Binary Analysis and Rewriting

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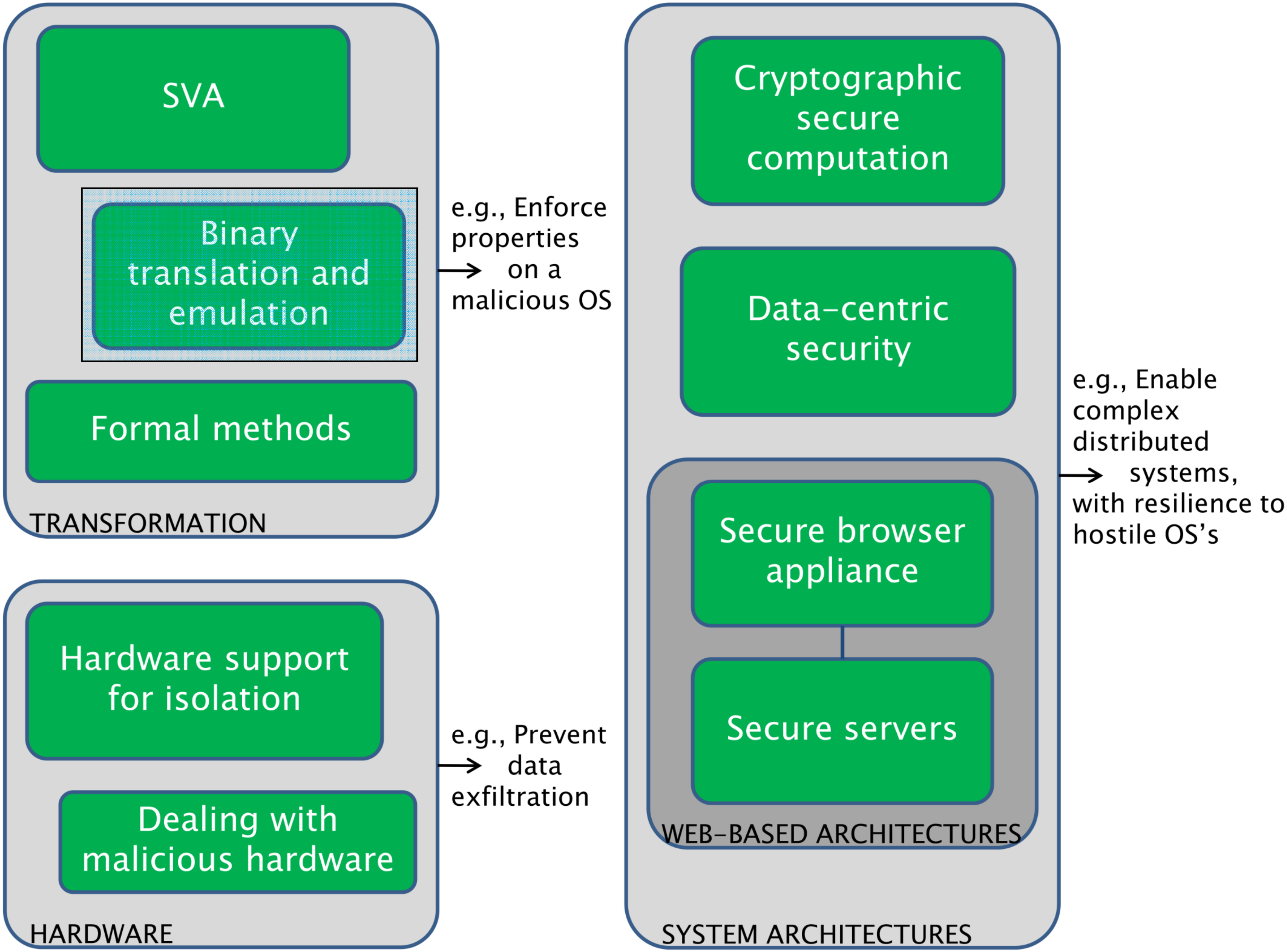

SVA
Binary translation and emulation
Formal methods
TRANSFORMATION
e.g., Enforce properties on a malicious OS
Hardware support for isolation
Dealing with malicious hardware
HARDWARE
e.g., Prevent data exfiltration
Cryptographic secure computation
Data-centric security
Secure browser appliance
Secure servers
WEB-BASED ARCHITECTURES
SYSTEM ARCHITECTURES
e.g., Enable complex distributed systems, with resilience to hostile OS’s

Binary Translation

- A popular approach for implementing virtual machine monitors (VMMs)
  - Examples: QEMU, VMWare, …
  - Provide foundation to secure applications from hostile OS
- Maximizes applicability
  - Can work with arbitrary OSes and applications available only in binary form.

Motivation (Why are we doing this?)

- Existing binary translators not well-suited for enforcing many important security properties
  - Information flow, control-flow integrity, object-granularity memory safety, XFI, …
    - Some properties ill-suited to pure dynamic enforcement
      - May require maintenance of some global invariants
    - Most of them incur very high overheads (4x to 10x slowdown)
      - Start-up times are even worse
- Suboptimal register and memory use
  - Excessive register spills and memory accesses surrounding instrumentation

Research Problems (What are the hard problems?)

