A Dyninst Primer
and
Project Updates

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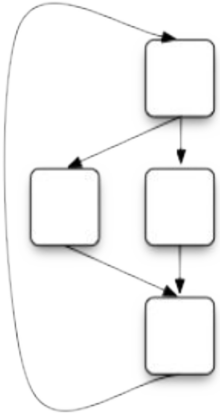
Scalable Tools Workshop
August 12, 2024

A Brief Introduction to Dyninst



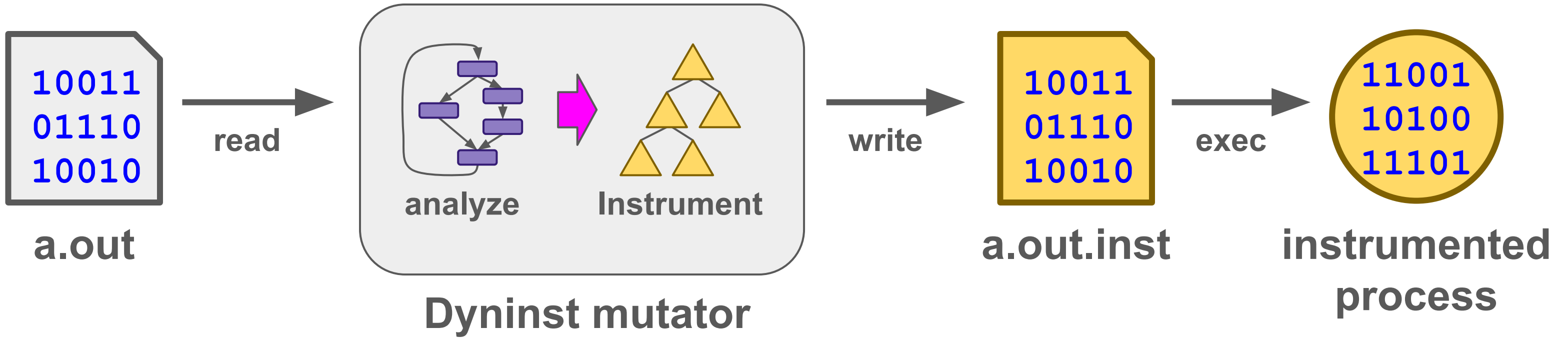
Dyninst: a tool for binary analysis, static and dynamic instrumentation, modification, and control

Overview of Dyninst

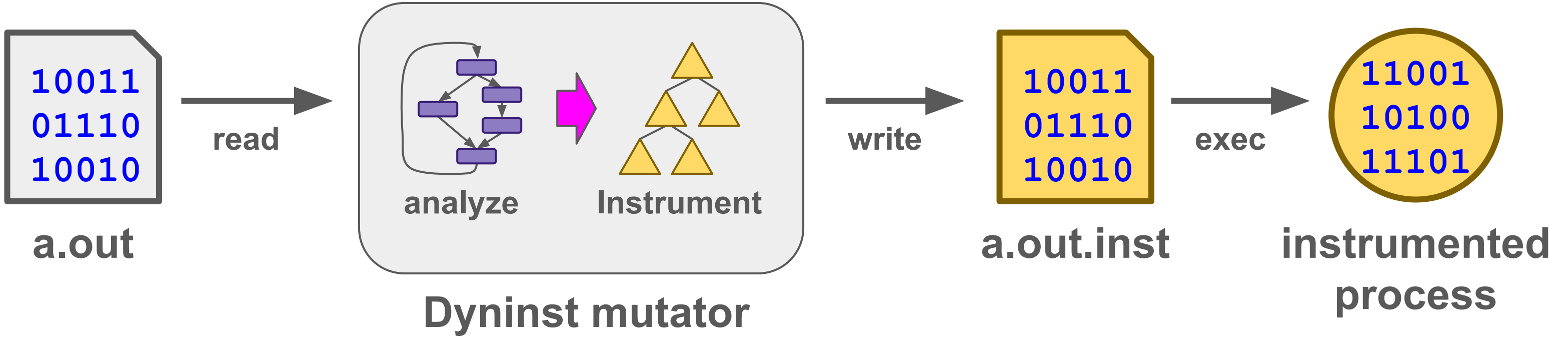
An machine independent interface to machine level binary analysis, instrumentation and control.

