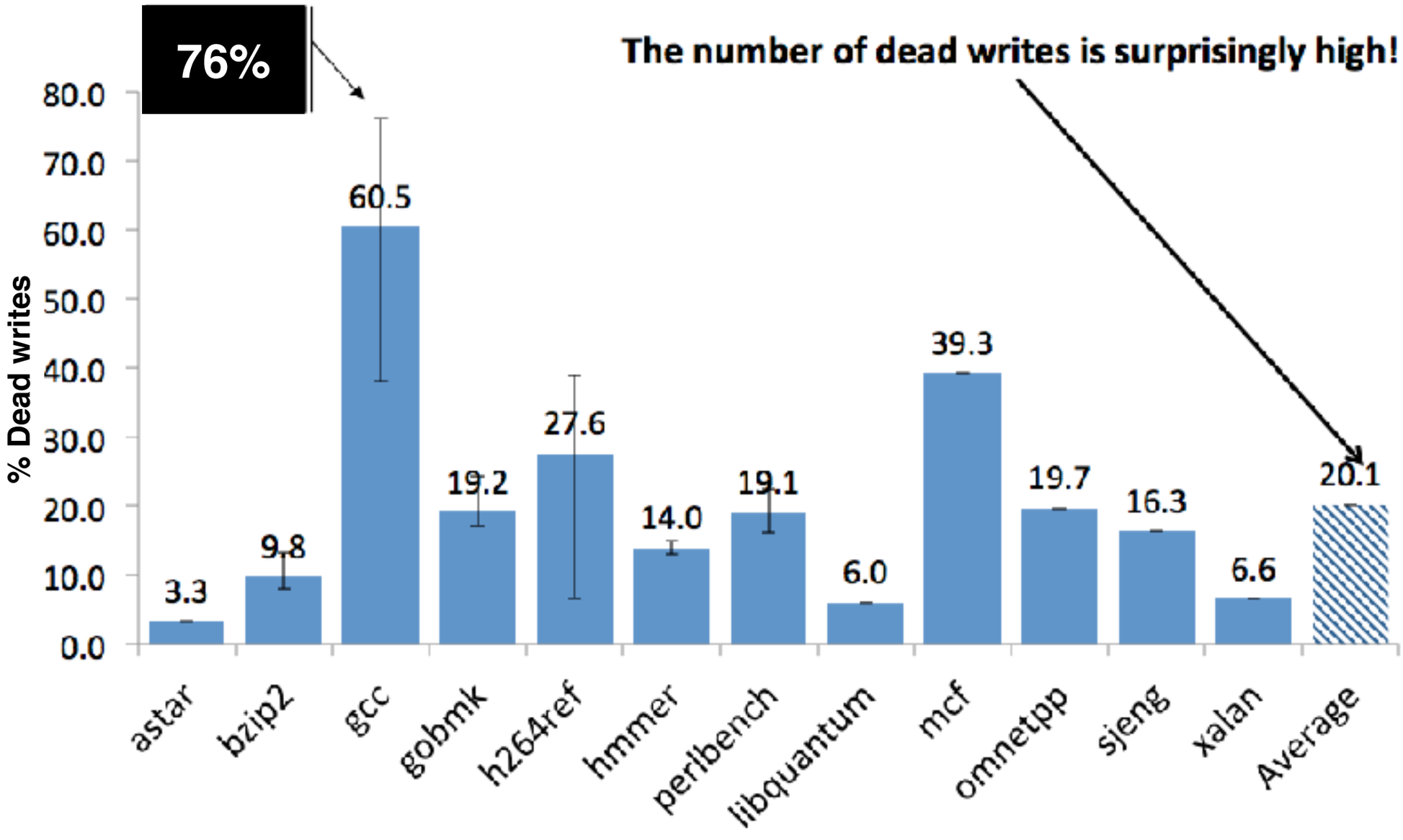
Dead Writes in SPEC CPU 2006

Lower is better



Across compilers and optimization levels

HMMER: Lack of Design for Performance

Unoptimized

```
for (i = 1; i <= L; i++) {
   for (k = 1; k <= M; k++) {
      ...
      ic[k] = mpp[k] + tpmi[k];
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-O3 optimized

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Declare as “restrict” pointers.
Can vectorize.