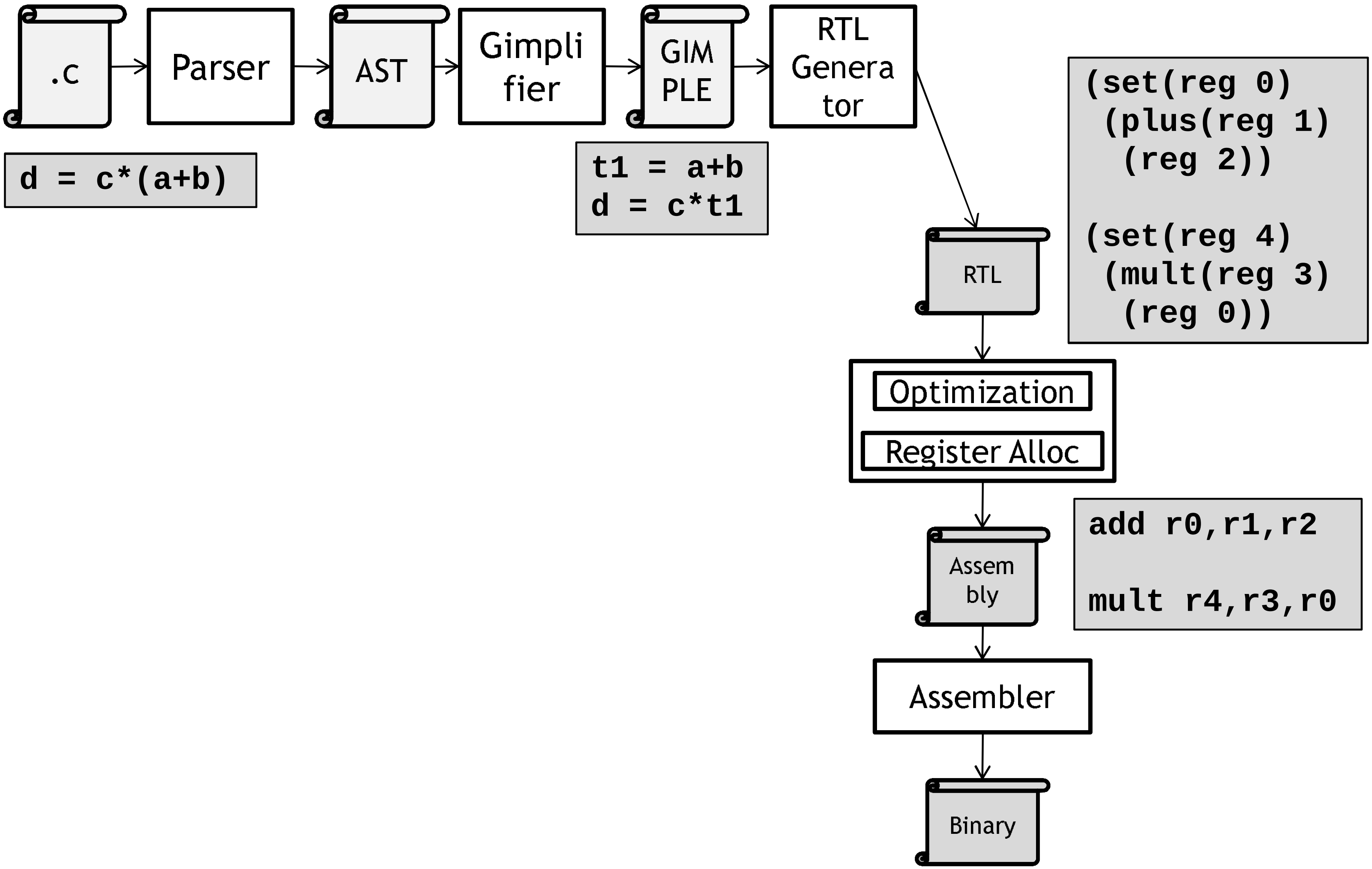
- Static analysis and optimization techniques for efficient enforcement of security properties
  - Optimization of original + instrumentation code
- Decoupling analysis and instrumentation from specifics of an instruction-set architecture (ISA)
  - Ideally, a single implementation across X86, ARM, MIPS, SPARC, PowerPC, etc.
  - Each ISA can be quite complex
    - X86: 1100+ instructions described by a 1500+ page manual

Our Approach (How do we proceed to solve them?)