- Control flow analysis produces intra- and inter-procedural control flow graphs (CFGs) with basic blocks, loops, and functions
- Dataflow analysis supports refined control flow analysis, register liveness and slicing
- Key abstraction is editing the CFG - not individual instruction replacement.
  - Enormously simpflies instrumentation
  - Closed under valid CFGs
- Static and Dynamic: Modify executable/libraries and running programs

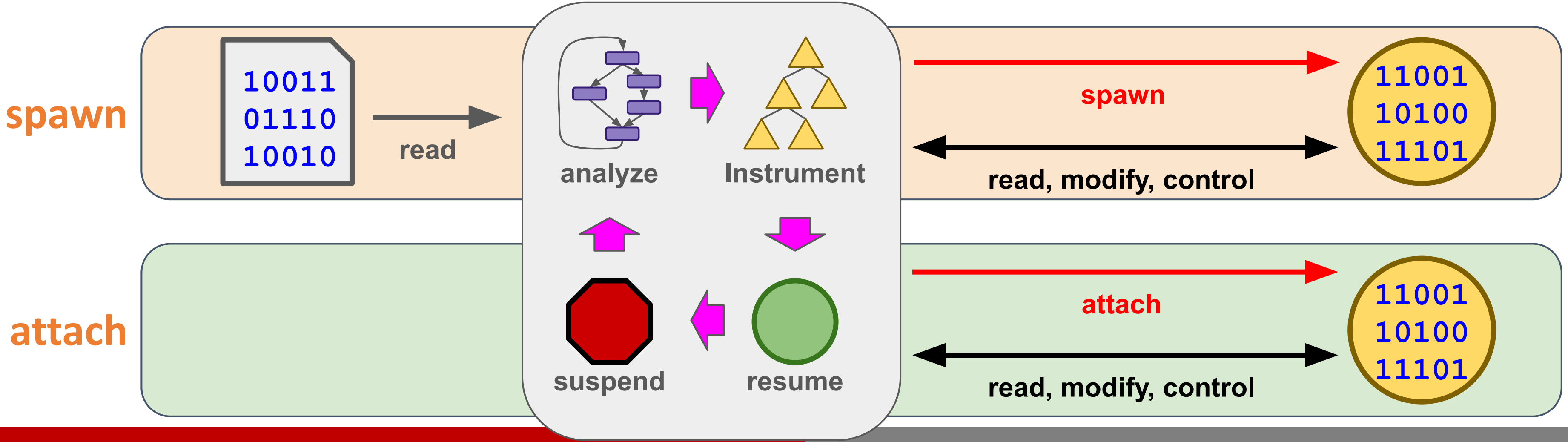
Static Instrumentation



Static Instrumentation



Dynamic Instrumentation



Some of Dyninst’s Capabilities

- Analysis of executables and libraries
  - Opportunistic: stripped, normal, and debug symbols.
- Instrumentation code specified by AST’s
- Can instrument any location in the CFG or almost any instruction
- Instrumentation
  - Static: Rewrite binaries
  - Dynamic: Modify running programs
- Platform independent process control

What you can do with Dyninst

Analysis

- find by name or address
  - functions
  - global variables
  - local variable
  - basic blocks
- analyze control flow
- analyze instructions
  - by operand expressions
  - by opcode
  - by type
- jump table analysis
- forward & backward slicing
- loop analysis

Instrumentation

- functions
  - entry
  - exit
  - call site
- loops
  - entry
  - exit
  - body
- branches
  - taken
  - not taken
- instructions

