MICHIGAN ENGINEERING
UNIVERSITY OF MICHIGAN

Spindle: Informed Memory Access Monitoring

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Group 4

What is Spindle?

A tool that performs ***static analysis*** in order to obtain regular and predictable patterns in ***memory accesses*** of a program

How does the memory access trace look like?

```
Load address1
Store address1
Load address2
Load address3
Load address4
Store address4
…
…
…
```

- Tells the sequence of memory addresses hence accesses
- Might have patterns > Spindle

Why is knowing memory accesses important?

Performance Optimization

- Locality analysis:
  - Temporal: access same memory location
  - Spatial: access nearby memory location
  - Improve cache utilization

- Cache efficiency:
  - Design algorithms and data structures
  - Exploit cache hierarchies
  - Reduce cache misses

Why is knowing memory accesses important?

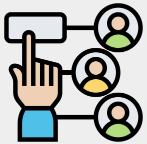
Memory prefetching

- Prefetching of Future Accesses:
  - Predict future memory accesses
  - Load data into cache before it is needed

Why is knowing memory accesses important?

Memory management

- Allocation and Deallocation:
  - Optimize memory allocation patterns
  - Reduce fragmentation



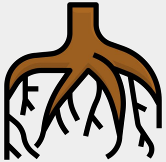
- Memory leak detection:
  - Anomalies: repeated allocations without corresponding deallocations
  - Maintains stability and reliability of an application

Why is knowing memory accesses important?

Debugging and Profiling

- Identifying Bottlenecks:
  - Identify performance bottlenecks due to memory usage
  - Focus optimization on crucial parts of the code

- Root Cause Analysis:
  - Diagnosing the root cause of problems
    - Segmentation faults
    - Out-of-memory errors
    - Inefficient memory usage



Why is knowing memory accesses important?

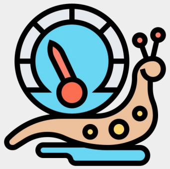
Resource Planning

- Resource Utilization:
  - Efficiency of system resources utilization
  - Useful in environments with constrained resources
    - Embedded systems
    - Cloud computing

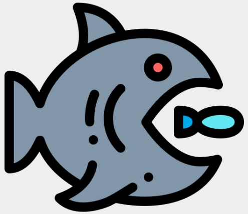
Other tools

- Valgrind and Intel PIN can produce a full list of memory access trace
- **Problems**

