# *Engineering Formal Security Policies for Proof-Carrying Code*

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# *Thesis Committee*

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# *Code Safety*

- We use an increasing number of programs
- The number of program sources is also increasing
- But are these programs safe for us to run?

- Technologies for *code safety* enable us to say "yes" before we run a program on our computer

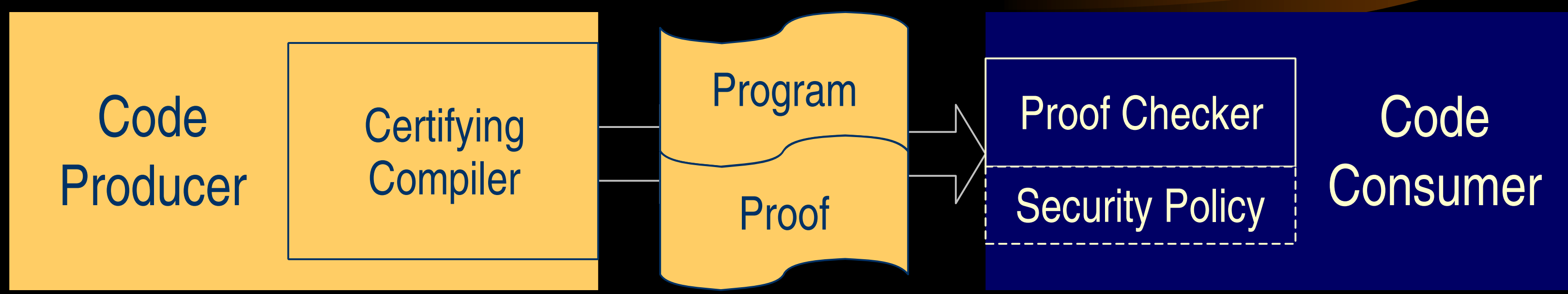
# *Challenges to Code Safety*

- Byte-code interpreters are slow
  - Unacceptable battery drain for small devices
- Just-in-time compilers are large and complex
  - Critical bugs can be expensive to fix
- Digitally-signed programs aren't trustworthy
  - Signature doesn't ensure that the code is actually safe
  - Everyone is vulnerable if the private key is compromised (*e.g.*, Microsoft)

# *The Right Architecture: Proof-Carrying Code (PCC)*

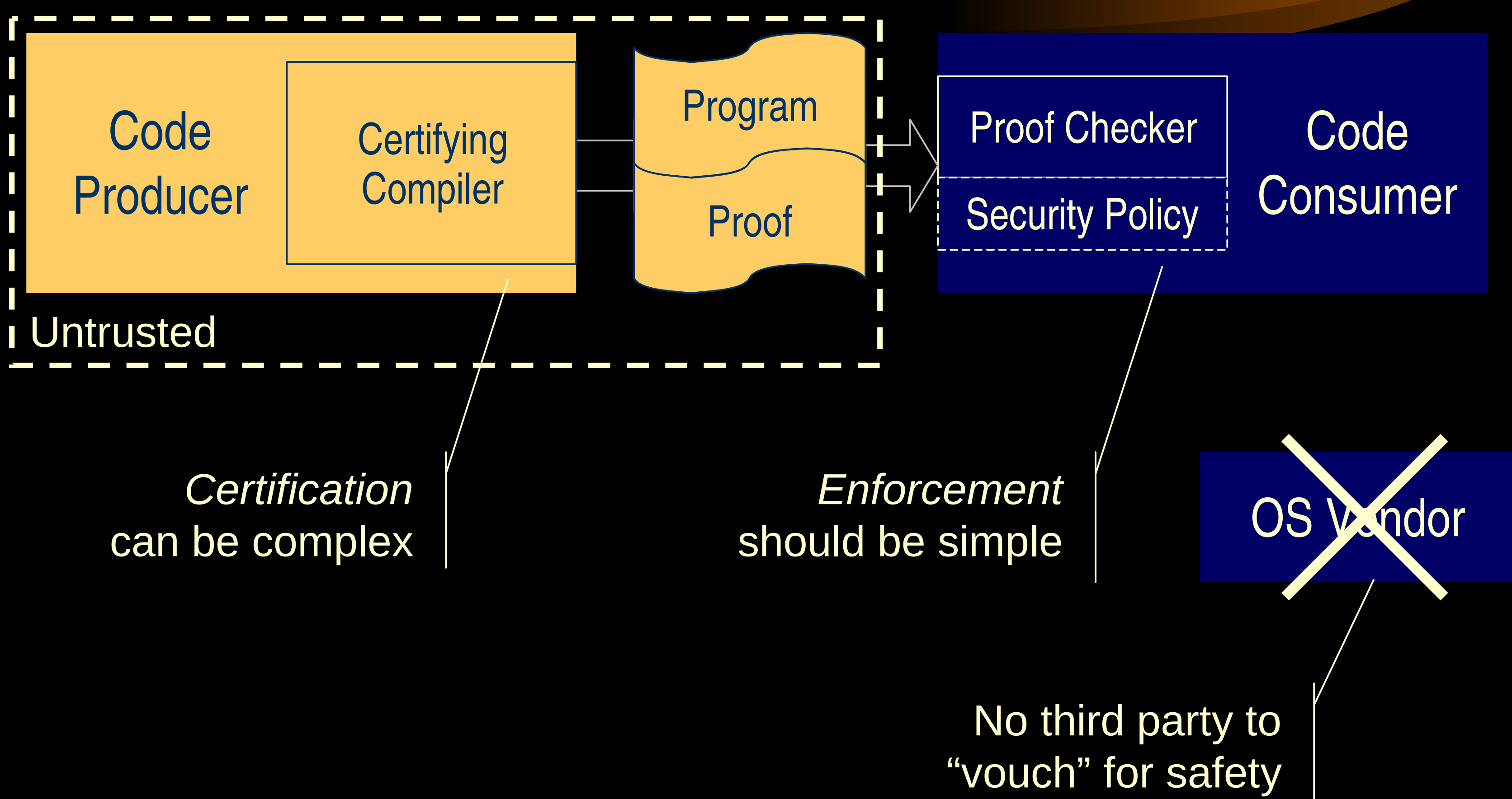
- Good performance
  - Compile in advance with all optimizations
  - Fewer run-time checks
- Small trusted computing base
  - Possible to verify informally
- No trusted third parties
  - Each host trusts only itself