What you can do with Dyninst

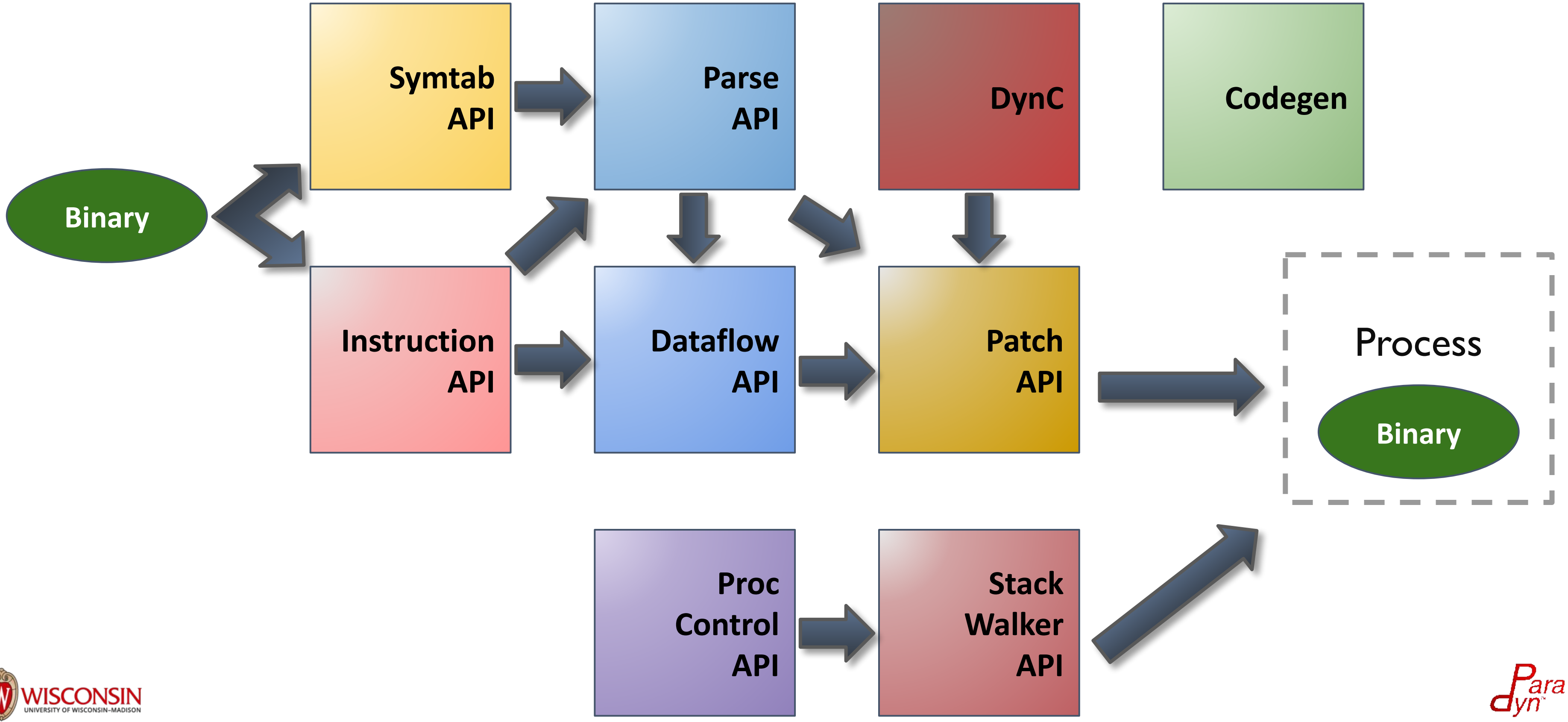
Runtime features

- process control
- read/write process memory
- stack walking
- load library

Applications

- code coverage
- performance time/counts
- peephole optimizations
- find all memory accesses
- change program behavior
- fix bugs via patching
- examine call stack
- create call graph
- disassembly
- and more…

Dyninst Components



Dyninst - Analysis

Binary file or running process:

```
7a 77 0e 20 e9 3d e0 09 e8
68 c0 45 be 79 5e 80 89 08
27 30 73 1c 88 48 6a d8 5a
d0 56 4d fe 92 57 af 40 0c
b6 f2 64 32 f5 07 b6 66 21
0c 85 a5 94 2b 20 fd 5b 95
e7 c2 42 3d f0 2d 7a 77 0e
09 e8 68 c0 45 be 79 5e 37
```

SymtabAPI

Symbols
- functions
- variables
- types
- …

Binary Properties
- segments
- sections
- ELF properties
- …

ParseAPI

Code Addresses

Parse Basic Block

InstructionAPI

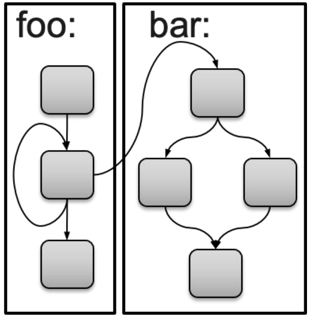
Parse Instruction
- type
- opcode
- operands & access
- …

```
mov  eax, edi
imul eax, esi
ret
```

Process Basic Block
- queue unseen destinations
- split blocks
- associate function(s)
- …

- parse code
- produce CFG
  - basic block nodes
    - straightline code
    - associated with functions(s)
  - control flow edges
    - from block to block
    - type: call, fallthrough, jump, branch taken, branch not taken, return, …
- jump table analysis

Control Flow Graph



DataFlowAPI

- register liveness
- forward slicing - *instructions affected by data*
- backward slicing - *instructions that affected data*
- stack height analysis
- loop analysis

Dyninst - Code Modification

- snippet - machine-independent AST of operations
  - read/write memory, registers, variables
  - basic math
  - function calls
  - conditional branches
  - jumps
  - …
- point - abstract location to modify CFG
  - function entry/exit
  - basic block entry/exit
  - memory writes
  - …
- snippet insertion - modification abstraction
  - modify CFG with snippet at point
  - generates machine specific code
  - maintains existing code's semantics