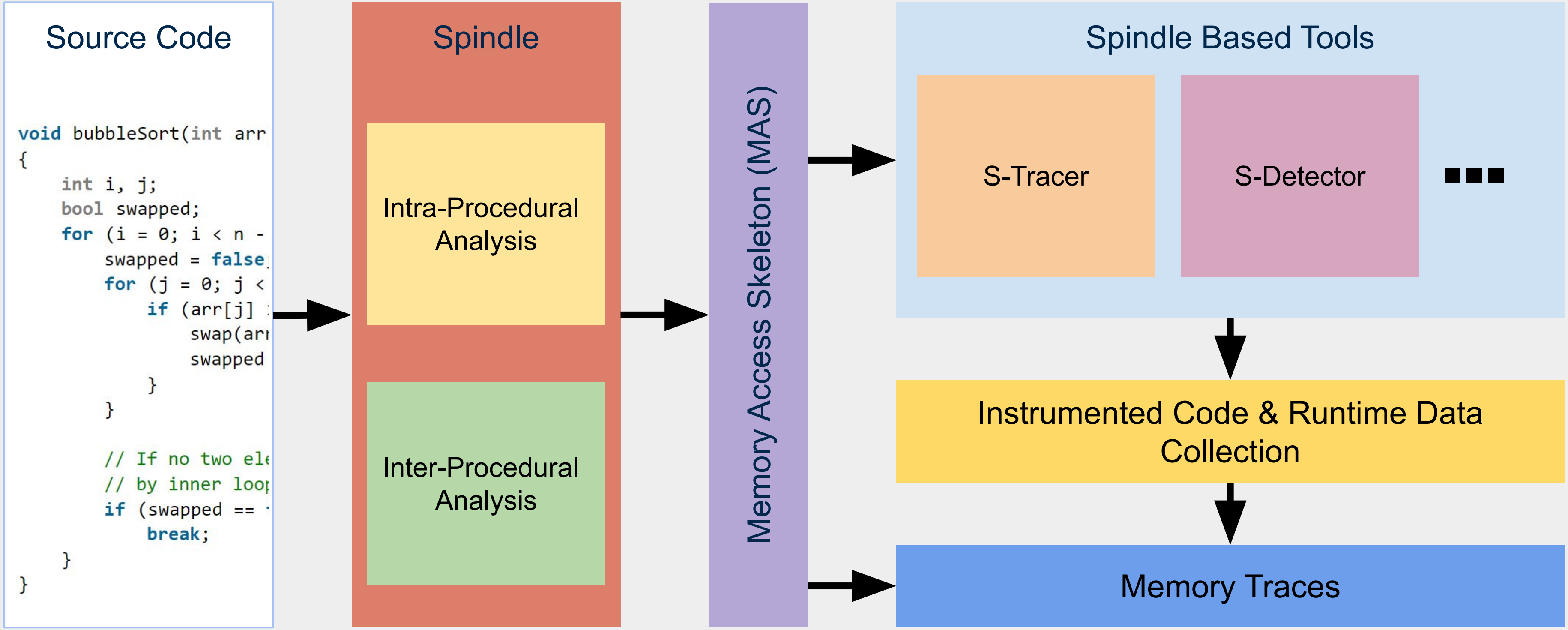
S l o w



Large Files

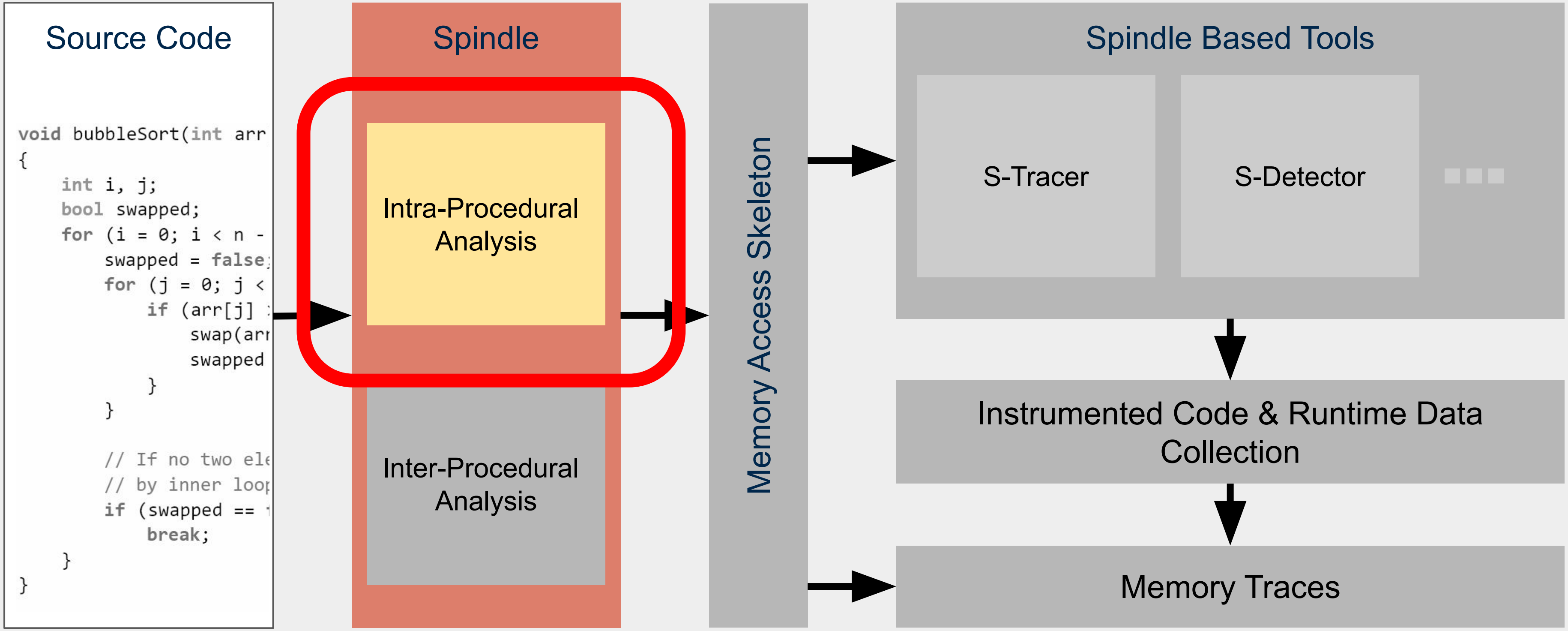


Spindle Overview



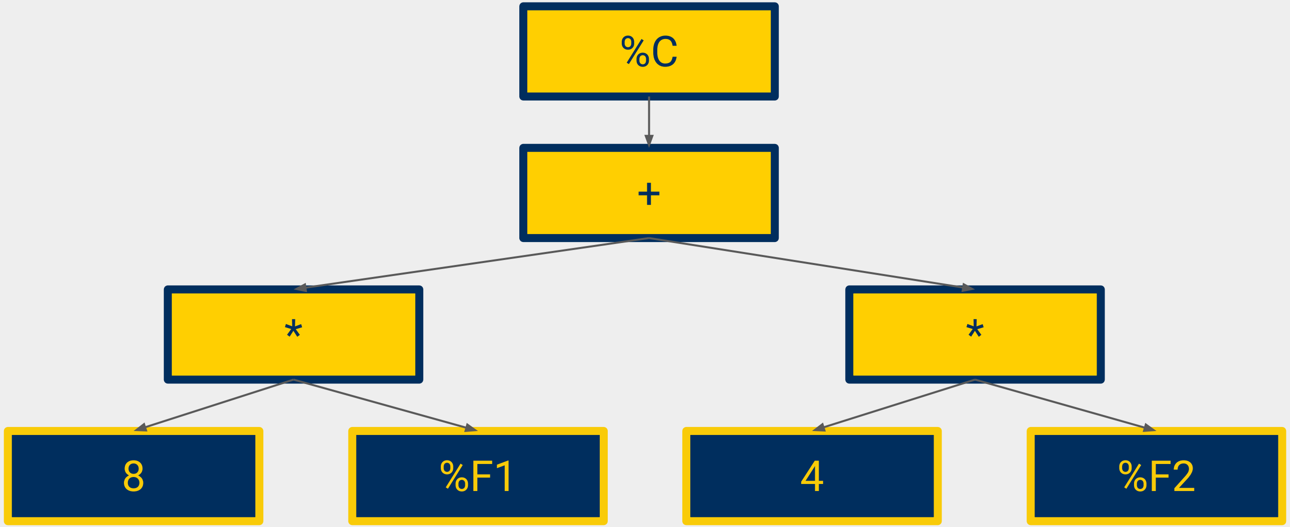
Cropped Bubble Sort Image: [GeeksforGeeks Bubble Sort Algorithm Article]

