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Towards Verified Decompilation using Lean 4

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Acknowledgements


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We are building this with help from

- Developers of Lean 4: Leonardo de Moura and Sebastian Ullrich
- CVC4 Team: Haniel Barbosa, Mathias Preiner, Arjun Viswanathan, Cesare Tinelli, and Clark Barrett
- UIUC X86_64 ISA formalization: Sandeep Dasgupta

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About Galois

- Galois focus is to ensure **trusted** systems are **trustworthy**.
- Predominant focus on consulting, tools, techniques and demonstrations.
- Contribute heavily to open source.
- Use spinouts for commercialization.
- We have expertise and hire in a variety of area: cryptography, data science, distributed systems, formal methods, hardware, programming languages, etc.

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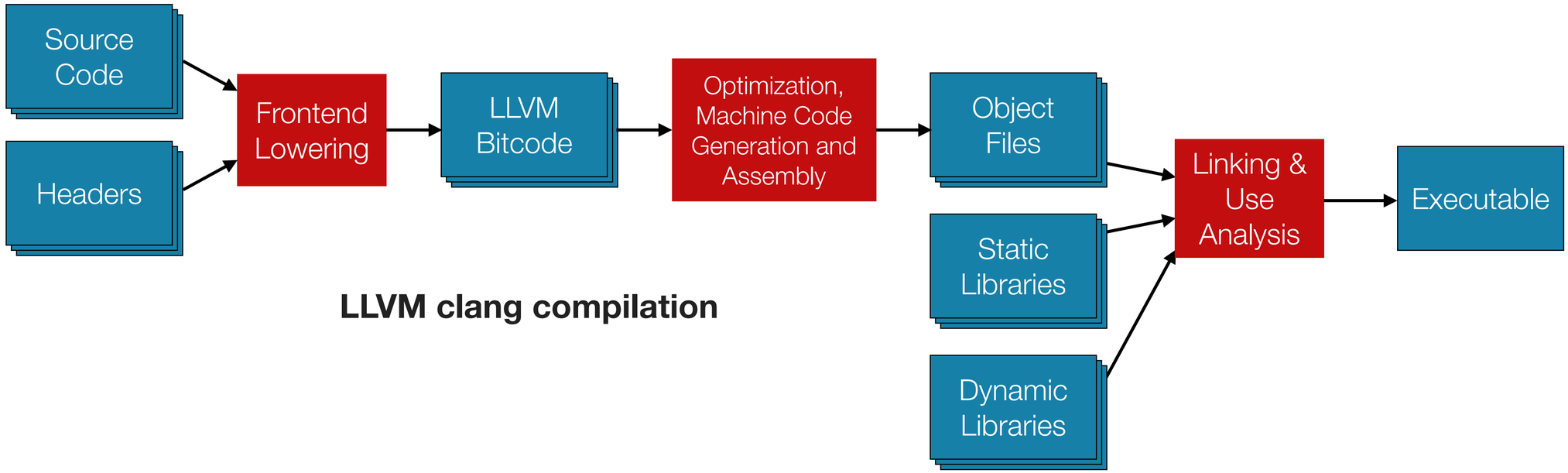
Lean at Galois

- Our SAW symbolic execution tools internally use a dependent calculus, SAWCore, for representing program values.
  - SAWCore has been heavily influenced by Lean.
- We have also had two projects using Lean for verification:
  - A protocol verification effort using Lean 3.
  - A LLVM decompiler verifier using Lean 4
- There are many people at Galois interested in other ITPs as well: Coq, Isabelle, ACL2

Decompilation

Decompilation

- **Decompilation** recovers information obscured during compilation to reverse the process.