Function Entry/Exit Instrumentation

```
00000000000005fa <add>:

5fa: push   %rbp
5fb: mov    %rsp,%rbp
5fe: mov    %edi,-0x4(%rbp)
601: mov    %esi,-0x8(%rbp)
604: mov    -0x4(%rbp),%edx
607: mov    -0x8(%rbp),%eax
60a: add    %edx,%eax
60c: pop    %rbp

60d: retq
```

Example of Dyninst inserting entry/exit instrumentation into a function.

```
int add(int a, int b)
{
    return a + b;
}
```

compiles to

Function Entry/Exit Instrumentation

```
0000000000005fa <add>:

5fa: push   %rbp
5fb: mov    %rsp,%rbp
5fe: mov    %edi,-0x4(%rbp)
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607: mov    -0x8(%rbp),%eax
60a: add    %edx,%eax
60c: pop    %rbp

60d: retq
```

libtrace.so

```
XXX <Trace>:
     …
…: // trace functionality
     …
…: retq
```

1. Open the binary/attach to or create the process with the function you want to trace

```
addrSpace = bpatch.processCreate(…);
```

Function Entry/Exit Instrumentation

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00000000000005fa <add>:

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1. Open the binary/attach to or create the process with the function you want to trace

```
addrSpace = bpatch.processCreate(…);
```

2. Insert the tracing library containing the function you want to call at entry/exit

```
addrSpace→loadLibrary("libtrace.so");
```

Function Entry/Exit Instrumentation

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0000000000005fa <add>:

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```
addrSpace = bpatch.processCreate(…);
```

2. Insert the tracing library containing the function you want to call at entry/exit

```
addrSpace→loadLibrary("libtrace.so");
```

3. Find the function you want instrumented

```
add = addrSpace→findFunction("add");
```

Function Entry/Exit Instrumentation

```
0000000000005fa <add>:

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60d: retq
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```

3. Find the function you want instrumented

```
add = addrSpace→findFunction("add");
```

4. Find the function you want to insert at entry/exit

```
trace = addrSpace→findFunction("Trace");
```

Function Entry/Exit Instrumentation

```
0000000000005fa <add>:

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60d: retq
```

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1. Open the binary/attach to or create the process with the function you want to trace

```
addrSpace = bpatch.processCreate(…);
```

2. Insert the tracing library containing the function you want to call at entry/exit

```
addrSpace→loadLibrary("libtrace.so");
```

3. Find the function you want instrumented

```
add = addrSpace→findFunction("add");
```

4. Find the function you want to insert at entry/exit

```
trace = addrSpace→findFunction("Trace");
```

5. Find the entry/exit points of the function

```
entry = add→findPoint(BPatch_locEntry);
exit  = add→findPoint(BPatch_locExit);
```

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Paradyn

Function Entry/Exit Instrumentation

```
00000000000005fa <add>:

5fa: push   %rbp
5fb: mov    %rsp,%rbp
5fe: mov    %edi,-0x4(%rbp)
601: mov    %esi,-0x8(%rbp)
604: mov    -0x4(%rbp),%edx
607: mov    -0x8(%rbp),%eax
60a: add    %edx,%eax
60c: pop    %rbp

60d: retq
```

libtrace.so

```
XXX <Trace>:
     …
…: // trace functionality
     …
…: retq
```

1. Open the binary/attach to or create the process with the function you want to trace

```
addrSpace = bpatch.processCreate(…);
```

2. Insert the tracing library containing the function you want to call at entry/exit

```
addrSpace→loadLibrary(“libtrace.so”);
```

3. Find the function you want instrumented

```
add = addrSpace→findFunction(“add”);
```

4. Find the function you want to insert at entry/exit

```
trace = addrSpace→findFunction(“Trace”);
```

5. Find the entry/exit points of the function

```
entry = add→findPoint(BPatch_locEntry);
exit  = add→findPoint(BPatch_locExit);
```

6. Create the instrumentation snippet (call Trace())

```
BPatch_funcCallExpr traceExpr(trace,…);
```

Function Entry/Exit Instrumentation

```
0000000000005fa <add>:
     call Trace
5fa: push   %rbp
5fb: mov    %rsp,%rbp
5fe: mov    %edi,-0x4(%rbp)
601: mov    %esi,-0x8(%rbp)
604: mov    -0x4(%rbp),%edx
607: mov    -0x8(%rbp),%eax
60a: add    %edx,%eax
60c: pop    %rbp
     call Trace
60d: retq
```

libtrace.so

```
XXX <Trace>:
     …
…: // trace functionality
     …
…: retq
```

1. Open the binary/attach to or create the process with the function you want to trace

```
addrSpace = bpatch.processCreate(…);
```

2. Insert the tracing library containing the function you want to call at entry/exit

```
addrSpace→loadLibrary("libtrace.so");
```