Intraprocedural Analysis



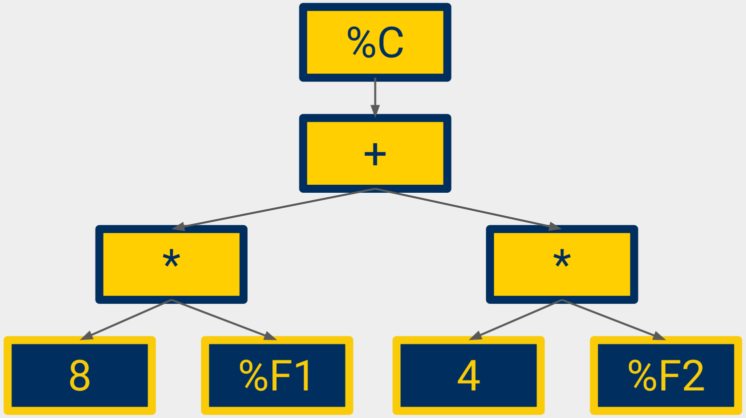
Memory Dependence Trees

%A = mul i32 8, %F1
%B = mul i32 4, %F2
%C = add i32 %B, %A
%D = load i32* %C

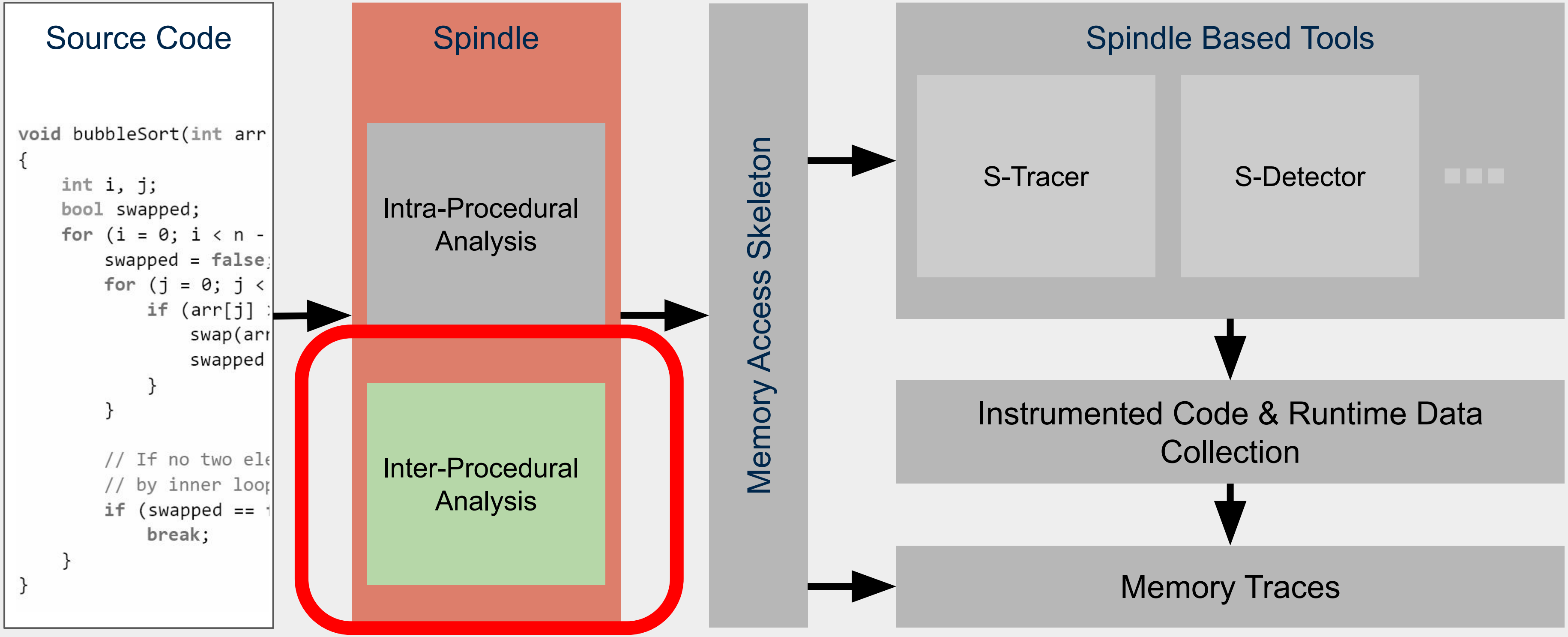


Types of Leaf Nodes

- **Constant value (compile time)**
- **Loop induction variable (compile time or runtime)**
- Base memory address (compile time or runtime)
- Function parameter (compile time or runtime)
- Data-dependent variable (runtime)
- Function return value (runtime)