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> 16% running time improvement
> 40% with vectorization

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DeadSpy and traditional value profiling cannot detect this redundancy

Value Agnostic vs. Value Aware

- DeadSpy: Value Agnostic
  - ✦ Does not inspect the value at a location; merely inspects the operation (read/write) on a location
- RedSpy: Value Aware
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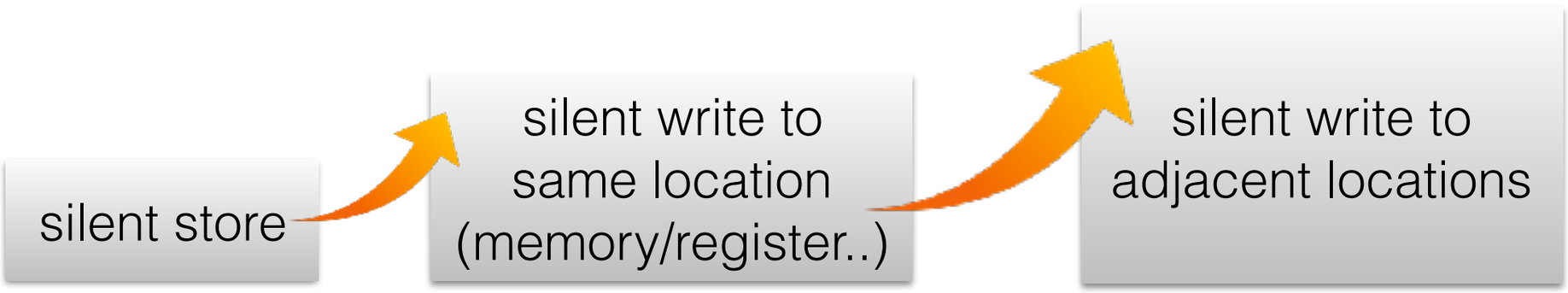

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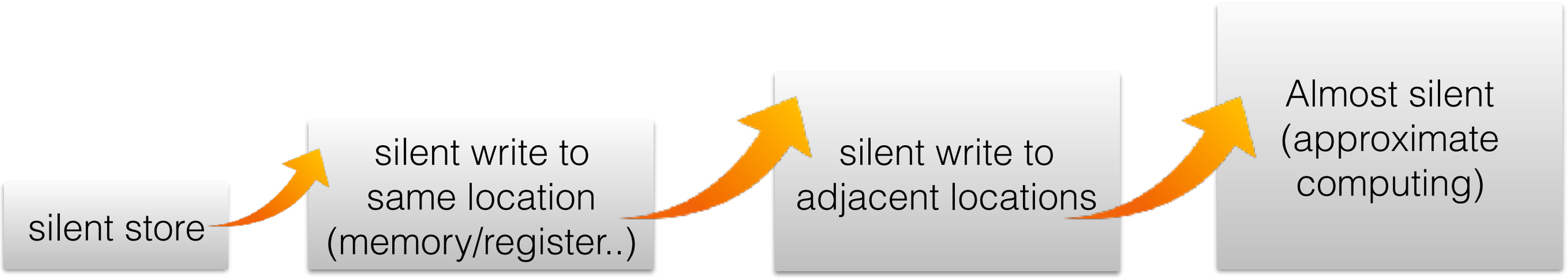

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Exact & approximate