3. Find the function you want instrumented

```
add = addrSpace→findFunction("add");
```

4. Find the function you want to insert at entry/exit

```
trace = addrSpace→findFunction("Trace");
```

5. Find the entry/exit points of the function

```
entry = add→findPoint(BPatch_locEntry);
exit  = add→findPoint(BPatch_locExit);
```

6. Create the instrumentation snippet (call Trace())

```
BPatch_funcCallExpr traceExpr(trace,…);
```

7. Insert snippets

```
addrSpace→insertSnippet(traceExpr,entry);
addrSpace→insertSnippet(traceExpr,exit);
```

Function Entry/Exit Instrumentation

```
0000000000005fa <add>:
     call Trace
5fa: push   %rbp
5fb: mov    %rsp,%rbp
5fe: mov    %edi,-0x4(%rbp)
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60a: add    %edx,%eax
60c: pop    %rbp
     call Trace
60d: retq
```

libtrace.so

```
XXX <Trace>:
     …
…: // trace functionality
     …
…: retq
```

Only minor modifications are needed to extend this example to:

- Basic Block Instrumentation
- Memory Tracing

Function Entry/Exit Instrumentation

```
00000000000005fa <add>:
     call Trace
5fa: push   %rbp
5fb: mov    %rsp,%rbp
5fe: mov    %edi,-0x4(%rbp)
601: mov    %esi,-0x8(%rbp)
604: mov    -0x4(%rbp),%edx
607: mov    -0x8(%rbp),%eax
60a: add    %edx,%eax
60c: pop    %rbp
     call Trace
60d: retq
```

libtrace.so

```
XXX <Trace>:
     …
…: // trace functionality
     …
…: retq
```

1. Open the binary/attach to or create the process with the function you want to trace

```
addrSpace = bpatch.processCreate(…);
```

2. Insert the tracing library containing the function you want to call at entry/exit

```
addrSpace→loadLibrary("libtrace.so");
```

3. Find the function you want instrumented

```
add = addrSpace→findFunction("add");
```

4. Find the function you want to insert at entry/exit

```
trace = addrSpace→findFunction("Trace");
```

5. Find the entry/exit points of the function

```
entry = add→findPoint(BPatch_locEntry);
exit  = add→findPoint(BPatch_locExit);
```

6. Create the instrumentation snippet (call Trace())

```
BPatch_funcCallExpr traceExpr(trace,…);
```

7. Insert snippets

```
addrSpace→insertSnippet(traceExpr,entry);
addrSpace→insertSnippet(traceExpr,exit);
```

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Basic Block Entry/Exit Instrumentation

```
0000000000005fa <add>:
     call Trace
5fa: push   %rbp
5fb: mov    %rsp,%rbp
5fe: mov    %edi,-0x4(%rbp)
601: mov    %esi,-0x8(%rbp)
604: mov    -0x4(%rbp),%edx
607: mov    -0x8(%rbp),%eax
60a: add    %edx,%eax
60c: pop    %rbp
     call Trace
60d: retq
```

libtrace.so

```
XXX <Trace>:
     …
…: // trace functionality
     …
…: retq
```

1. Open the binary/attach to or create the process with the function you want to trace

```
addrSpace = bpatch.processCreate(…);
```

2. Insert the tracing library containing the function you want to call at entry/exit

```
addrSpace→loadLibrary("libtrace.so");
```

3. Find the function you want instrumented

```
add = addrSpace→findFunction("add");
```

4. Find the function you want to insert at entry/exit

```
trace = addrSpace→findFunction("Trace");
```

5. **Find the entry/exit points of all basic blocks**

```
add→getCFG()→getAllBasicBlocks(blocks);
for(auto block : blocks) {
  entry.push_back(block→findEntryPoint())
  exit.push_back(block→findExitPoint());  }
```

6. Create the instrumentation snippet (call Trace())

```
BPatch_funcCallExpr traceExpr(trace,…);
```

7. Insert snippets

```
addrSpace→insertSnippet(traceExpr,entry);
addrSpace→insertSnippet(traceExpr,exit);
```

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Load/Store Operations Instrumentation

```
0000000000005fa <add>:
     call Trace
5fa: push   %rbp
5fb: mov    %rsp,%rbp
     call Trace
5fe: mov    %edi,-0x4(%rbp)
     call Trace
601: mov    %esi,-0x8(%rbp)
     call Trace
604: mov    -0x4(%rbp),%edx
     call Trace
607: mov    -0x8(%rbp),%eax
60a: add    %edx,%eax
     call Trace
60c: pop    %rbp
     call Trace
60d: retq
```

libtrace.so

```
XXX <Trace>: …
```

1. Open the binary/attach to or create the process with the function you want to trace

```
addrSpace = bpatch.processCreate(…);
```