Interprocedural Analysis



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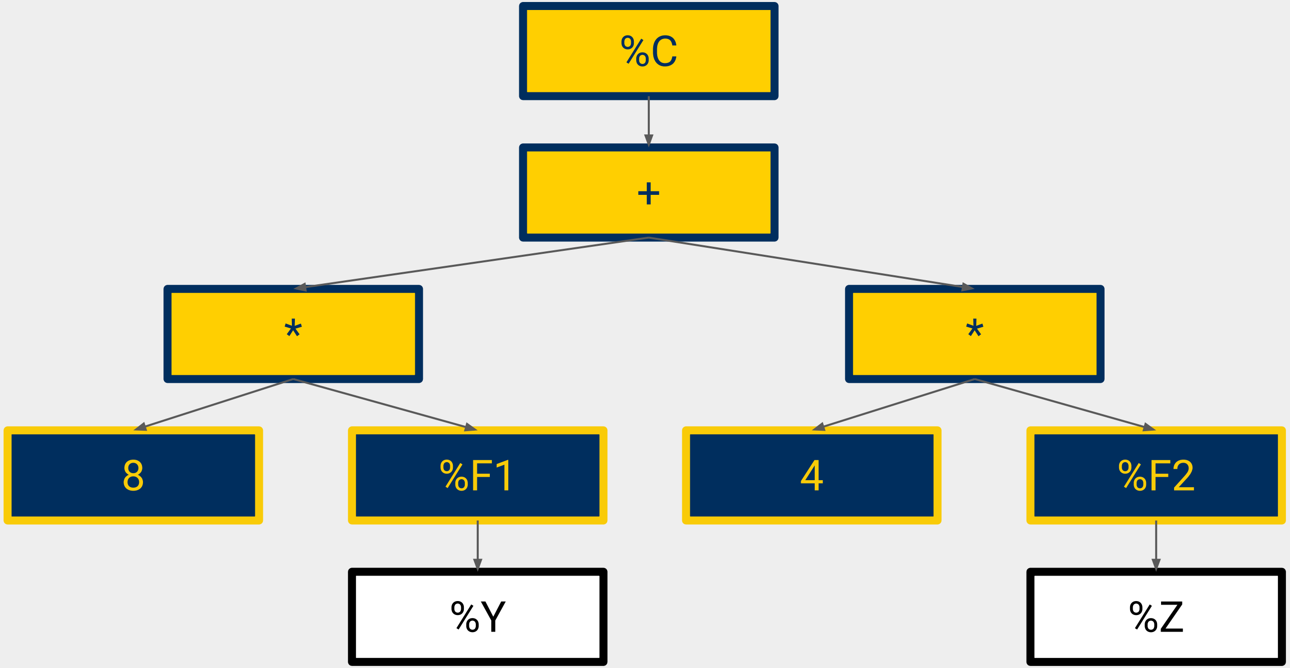