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- Temporal value locality (temporal redundancy)
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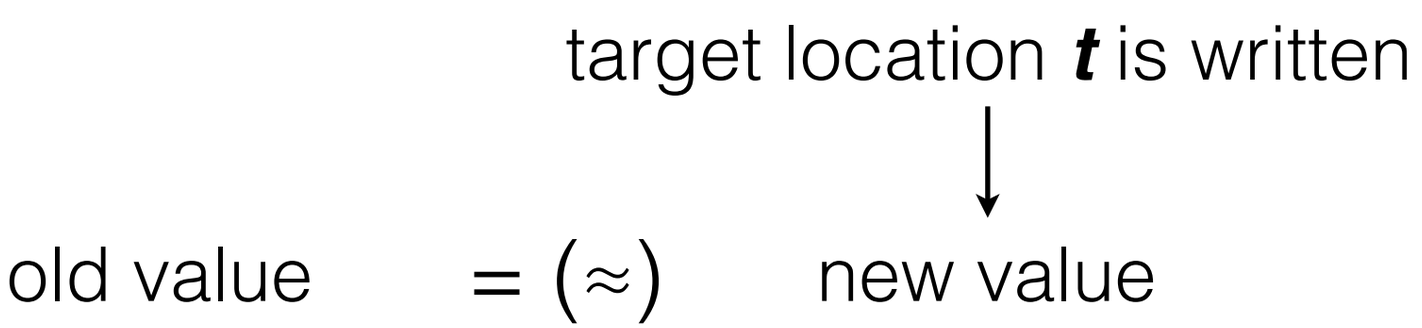

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old value = (≈) new value

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old operation <redundant with> current operation

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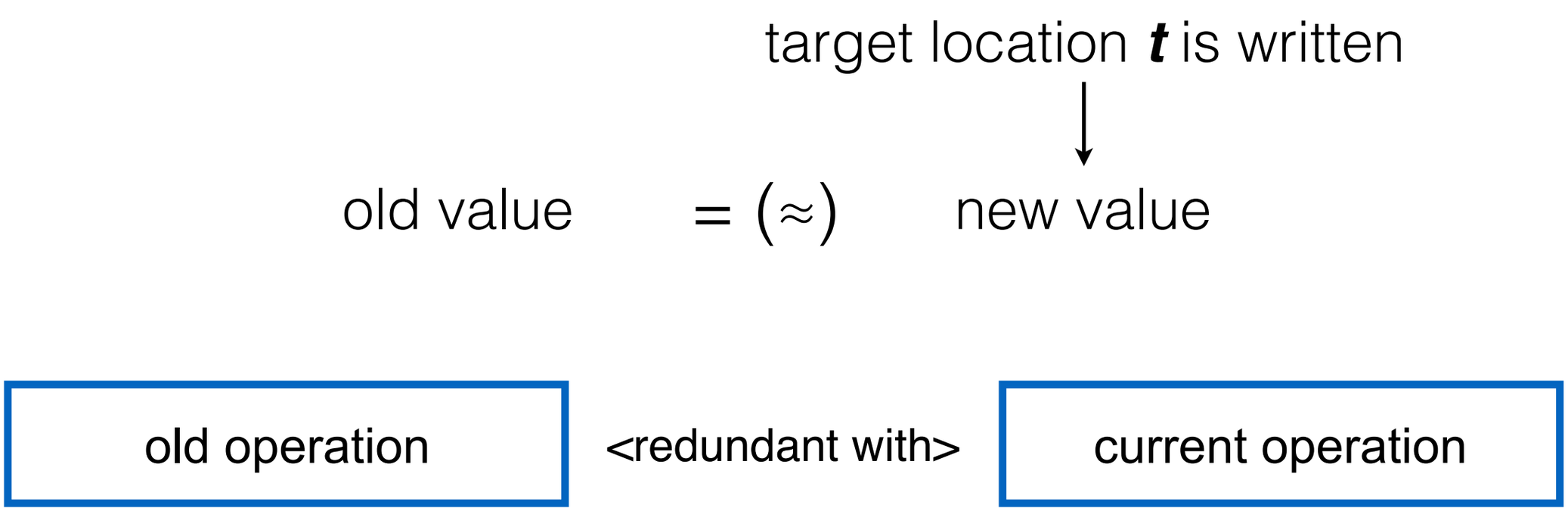

CCTLib

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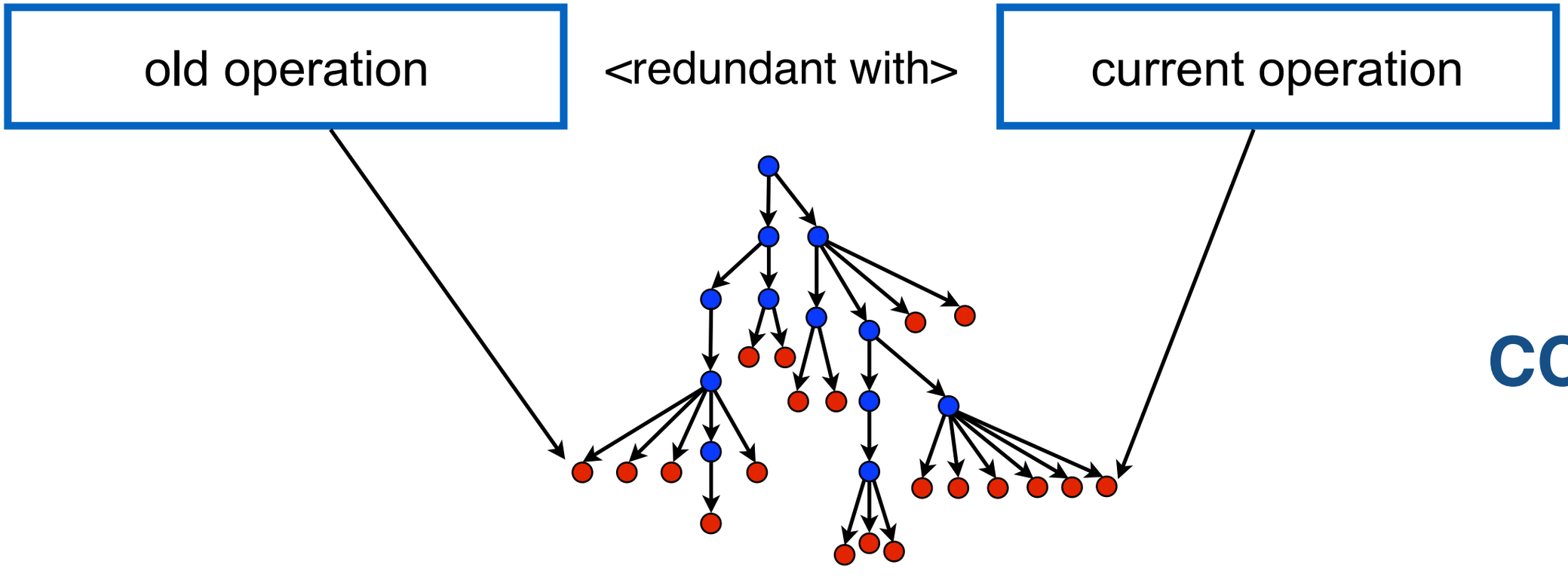


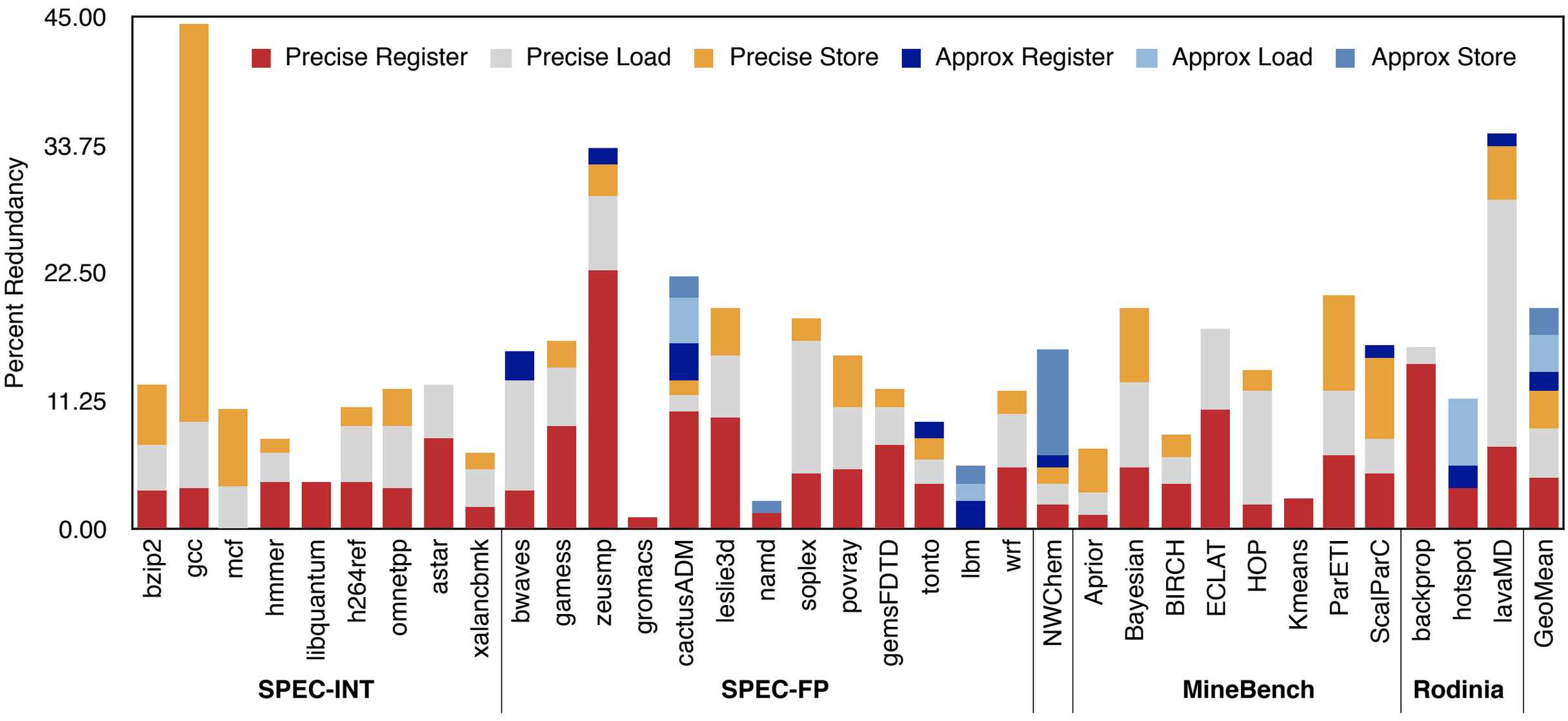
CCTLib

RedSpy: Spatial Value Locality

- User provides instrumentation points
  - Where? call predefined function
  - How? array, size, checking stride, approximation
- CCTLib scans while data structure and identifies the ratio of unique values to total elements

RedSpy: Experiments

- Temporal redundancy
  - ✦ GCC 4.8.5 -O3 PGO



GeoMean precise reg-reg = 4.46% GeoMean precise load = 4.45% GeoMean precise store = 3.13%

GeoMean approx reg-reg = 1.71% GeoMean approx load = 3.37% GeoMean approx store = 2.33%

Case Study: h264ref SPEC CPU2006

- Redundant writes to same location (temporal redundancy)
  - ✦ 13% loads and 13% stores are redundant

```
for (pos = 0; pos < max_pos; pos++) {
   ...