LLVM clang compilation

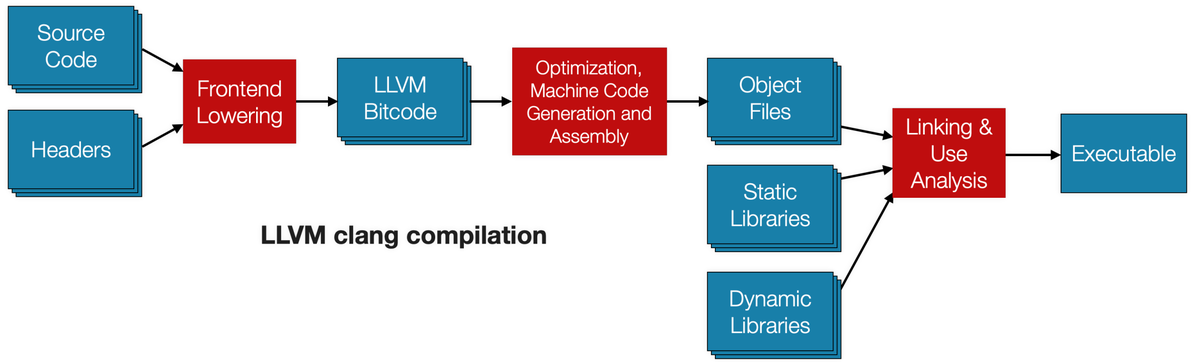
Decompiler Uses

- Decompilation is currently used for **program understanding**.
  - Decompile to a **language understandable by people**.
  - Use a combination of static analysis, heuristics, and hints from the user.
  - Without hints or existing source to target, it is likely impossible to recover the original source.
- Research looking into using decompiler to **recompile** an application.
  - Use new security measures or optimizations on legacy applications to take advantage of new features or security mechanisms.
  - Patch an existing binary.
  - Porting a compiled binary from one platform to another.

Recompilation Observations

Recompilation use case differences.

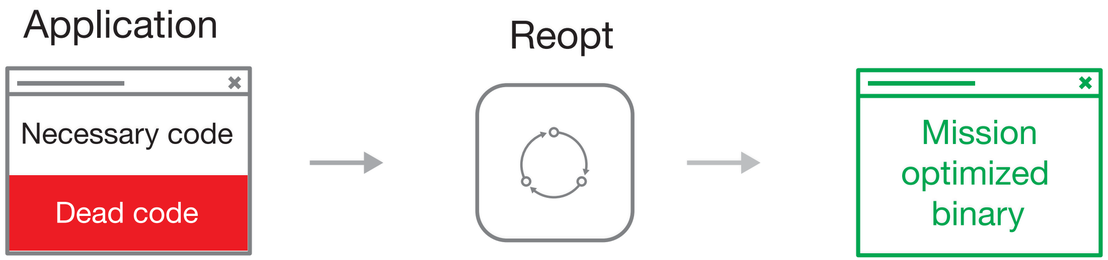
- Sufficient to lift to **compiler IR** or object file representation rather than source.
- **Assured** decompilation is much more important.