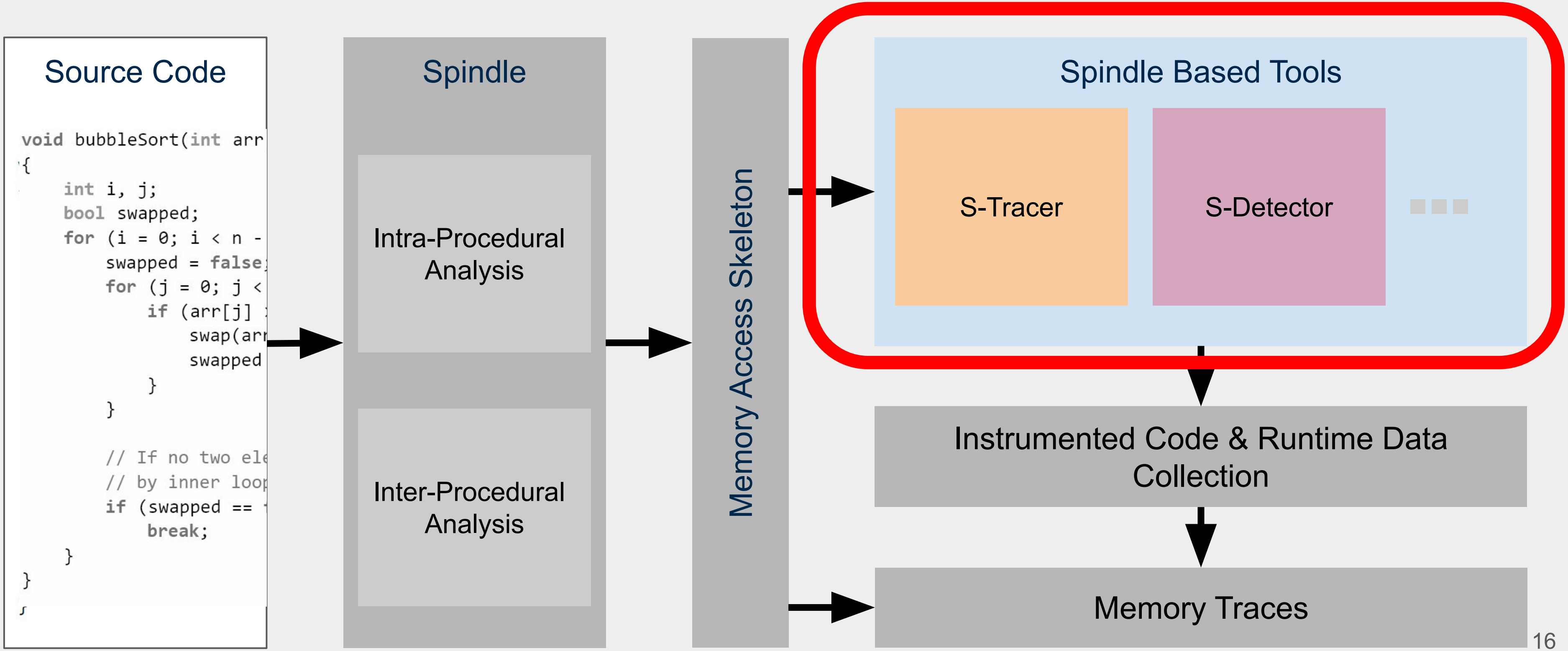
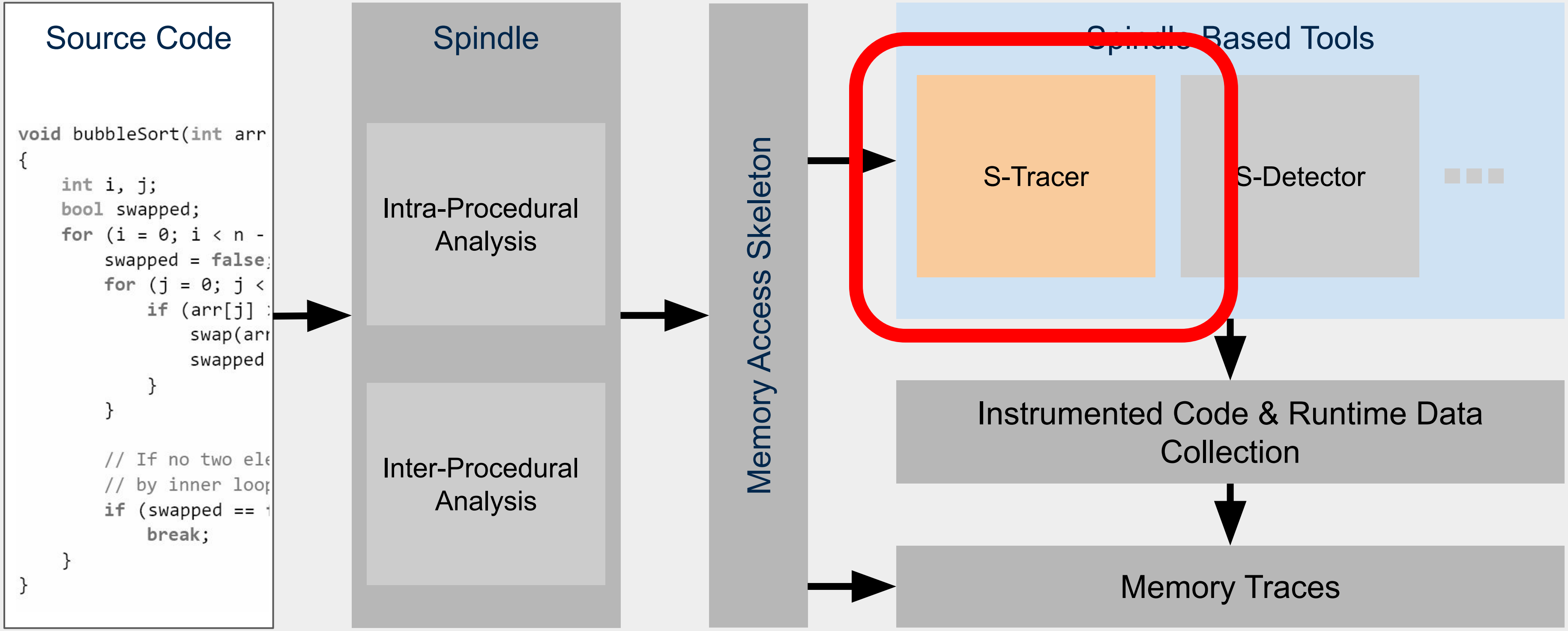