# PCC: Vision [Necula/Lee 96]




- A *code producer* sends a program and its safety proof to a *code consumer*
  - A *certifying compiler* constructs the program and proof
  - A *proof checker* checks them against a security policy

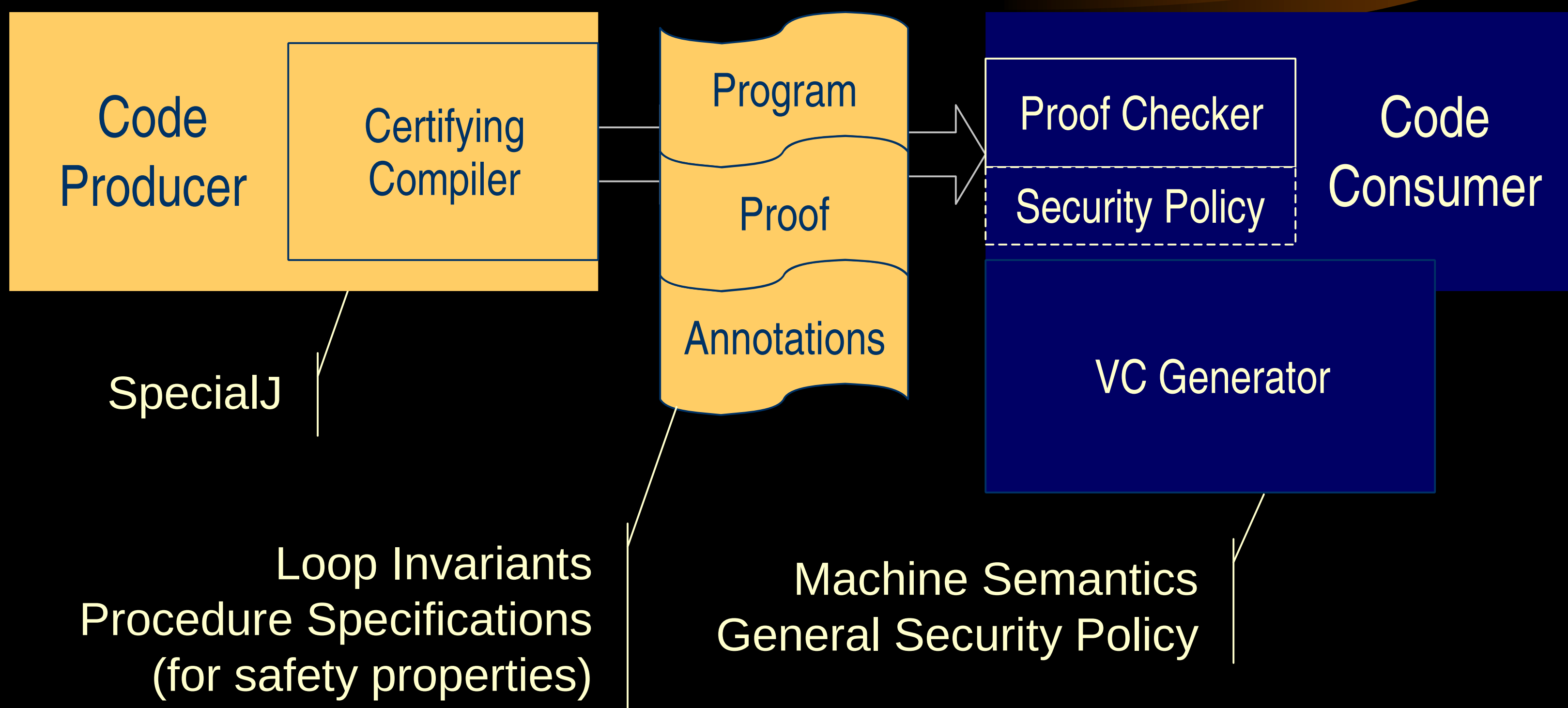
# PCC: Principles



# *PCC: Practice*

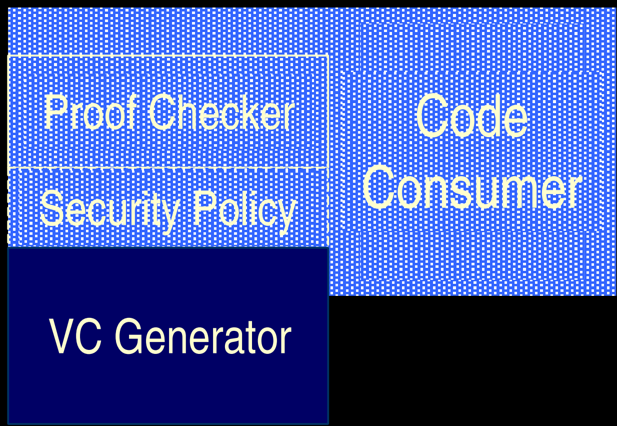
- SpecialJ Certifying Compiler [Colby, *et al.* 00]
  - Developed by Cedilla Systems
  - Certified, optimized x86 machine code from Java source code (no byte-code interpreter)
  - Safety policy is Java type safety
  - Translation to object code preserves type safety
  - Scales to large programs (*e.g.*, JDK 1.3, HotJava)
- LF Logical Framework [Harper, *et al.* 87]
  - Flexible internal language for propositions and proofs
  - Proof checking is type checking

# PCC: Reality


Code
Producer
Certifying
Compiler
Program
Proof
Annotations
Proof Checker
Security Policy
Code
Consumer
VC Generator
SpecialJ
Loop Invariants
Procedure Specifications
(for safety properties)
Machine Semantics
General Security Policy

# *Verification-Condition Generator*

- Verification condition (VC) is true only if program is safe (but not necessarily correct)
- Derived by *symbolic evaluation* [Necula/Lee 97]
  - Simulates program operations on abstract state
- Proofs are scalable, but the VC generator is
  - complex: 16,000 lines of dense C
  - machine specific
  - compiler specific
  - source-language specific