- Develop novel compiler-based methods for overcome the drawbacks of today’s techniques
  - Leverage compiler infrastructure for efficient instrumentation and retargetability
    - Architecture-independent binary instrumentation using compiler machine descriptions
  - Robust, scalable static analysis of low-level code
    - Provides crucial missing pieces to complete the loop in compiler-based instrumentation

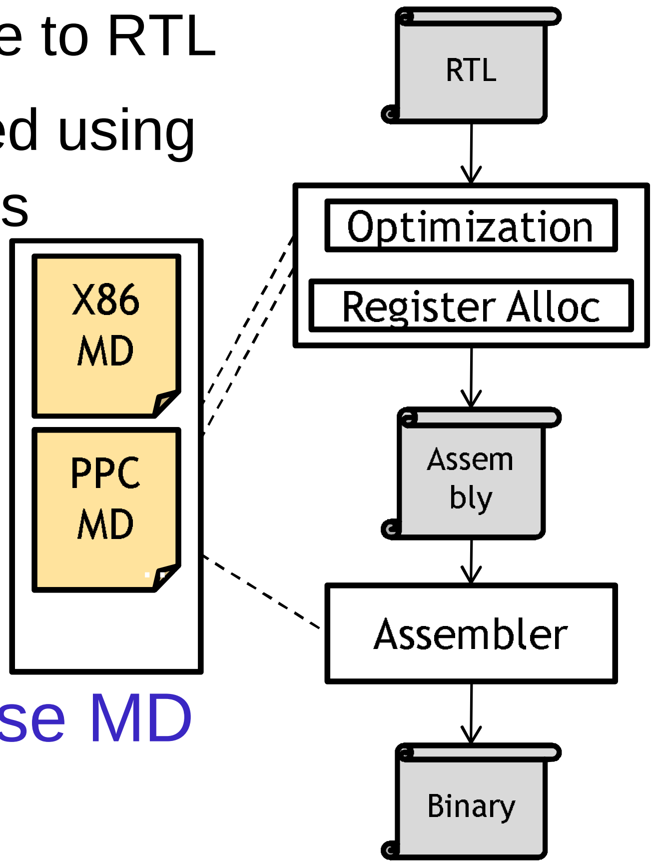
Architecture-Neutral Binary Instrumentation from Machine Descriptions