Spindle-Based Tools



S-Tracer



Source Code
void bubbleSort(int arr
{
int i, j;
bool swapped;
for (i = 0; i < n -
swapped = false;
for (j = 0; j <
if (arr[j]
swap(arr
swapped
}
}
// If no two ele
// by inner loop
if (swapped ==
break;
}
}
Spindle
Intra-Procedural Analysis
Inter-Procedural Analysis
Memory Access Skeleton
Spindle-Based Tools
S-Tracer
S-Detector
Instrumented Code & Runtime Data Collection
Memory Traces

S-Tracer

- Memory **Trace** Collector
- Existing methods: record every memory access
  - Large memory trace size
  - Slowdown of program
- Use MAS and dynamically collected data:
  - Highly compressed memory traces
  - Lower runtime overhead

Static Trace

```
Function BubbleSort(dyn_A, dyn_N) {
 Loop0: L0, 0, dyn_N, 1 {
  Loop1: L1, L0, dyn_N, 1 {
   Load1: dyn_A+L0; Load2: dyn_A+L1;
    Branch: dyn_flag {
     Call Swap(dyn_A, L0, L1);
}}}}
Function Swap(S, i, j) {
 Load3 : S+i; Load4 : S+j;
 Store1: S+i; Store2: S+j;
}
```

Dynamic Trace

```
BubbleSort {
 dyn_A:
  0x7fffdfc58320;
 dyn_N:
  10;
 dyn_flag:
  {0,0,1,1,0,...,1,1};
}
```

S-Tracer Evaluation

- Evaluation workloads:
  - Regular memory accesses
  - Irregular graph algorithms
  - Multithreaded
- Compared against the PIN (Intel) tool
- Trace Size
  - Over **100x** trace size reduction for regular access patterns
  - Worst case size reduction: **6.93x**

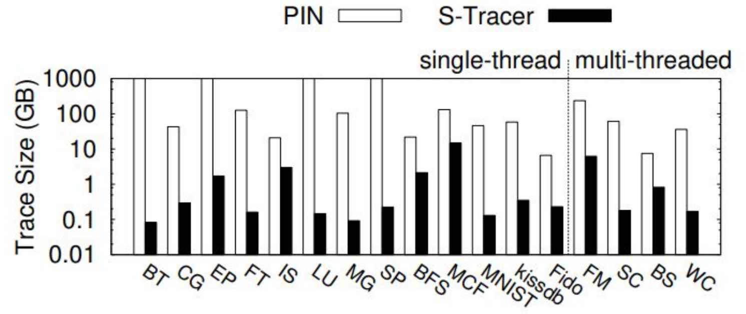


Figure 13: Trace size comparison

S-Tracer Evaluation

- Runtime Overhead
  - PIN: **502x** average slow down
  - S-Tracer: **6.5x** average slow down