   if(...)  PelYline_11 = FastLine16Y_11;
   else  PelYline_11 = UMVLine16Y_11;

  for (blky = 0; blky < 4; blky++) {
for (y = 0; y < 4; y++) {
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parameters seldom change

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- Optimization
  - Inline the two functions
  - 1.34x speedup; 23% energy saving

Case Study: Rodinia hotspot

- Approximately same values
  - ✦ Elements in array `result` are similar (<1%)

```
for (r = 0; r < row; r++) {
  for (c = 0; c < col; c++) {
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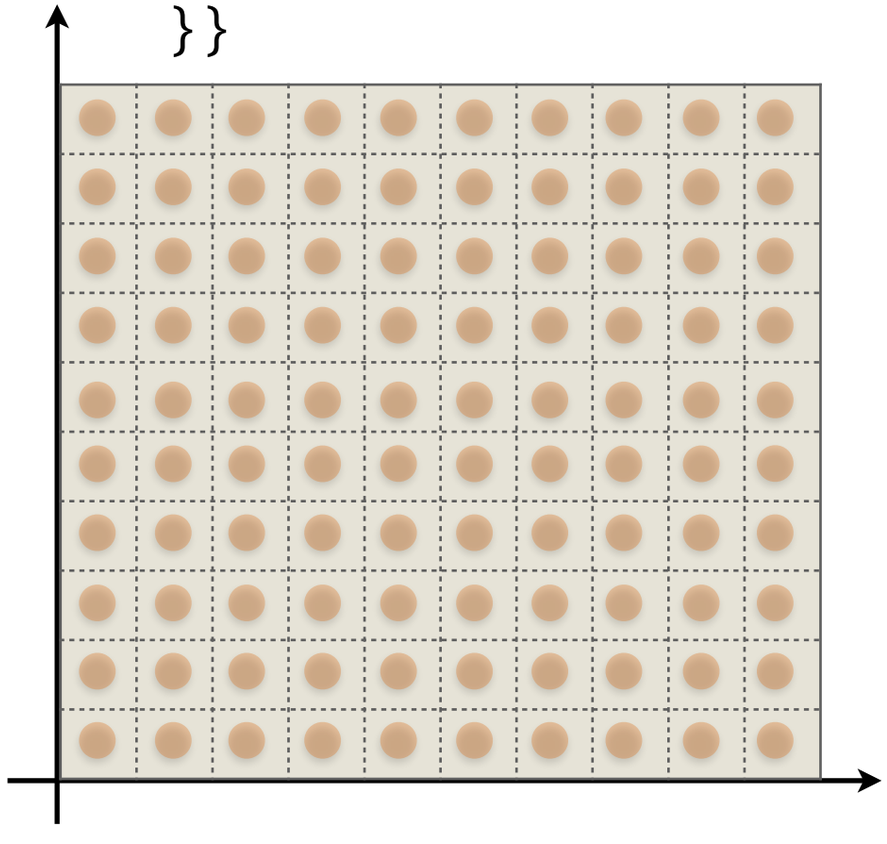