Architecture of GCC

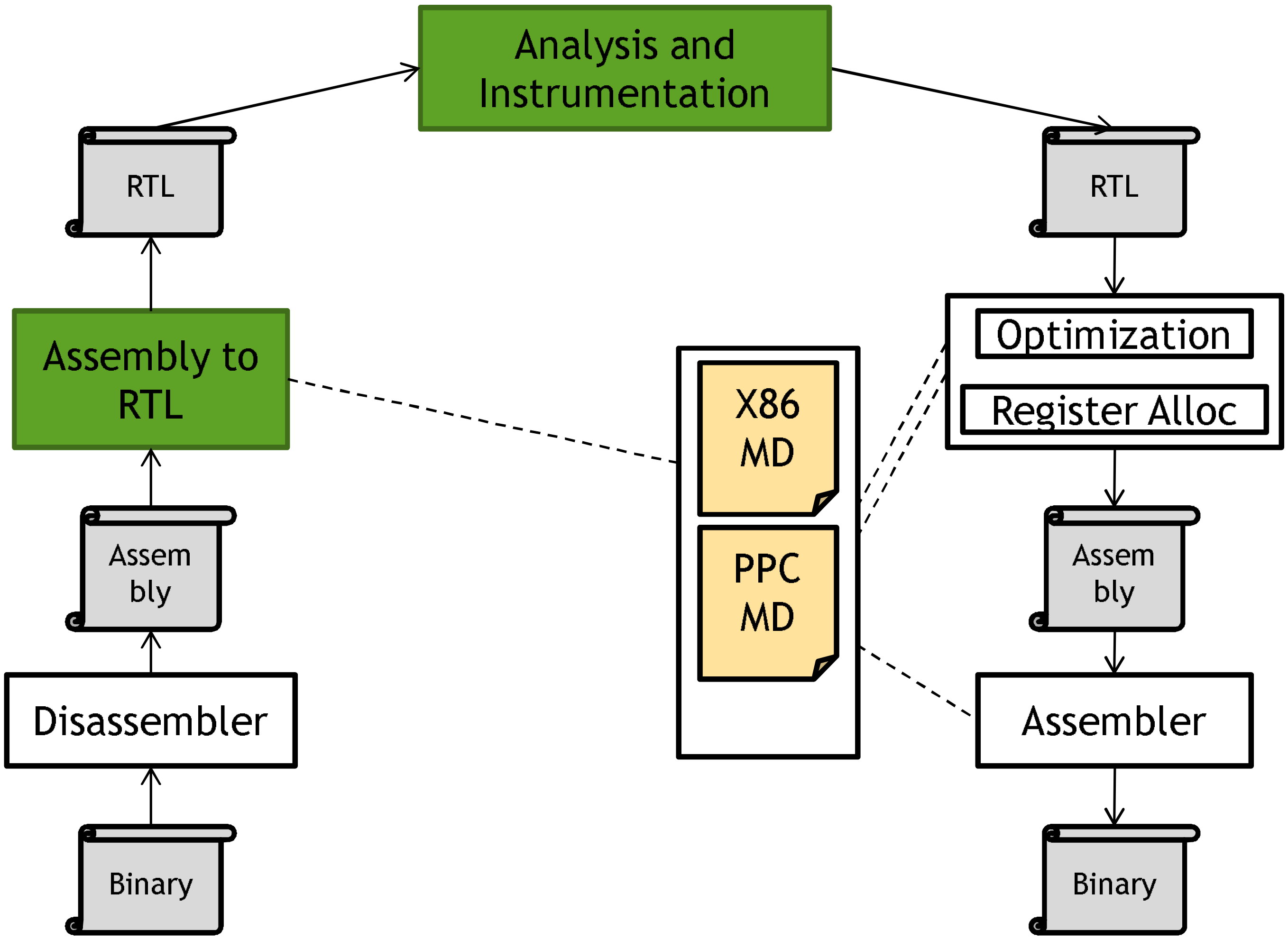


Leveraging Compiler Infrastructure

- Leverage architecture-independent code generators [Davidson and Fraser 1984] (and many others)
  - Translate intermediate code to RTL
  - Quality of final code ensured using extensive RTL optimizations
  - Final step uses machine descriptions (MD)
    - rules that map RTL snippets to assembly
    - Pattern-driven process
- Key Question: Can we use MD rules in reverse?



Compiler-based binary instrumentation



Benefits of using compiler infrastructure

- Eliminate error-prone step of developing instruction semantics
  - Specifications used in compilers extensively tested
    - Or else the compiler would generate incorrect code!
- Reuse back-end optimization phases for optimizing instrumented code
  - GCC runs about 40 different optimizations on RTL …
- Retargetability!

Example

```
(define_insn "*strsetqi_rex_1"
  [(set (mem:QI (match_operand:DI 1 "register_operand" "0"))
        (match_operand:QI 2 "register_operand" "a"))
   (set (match_operand:DI 0 "register_operand" "=D")
        (plus:DI (match_dup 1) (const_int 1)))]
  "!TARGET_64BIT"
  "stosb"
  )
```

- A few other MDs produce stosb
  - In this case, it moves EAX to ES:EDI, increments EDI

- General form: RTL/Cond → ASM
- RTL uses `match_operand` to specify *predicates* and **constraints** on operands, and `size annotations` to specify operand sizes

Example

```
(define_insn "*pushsi2"
  [(set (match_operand:SI 0 “push_operand” “=<”)
     (match_operand:SI 1 “general_no_elim_operand” “ri*m”))]
  "!TARGET_64BIT"
  “push %1"
  )
```

- General form: RTL/Cond → ASM
- RTL uses `match_operand` to specify *predicates* and **constraints** on operands, and `size annotations` to specify operand sizes

So, what is the catch?

- MD rules are meant to be used to translate RTL to ASM. Using them in reverse can be difficult:
  - Is the mapping invertible?
    - Predicates, constraints and conditions are ultimately checked by C-code that can be used only in forward direction
      - Map ASM to RTL --- this requires just the operands to be mapped, a simple process
      - With this mapping, use MD in forward direction to check if same ASM is generated. Otherwise, rule is not applicable
    - What if RTL operands are missing in ASM?
      - Use operand constraints to infer extra operands, or try all possibilities
    - ASM can be a piece of C-code that generates assembly
      - Solution: symbolic execution of problem code

So, what is the catch? (Continued)

- MD rules are meant to be used to translate RTL to ASM. Using them in reverse can be difficult:
  - Is it sound?
    - What if ASM depends on conditions unspecified in RTL?
    - Or, ASM does “more” than the RTL?
  - We can formally establish this
    - for instructions covered by the compiler’s MD

Status

- GCC's x86 MD is 34K lines
  - A few instructions are not covered by GCC
    - Just 3 of these used in complex apps (LLVM-compiled)
      - Firefox (5M instructions), GIMP (1.4M instructions)
  - We can so far handle about 50% of the x86 MD
- Implementation status:
  - Non-trivial applications can be handled
    - Some SPEC INT executables (e.g., gzip) can be disassembled, reassembled and run
  - Simple instrumentations
    - Null-pointer check (bzip2)

Related Work

- Efforts to simplify instruction semantics specification
  - CTL (UQBT), TSL (CodeSurfer), VEX (Valgrind), BIL (BAP), Harvard team's DSLs, …
  - We pursue a complementary approach: avoid the need for new specifications
    - Makes full treatment of large, complex ISAs approachable
    - Works well if your goals are similar to those of compilers
  - These specifications can be used to develop MDs for missing instructions, or improve precision
- Efforts to discover errors in emulators (Berkeley team)
  - Our focus is on property enforcement
    - Compiler MDs use a lot of over-approximations, and don't provide a good basis for high-fidelity emulation