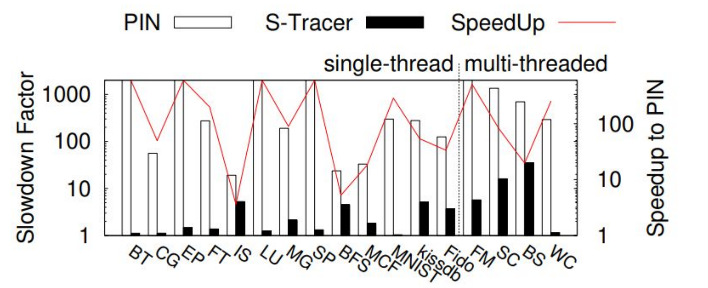
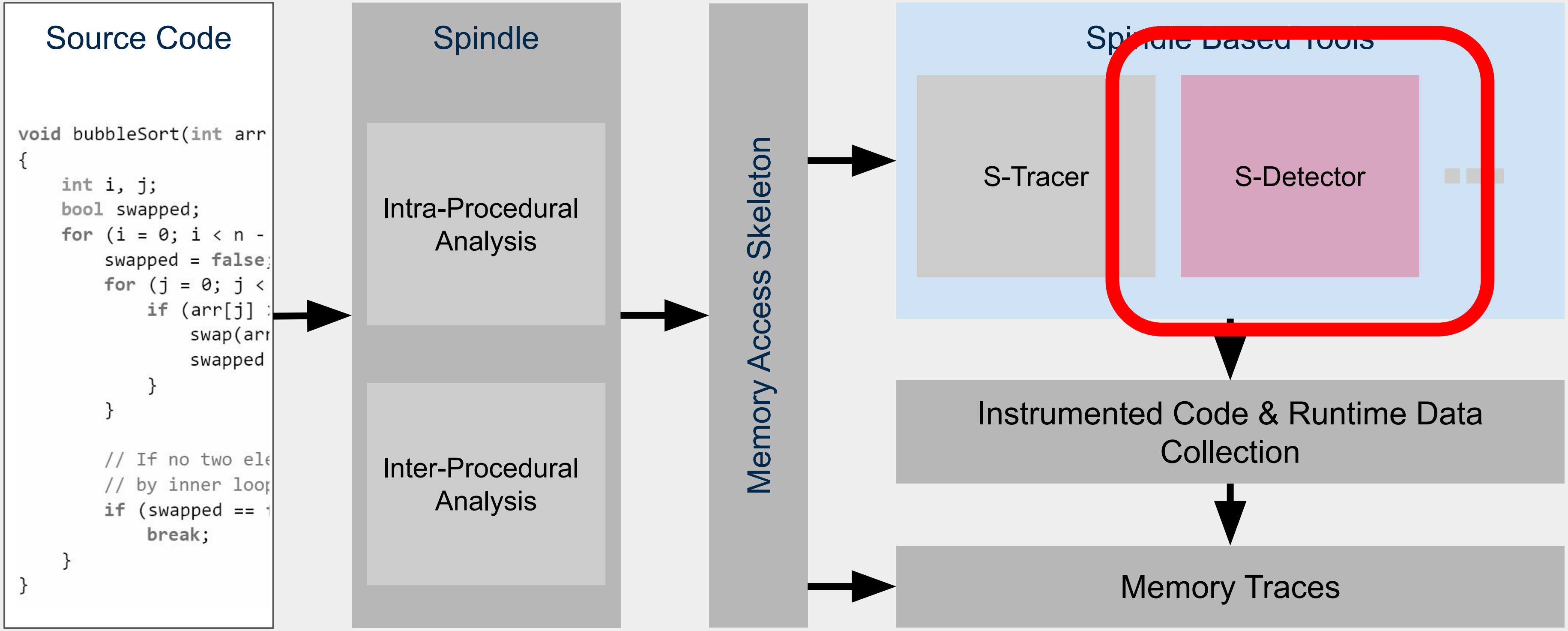


Figure 14: Application slowdown by S-Tracer and PIN with I/O (left) and S-Tracer speedup over PIN (right)