2. Insert the tracing library containing the function you want to call at entry/exit

```
addrSpace→loadLibrary("libtrace.so");
```

3. Find the function you want instrumented

```
add = addrSpace→findFunction("add");
```

4. Find the function you want to insert at entry/exit

```
trace = addrSpace→findFunction("Trace");
```

5. **Find the load/store instructions in the function**

```
std::set<BPatch_opCode> axs;
axs.insert(BPatch_opLoad);
axs.insert(BPatch_opStore);
lsp = add→findPoint(axs);
```

6. Create the instrumentation snippet (call Trace())

```
BPatch_funcCallExpr traceExpr(trace,…);
```

7. **Insert snippets**

```
addrSpace→insertSnippet(traceExpr,lsp);
```

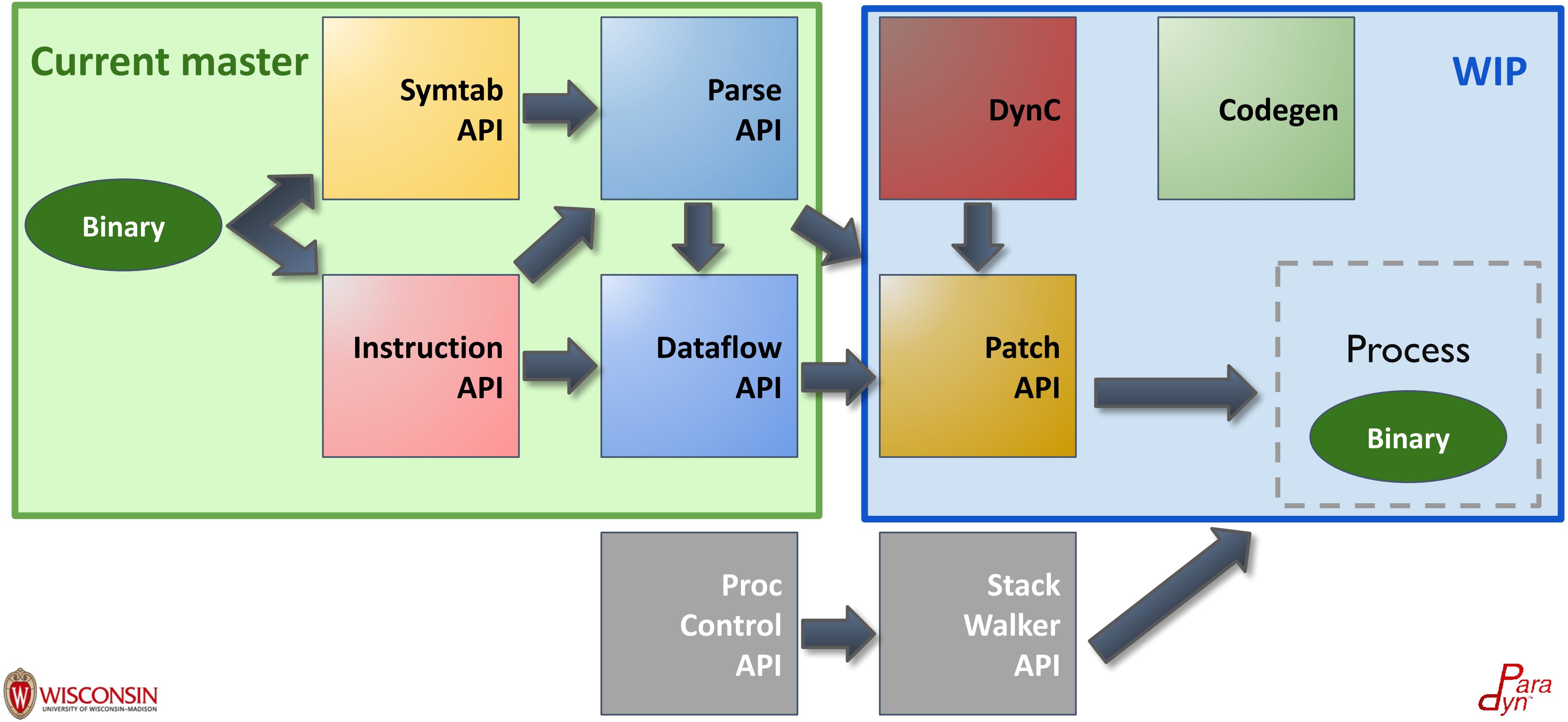
What is new since June 2023?