LLVM clang compilation

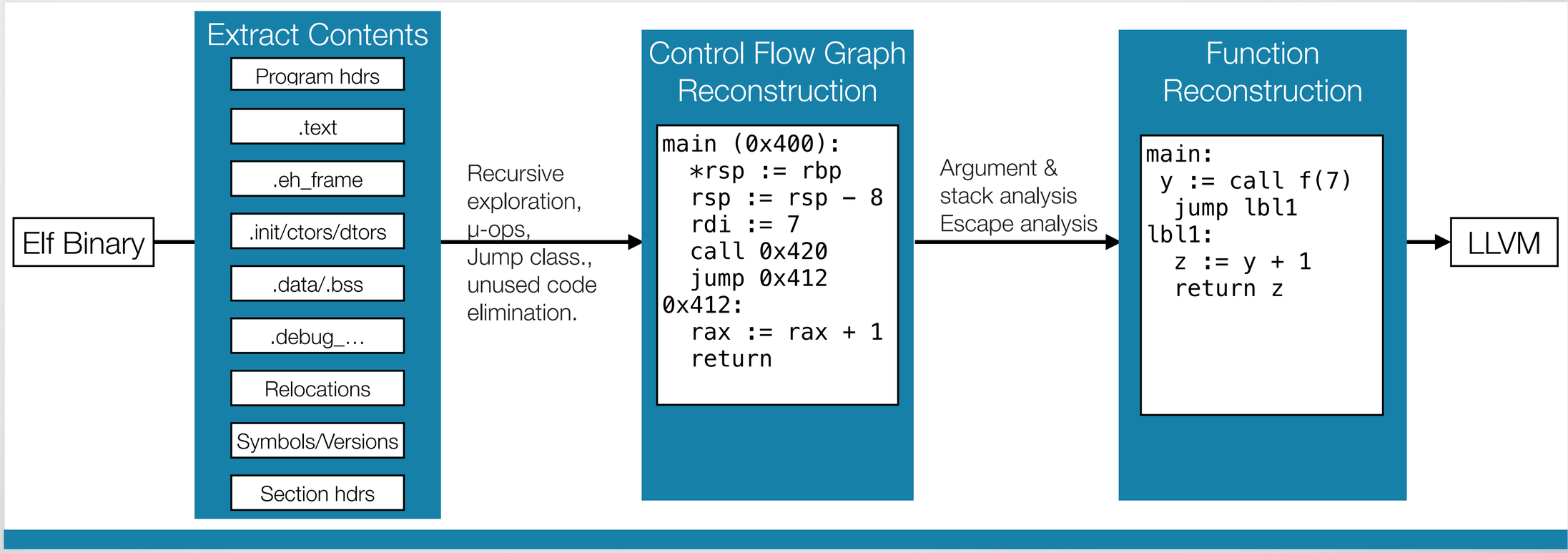
Program Recompilation

- My talk today is focused on binary raising for **reopt**, a tool for optimization of compiled executables.



- This can be used for optimization, dead code elimination, and hardening legacy binaries.

Reopt's Decompilation Pipeline



Verification

Verification Properties

Recompilation Soundness

- Every observable execution in the LLVM should be possible in the machine code program.

$$t \in traces(P_{LLVM}) \Rightarrow \exists\ t' \in traces(P_{MC}),\ t \equiv t'$$

Verification Soundness

- If a property is true of the raised program, then it should be true of the machine code program.

Observational Equivalence

- Our current notion of equivalence is based on event traces.
- Required events include:
  - Writes to non-stack addresses.
  - Other operations that may raise signals (e.g., divide-by-zero).
  - System calls
- Internally, we make additional equivalence checks for compositional purposes.

Verification Approaches

1. Build a **verified decompiler** using interactive theorem proving.

- Decompilation is an open-ended problem.
- Very complex to implement, and needs continued improvement.

2. Use an automated checker to check the programs are equivalent.

- Program equivalence is ordinarily decidable…
- However, the decompiler output is structurally similar to input binary.
- We have developed a **compositional approach** that checks equivalence of **basic blocks** using SMT solving.

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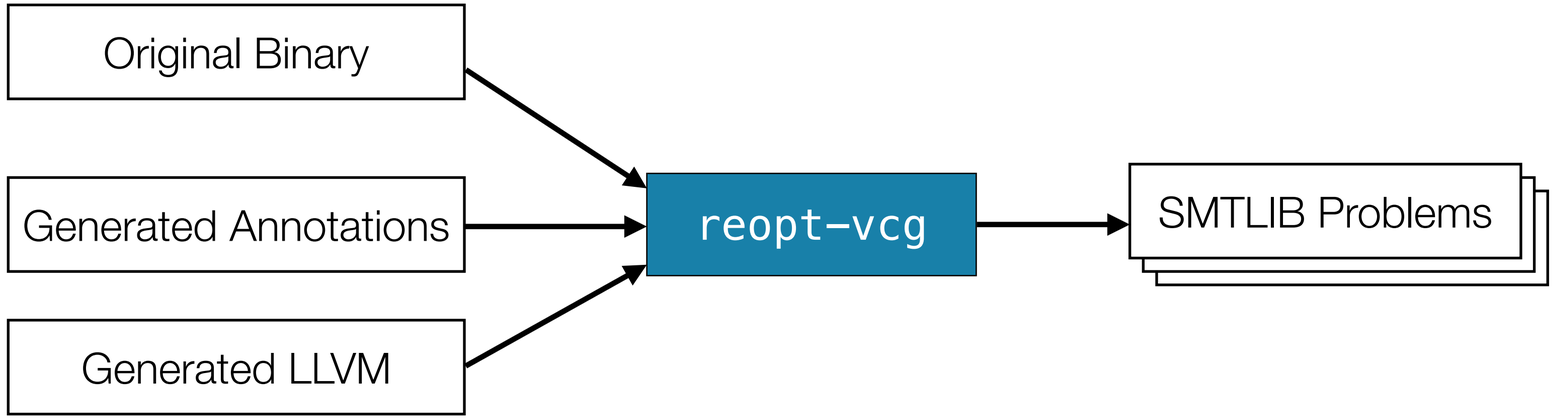
Verification Approach