S-Detector



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S-Detector

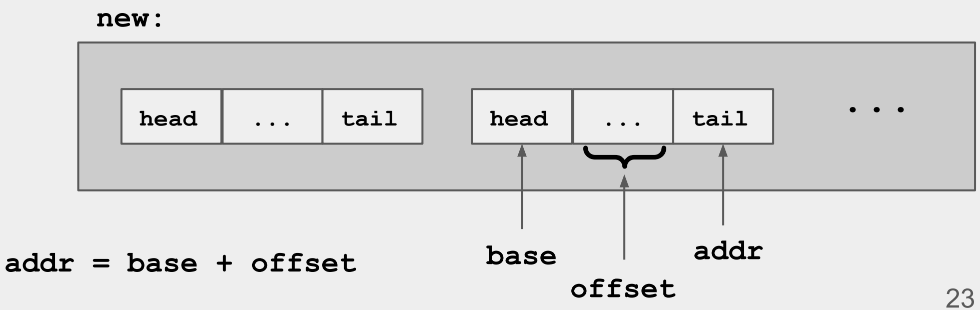
- Memory bug **detector**
  - Invalid Accesses
    - Out-of-bound array access, use after free
  - Memory Leaks
    - Unfreed allocated objects after termination

- Existing methods: Insert memory checking instructions
  - Problem: Significant program slowdown

S-Detector

- Use static information (eg MAS) to eliminate unnecessary instrumentation
- MAS informs us the coarse-grained memory accesses of object
    - Prune instruction-level checks by using object-level checks
    - Only need to check:
        - Valid Offset: `offset < struct_size`
        - Valid memory range of `[base, base + size]`

```
while (pos - 1 && red_cost >
              (cost_t)new[pos/2-1].flow){
   new[pos-1].tail = new[pos/2-1].tail;
   new[pos-1].head = new[pos/2-1].head;
   // Three more accesses to struct members
   // of new[pos-1] and new[pos/2-1].
   pos = pos/2;
   new[pos-1].tail = tail;
   // Four more accesses to struct members
   // of new[pos-1].
}
```



S-Detector Evaluation

- Average* runtime overhead
  - ASan: **66%**
  - Baseline: **184%**
  - Optimized: **26%**
- Avoided **64%** of runtime memory checks
- Evaluated on 11 C programs from the SPEC CPU 2006 benchmarks
- Compared to AddressSanitizer (Google) and Dr. Memory

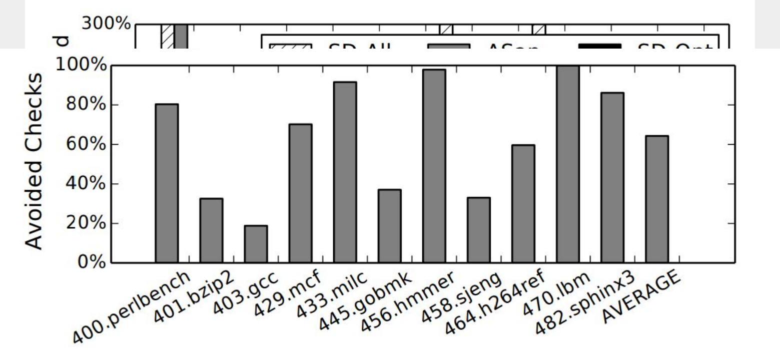


Figure 11: Reduction in runtime memory checks

Figure 10: Overhead comparison (bars over 300% truncated)

* Geometric mean of all test programs

Commentary

- S-Detector PoC only handles invalid accesses and memory leaks, but they chose to compare to tools that do not do static analysis
- Cannot capture dynamically linked libraries at the IR level
  - Requires fallback to dynamic instrumentation
- No quantitative analysis of the number of memory bugs caught by S-Detector compared to existing methods
- The MAS representation is currently limited to structured, predictable memory access components
- The MAS usage is not explained in the paper in very substantial detail

Thank you

Questions?

Outline

- Motivation (Nada)
  - Why do we care about tracing memory accesses?
  - Why is related work insufficient?
- Framework (Ivris)
  - M-CFG, computable and non computable types, sample trace
  - Adding static analysis helps us improve on current tools
- Static Analysis (Luke)
  - Intra-procedural
  - Inter-procedural
- Evaluation (Ryan)
  - S-Detector and Evaluation
  - S-Tracer and Evaluation
- Weaknesses and Improvements (Nada)

Contribution: Static Analysis to Reduce Runtime Overhead

- Reduce the runtime overhead of current memory analysis tools without compromising function by introducing static analysis
- Provide a representation of the memory accesses constructed from static analysis usable and modifiable later in instrumentation (MAS)
- Demonstrate flexibility of Spindle's analysis for constructing a variety of memory analysis tools

Memory Access Skeleton?

- Representation of the memory accesses for a given program
    - Needs to be usable in instrumentation phase and should be able to have blanks filled in for memory addresses not available at compile-time
- Segue into the intra and interprocedural analysis we use to construct this