- Version 13.0.0 released (https://github.com/dyninst/dyninst/releases)
- InstructionAPI
  - added missing x86 instructions
  - improved x86 NOP determination
  - prepared for capstone
  - redesigned registers and ABI classes
  - added new x86 registers
  - improved instruction disassembly formatting
  - improved system call/interrupt detection
- Improve module & line map on unusual ELF files for thread-safety and pathnames
- Support liveness on all architectures
- Added interface to parallel parse a vector of addresses
- Github CI improvements - more platforms and tests
- Code Cleanup, bug fixes and new compiler support
- Cmake rewrite
- Work in progress: GPU support & RISC-V

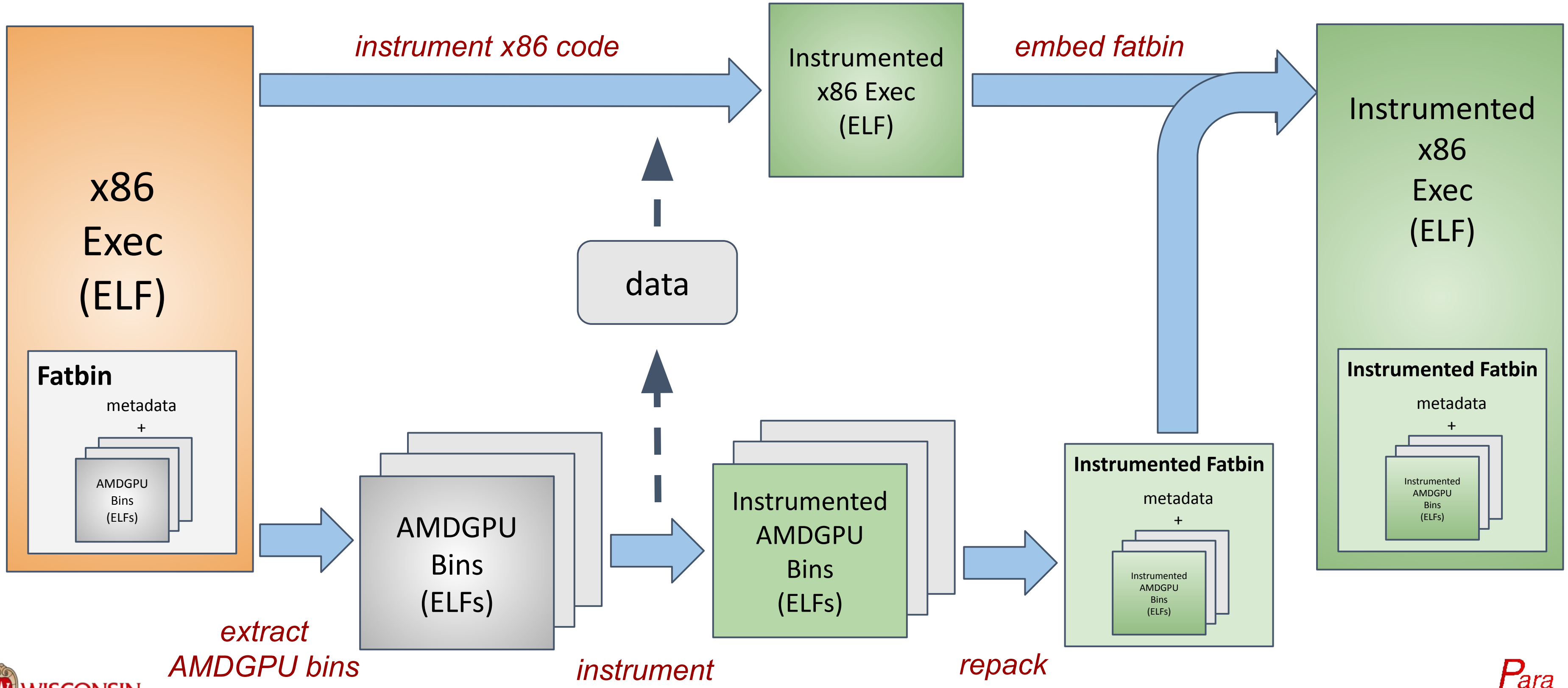
Enhancements - AMD GPUs

- Improved MI100/MI200/MI300 instruction parsing
  - Instruction decoder generated from 2024 AMD XML specs
- Basic data flow analysis to support control flow analysis
- Liveness analysis
- Basic support for code patching
- Improved instruction formatting
- Bug fixes
- Dropped support to MI25 (VEGA) GPUs