Robust and scalable Static analysis of low-level code

Challenges in low-level binary code

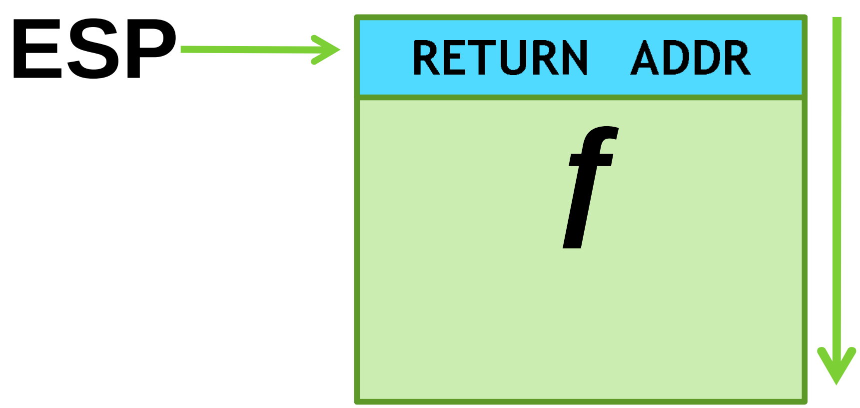
- Variable boundaries or types
- Function boundaries
- Parameter passing in optimized code
  - Missing pushes, parameter passing via registers,…
- Distinguishing local variables from other accesses
- Position-independent code (PIC), non-standard use of stack, functions with side-effects, ABI-compliance, …
- Hand-written assembly, exceptions, multi-threading, …

Static analysis of low-level code

- To solve these challenges, previous approaches
  - make optimistic assumptions, or rely on compiler idioms
    - often fail on optimized code and/or large programs
    - don’t work for other compilers, or hand-written assembly
- Our solution:
  - Use systematic analysis to reduce assumptions/heuristics
  - Accurately tracks local variables by analyzing values held in registers and on the stack
  - Trades off ability to reason about global memory to obtain scalability and modularity

Stack Analysis

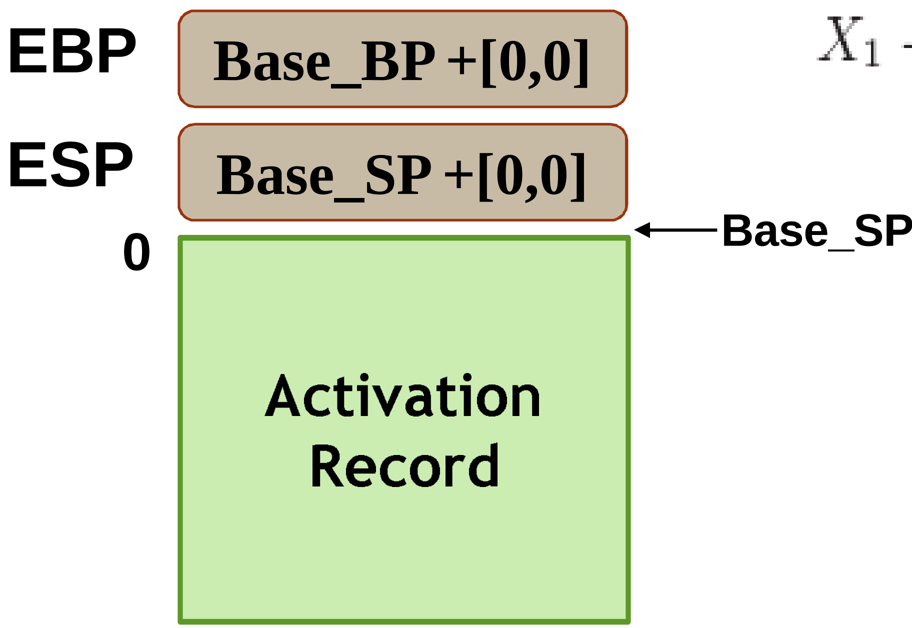
- Analyzes one function at a time
- Examines the use of stack to
  - Determine parameters
    - Number of them, whether in registers or on stack
  - Caller- and callee-saved registers
  - Summarize effect on parameters
    - Preservation of SP, return to caller, changes in parameter or register contents,…