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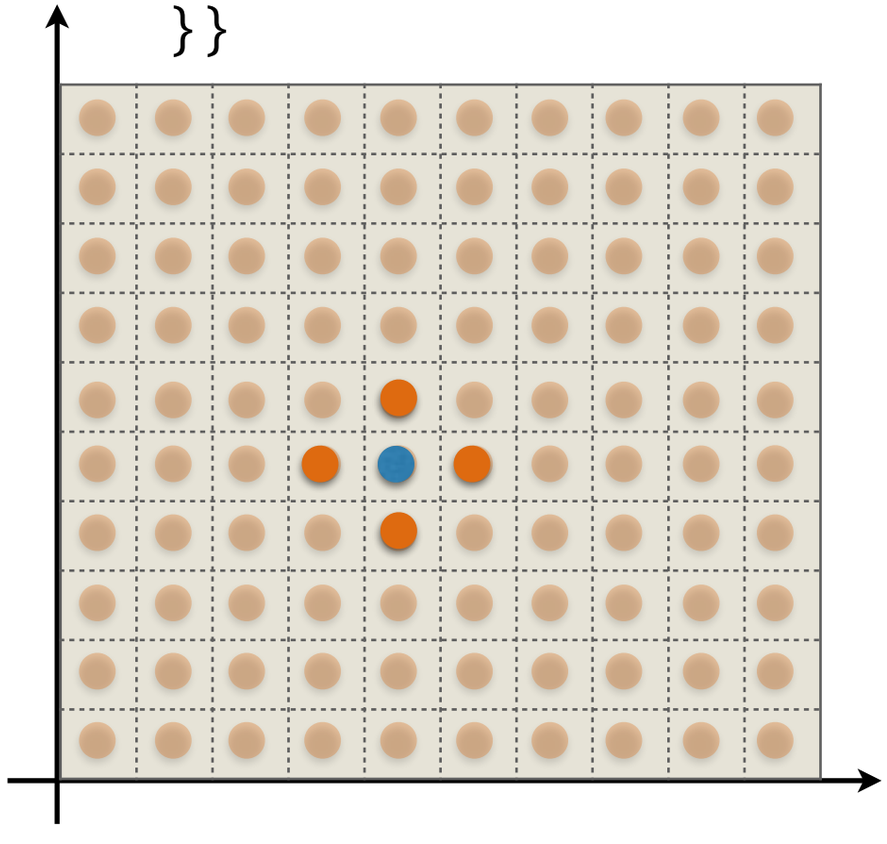

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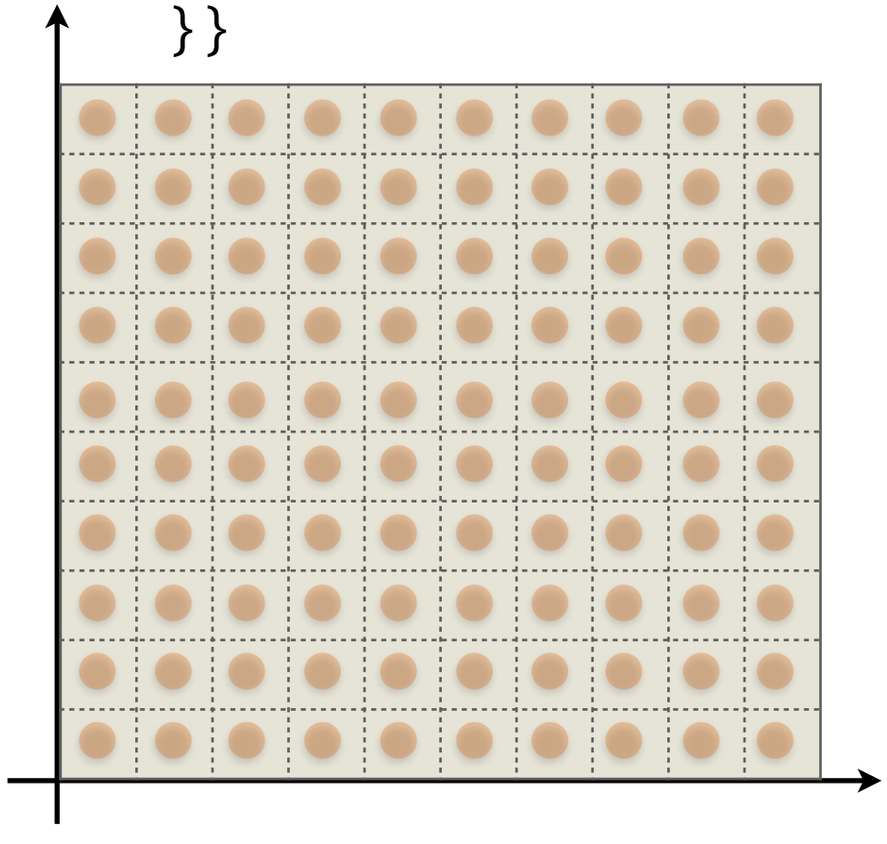

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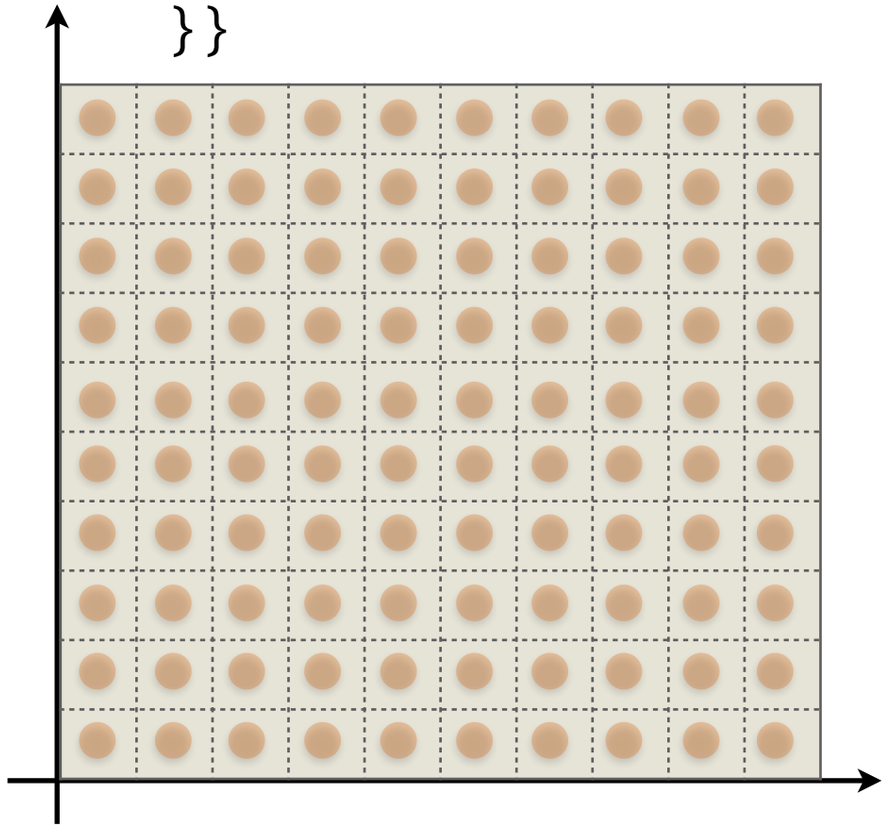

- Optimization
  - calculate the first and middle column
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  - mean relative error: <0.6%

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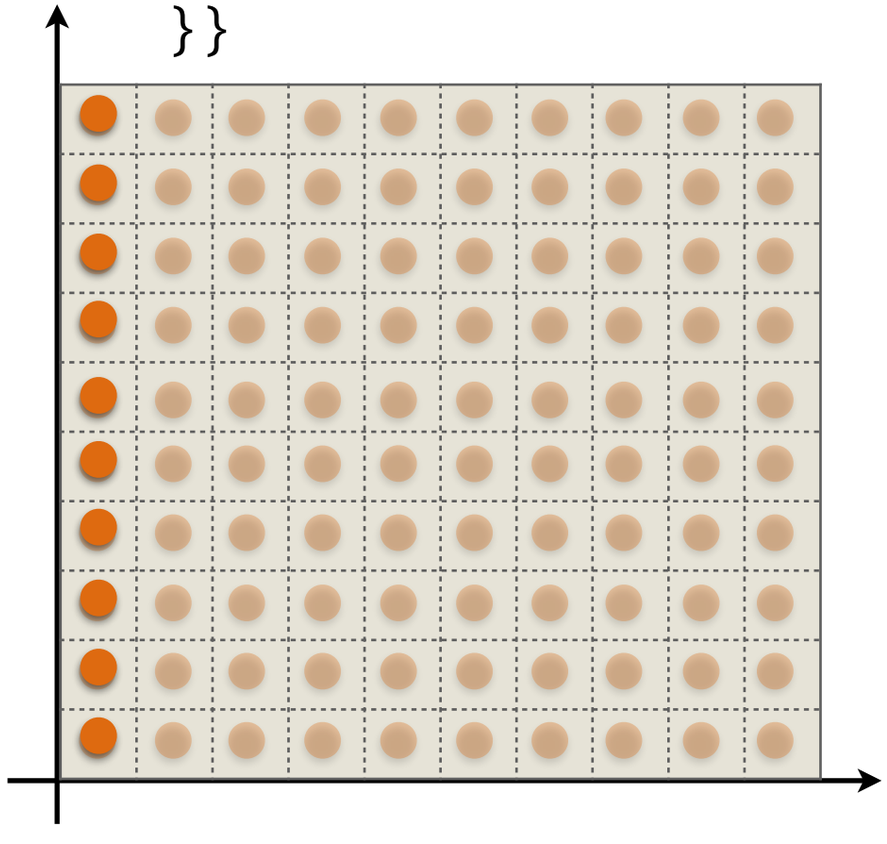

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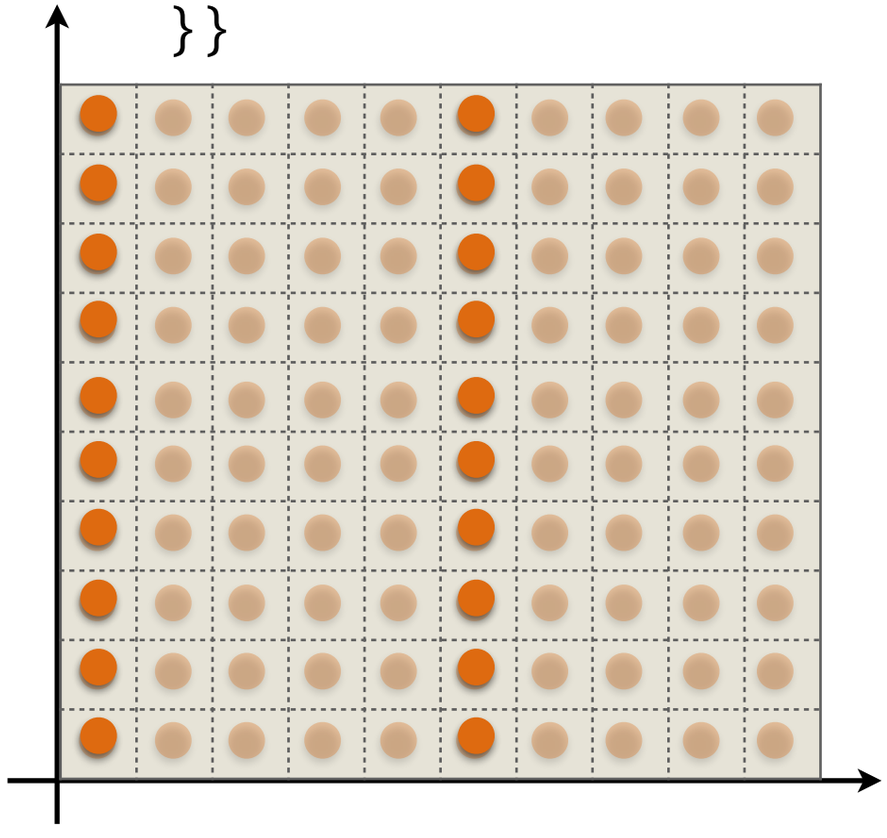
       2.0*temp[r*col+c]) / Rx + (amb_temp - temp[r*col+c]) / Rz);