AMDGPU - Working* Components



Workflow for AMDGPU Instrumentation



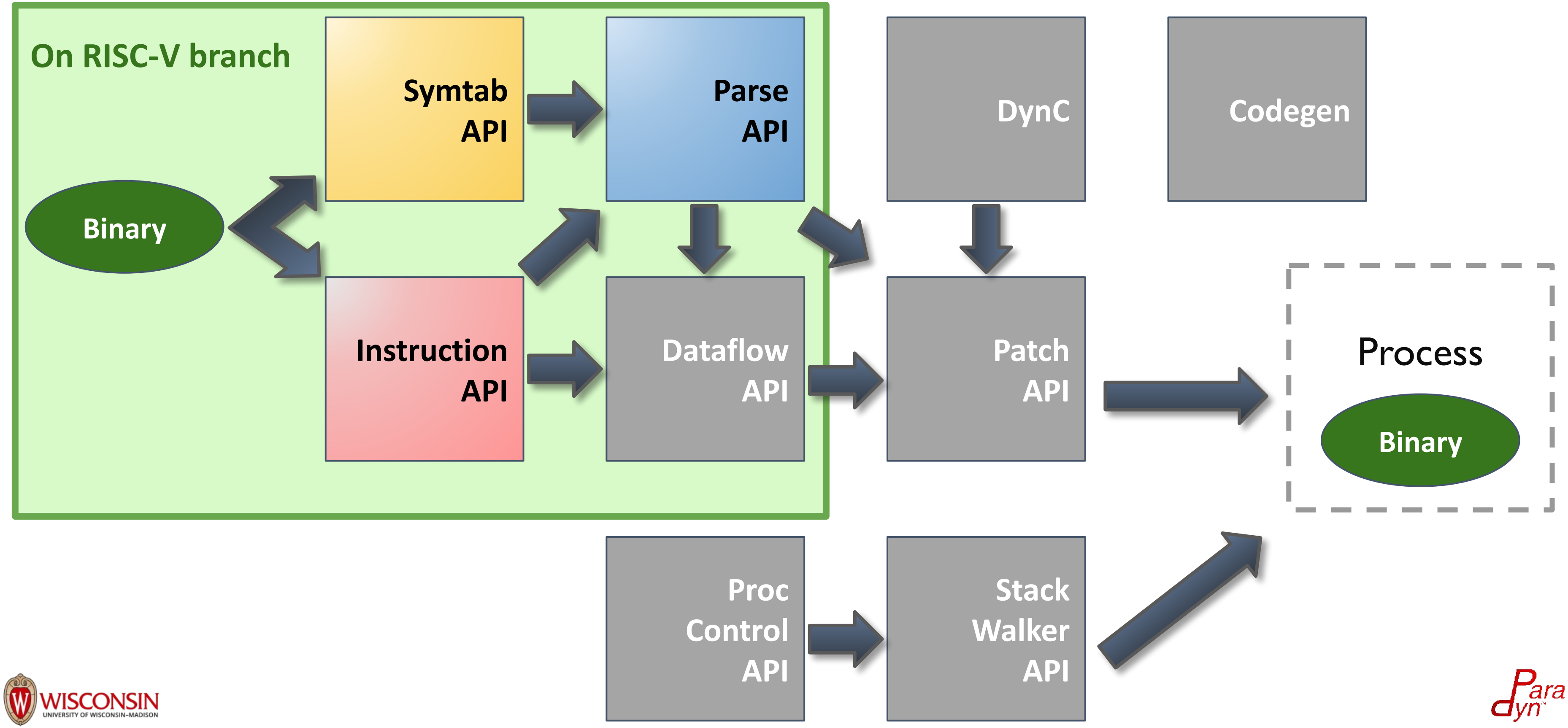
AMDGPU Work in Progress

- Currently, a special build of Dyninst due to cross-target instrumentation (codegen) limitations
- Instrumentation using scalar instructions only
- Inserting arithmetic and relational snippets
- Began work on instrumentation AST types:
  - Instrumentation variables
  - Control flow operations (if/then/else, jump, while loop)

RISC-V Work in Progress

- RISC-V defines 32-bit (rv32imafdc) and 64-bit (rv64imafdc)
    - Our initial focus is 64-bit
- Implemented APIs include:
    - SymtabAPI – elf parsing
    - InstructionAPI – decode and format, based on Capstone
    - ParseAPI – create control flow graph
- Additional validation on more complex binaries need to be performed
- DataflowAPI in progress. Need instruction semantics spec for RISC-V, probably based on SAIL
- Other APIs still to come

RISC-V - Working Components



Capstone

- Disassembly framework (with some semantic information) for various ISAs, including x86, Arm, PowerPC, RISC-V
- Supported RISC-V instruction subsets: I, M, A, F, D, C
- Capstone was missing functionality needed by Dyninst
  - Read/Write information on registers & memories
  - Size information on registers & memories
- Solution: Modified Capstone, collaborated with the Capstone team, and the pull request was merged into the Capstone project

Questions?

https://github.com/dyninst/dyninst