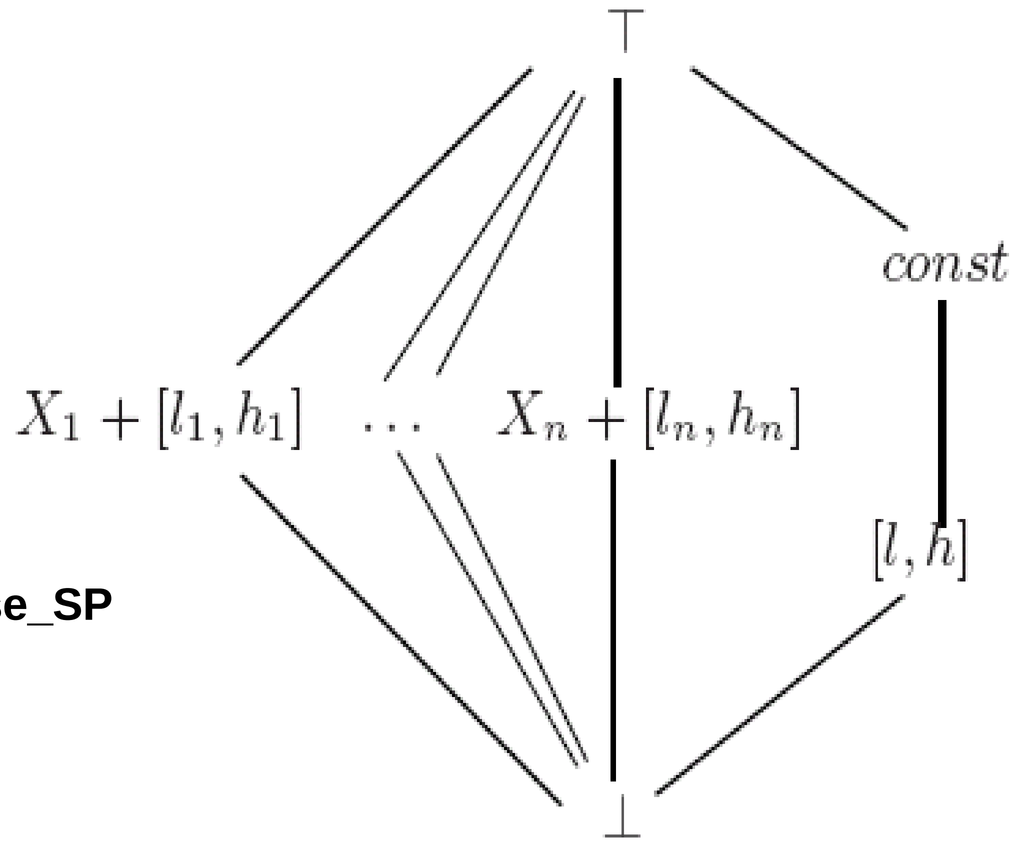


Abstract Interpretation for Stack Analysis

<*f*> :

```
push  %ebp
mov %esp, %ebp
sub $16, %esp
```





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Abstract Interpretation for Stack Analysis

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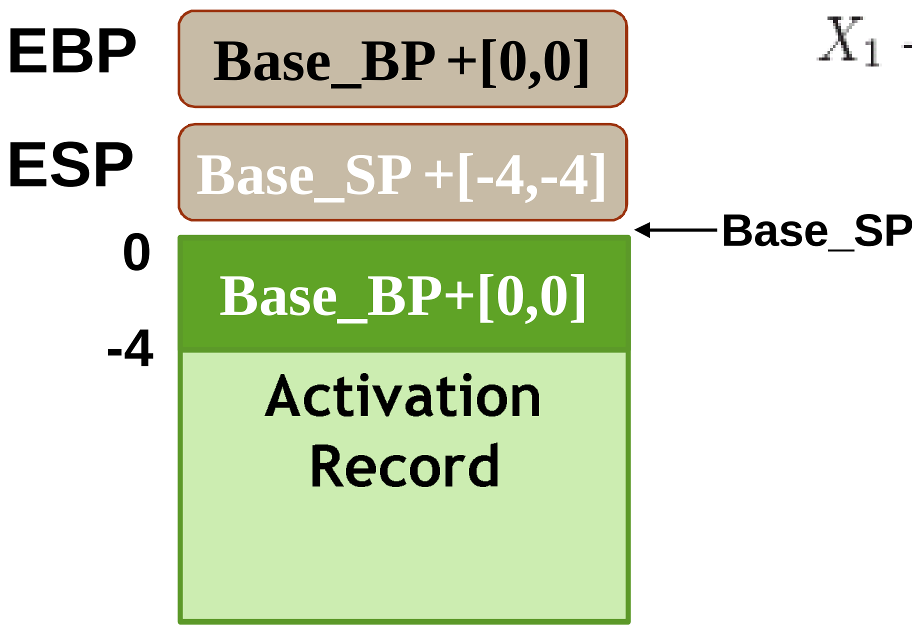