- We have implemented a verifier based on translation validation.



Correctness claim: If all SMTLIB SAT problems are unsat, then the generated LLVM refines the original binary

Compositional Proofs

- The key to making this work is to develop a compositional proof strategy, and this uses additional proof obligations:
  - Functions must respect the ABI (how arguments are passed, callee-saved registers, etc)
  - The bottom of the stack must have unallocated guard pages, and no function stack frame is larger than the guard page region.
  - Our block annotations describe preconditions on each block, which can be assumed at the start of each block execution, and must be proven when jumping to a new block.
- One limitation, as we do not control LLVM stack usage completely, the recompiled LLVM program may use more stack space than the original machine code program.

Current Verifier Status

- Reopt generates the annotation files.
- Working on small test programs, and now debugging issues on a larger web server example.
- Code statistics

Tool/Library	Rough LOC
reopt	134kloc
reopt-vcg (- semantics)	23kloc
Lean x86 semantics	62kloc

- reopt and reopt-vcg are publicly available, but still under active development.

  `https://github.com/GaloisInc/reopt`

  `https://github.com/GaloisInc/reopt-vcg`

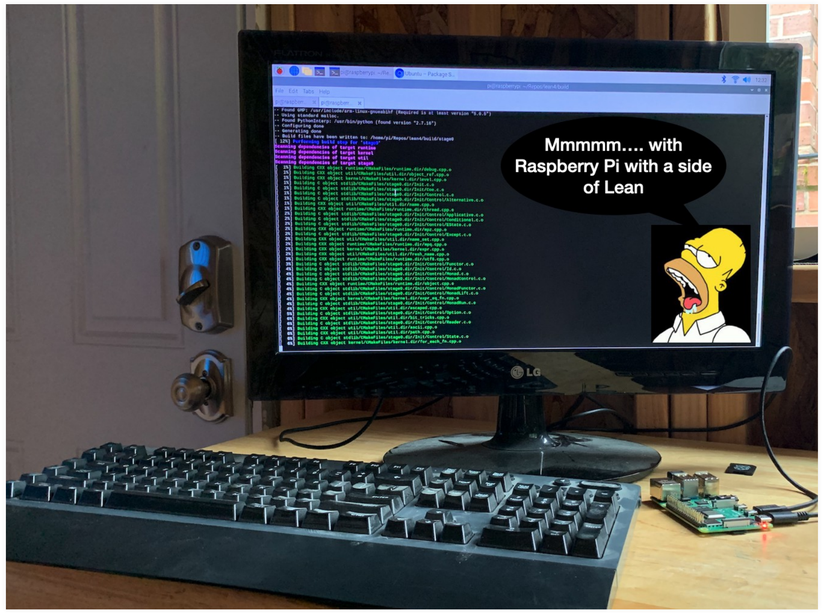
- Fledgling libraries in Lean 4 for:
  - LLVM bitcode parsing
    - Links against libllvm (using `@extern` attribute)
  - Elf object file parsing
  - x86_64 machine code decoding and interpreting
    - As of yesterday we can import semantics specific using UIUC K x86_64 formalization.
  - SMT Generation and running external solvers.

Planned Work

- Continue expanding the scope of programs we can decompile and verify.
- Type analysis of heap in machine code programs.
  - Needed for sound verification of programs with indirect function calls.
- Formalize correctness of reopt-vcg

One more thing

- We are also working on getting Lean 4 controlling a robot.
- Andrew Kent is working on this.
- We are really excited about a programming language with powerful verification capabilities.



Thank You