     }
     result[r*col+c] =temp[r*col+c]+ delta;
} }
```



- Optimization
  - calculate the first and middle column
  - 2.21x speedup; 70% power saving
  - mean relative error: <0.6%

Case Study: Rodinia hotspot

- Approximately same values
  - Elements in array `result` are similar (<1%)

```
for (r = 0; r < row; r++) {
  for (c = 0; c < col; c++) {
  ...{
       delta = (step / Cap)*(power[r*col+c] + (temp[(r+1)*col+c]+temp[(r-1)*col +c]
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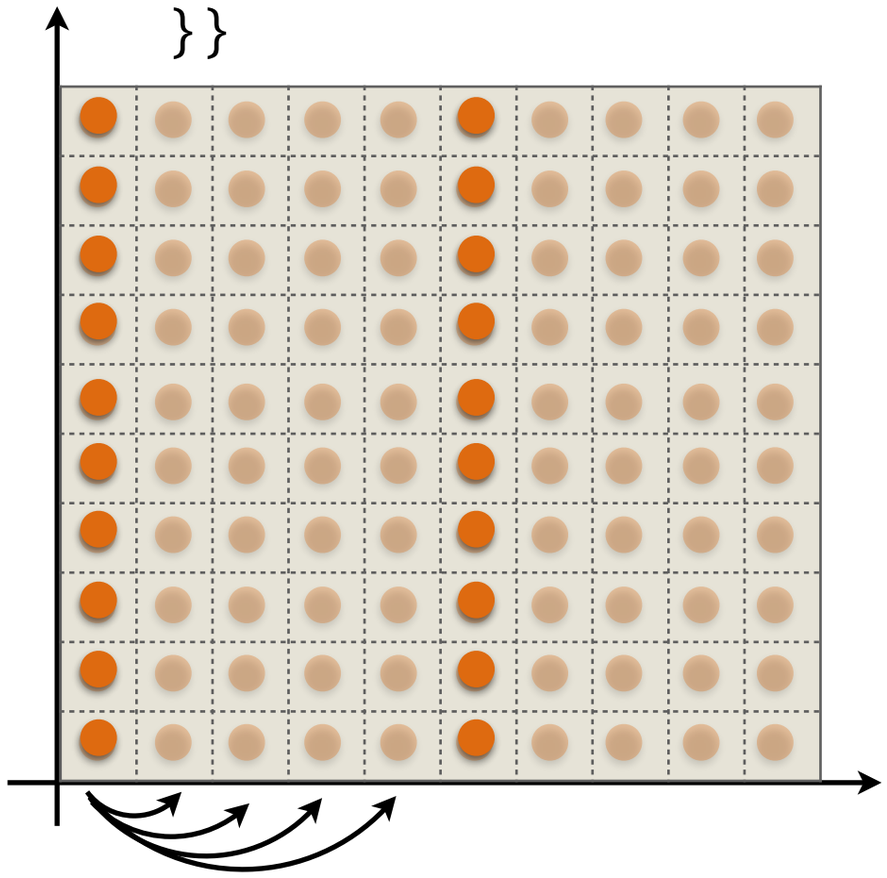

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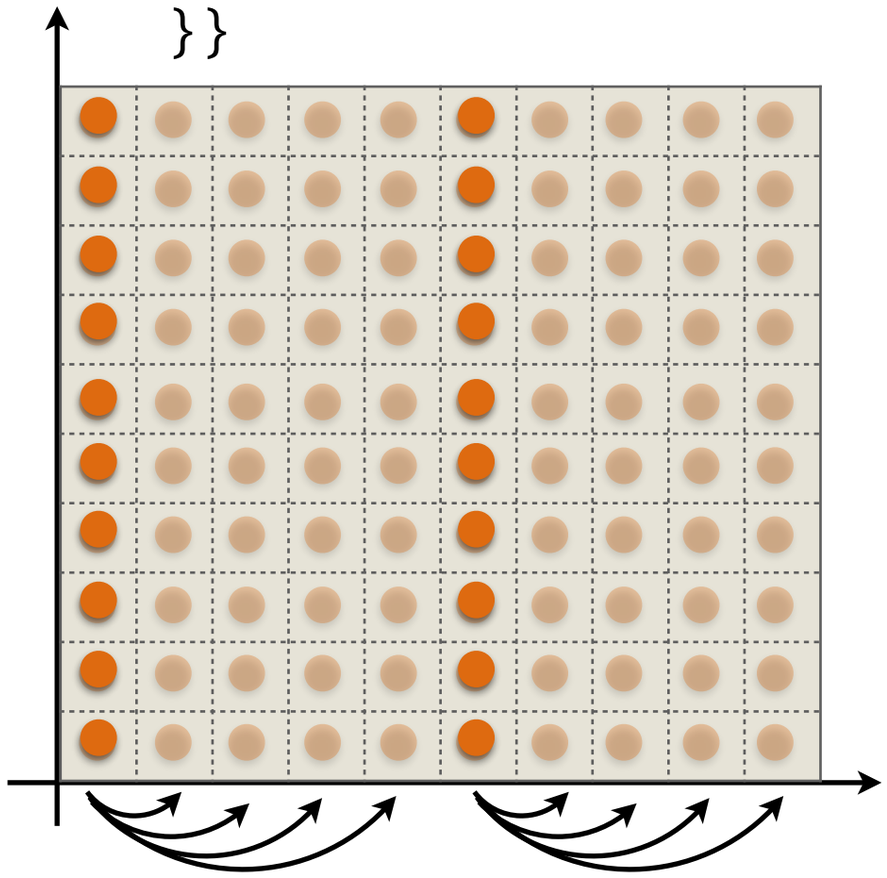

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Summary

- Production programs suffer from myriad inefficiencies in software
  - ✦ Compilers and traditional tools are insufficient
- Fine-grained monitoring tools are necessary for identifying several kinds of program inefficiencies
  - ✦ Fine-grained tools can provide semantic information for developer productivity
- CCTLib provides efficient calling context collection for production workloads at moderate overhead
- CCTLib is open source: https://github.com/CCTLib/cctlib
- Pin tools built with CCTLib pinpoint software inefficiencies and offer new venues to tuning