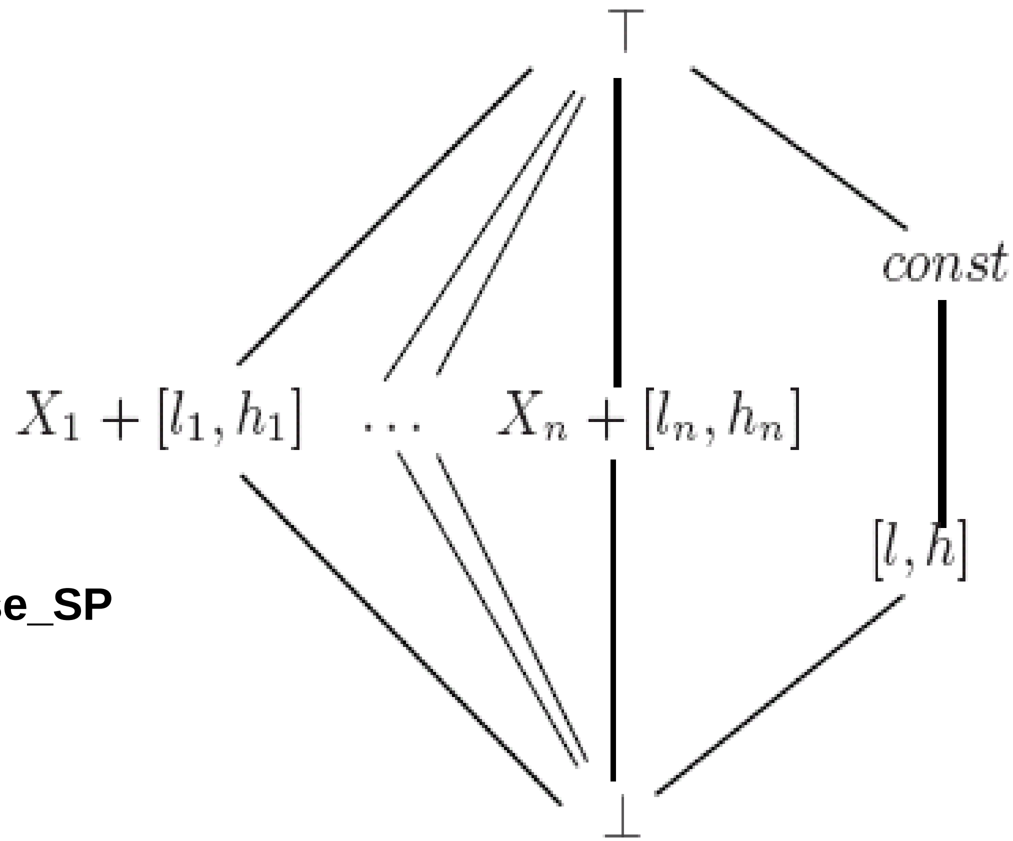

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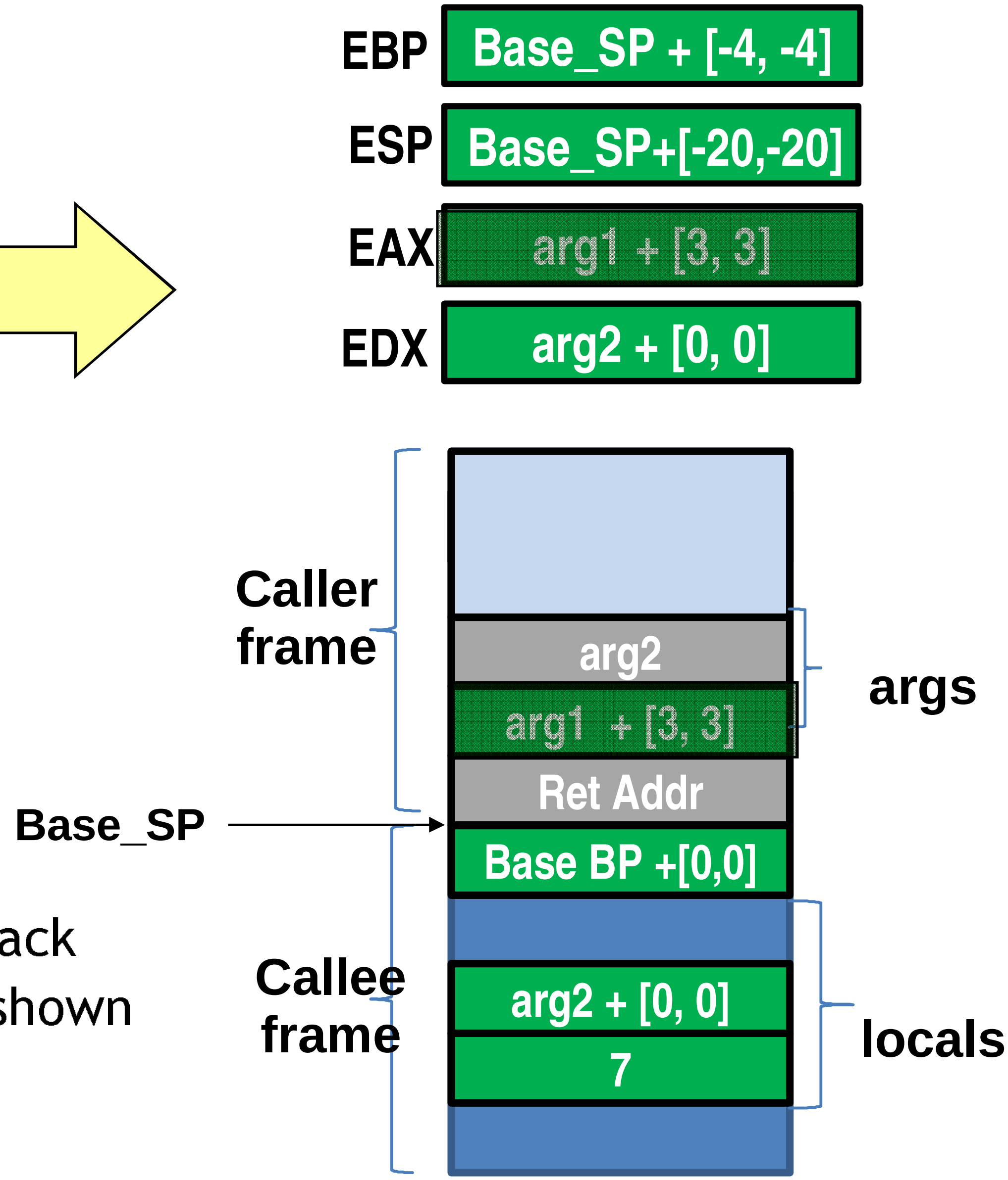
Stack Analysis (contd)

```
<f>:
push  %ebp
mov %esp, %ebp
sub $16, %esp
mov 8(%ebp), %eax
add $3, %eax
mov %eax, 8(%ebp)
mov $7, -12(%ebp)
mov 12(%ebp), %edx
mov %edx, -8(%ebp)
leave
ret
```

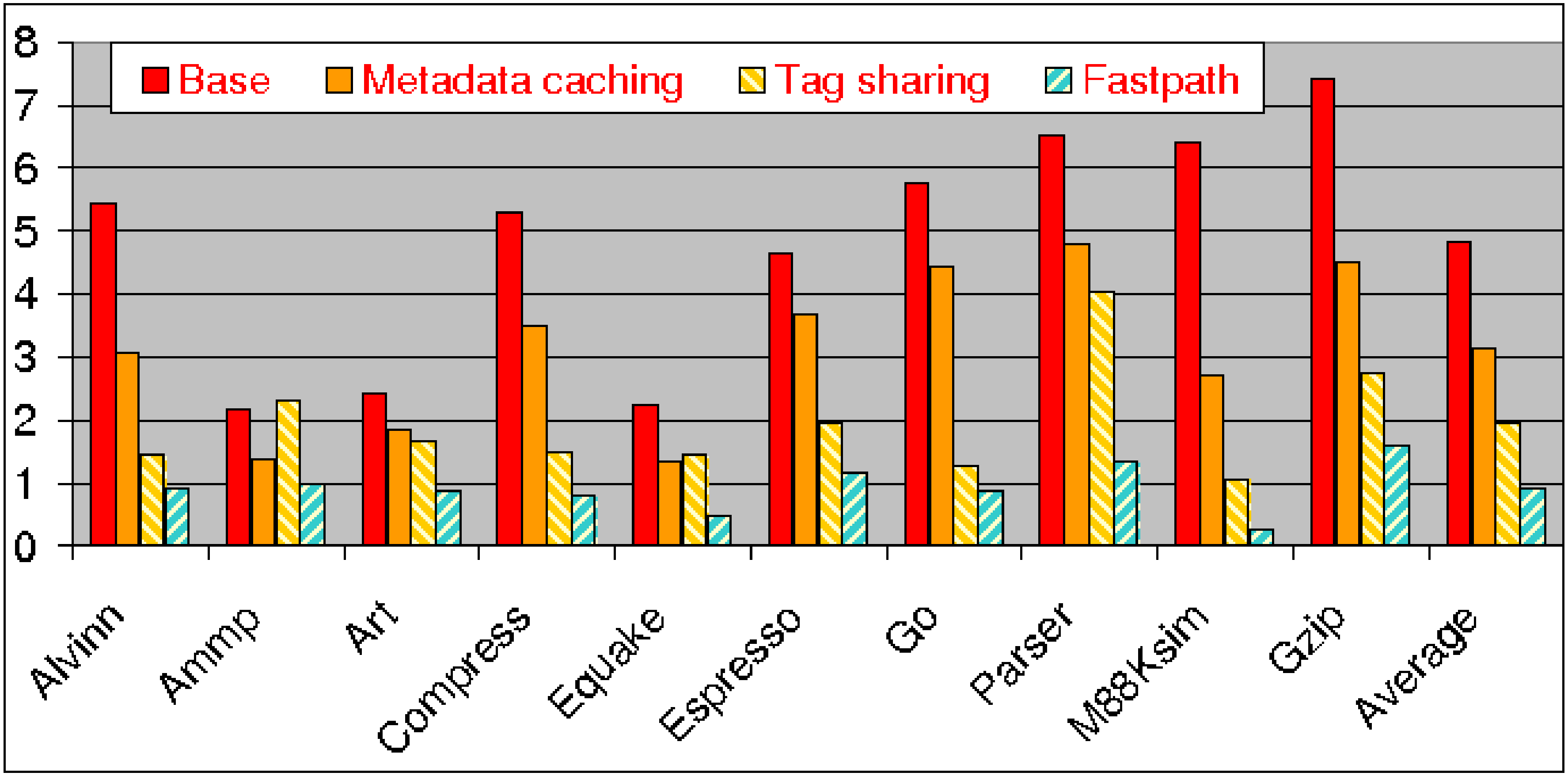


- Summary for *f*:
  - No change to ESP
  - Two input parameters on stack
  - EAX, EDX, arg1 changed as shown
  - Others unchanged

Static analysis benefits: Reducing taint-tracking overhead

- Analysis+Optimizations lead to a *6 times* performance improvement!

- 4x performance improvement over purely dynamic techniques



Summary and Future Work

- Develop novel compiler-based methods for efficient and robust binary instrumentation
  - Dramatically reduce efforts for modeling instruction sets
  - Robust, scalable static analysis of low-level code
    - Provides crucial missing pieces to complete the loop in compiler-based instrumentation
      - Abstract interpretation for accurate analysis of register, stack use
      - Type inference for discovery of code pointers
- Future work
    - Experimentation and evaluation
    - Robust and efficient binary instrumentation for information flow and related properties
    - Application to hostile OS defense