  - security-policy specific



# *How is the Security Policy Represented?*

- A combination of lots of C code and typing rules
  - Type systems are relatively trustworthy
  - But C code is more obscure and error prone

# *What if we want …*

- more than Java type safety?
  - *e.g.*, resource bounds, information flow
- to manage security policies?
- to manipulate security policies?

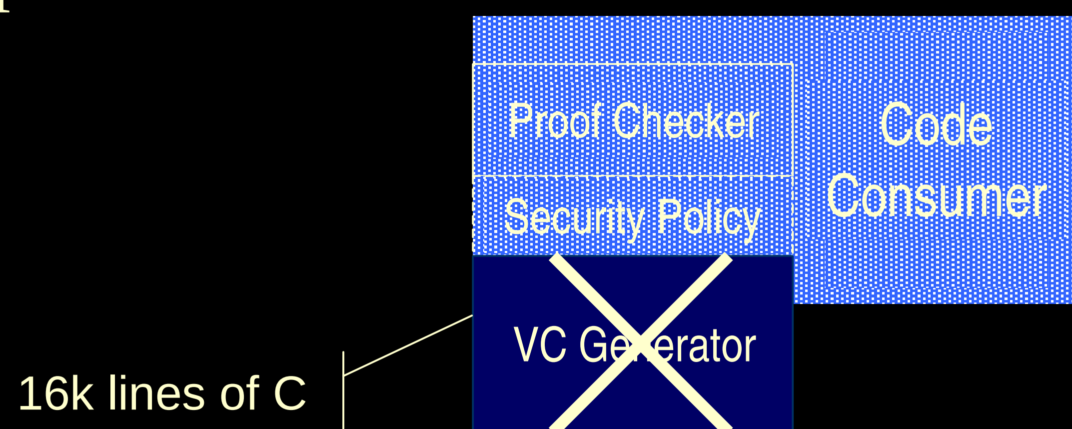
- We need to change the VC generator!
  - A better solution: a *universal* enforcement mechanism
  - Separate *policy* from *mechanism*

# *A Formal Language for Security Policies*

- Formal security policies for a universal checker
  - Security policy can be part of the certificate
- Temporal logic is an attractive policy notation
  - Direct specifications: $\Box(\mathtt{pc} < \mathtt{1000})$
  - Well-understood semantics
  - Can express a wide variety of security properties
  - Can reuse existing type-safety specifications [Necula/Lee 97]

# *The Goal*

- To achieve PCC by
  - Proving *directly* that a program satisfies a formal security policy
  - Instead of generating and proving an intermediate VC
- No VC generator
- Key question: is it practical?



# *The Approach: Verifiable Logic Programs*

- Certificate is a *program* for generating a proof
  - Extracts and proves its own VCs
  - Sound by construction
- Drawback: proof checking is slower (so far)
  - Proving more than SpecialJ safety proofs
- Possible "next step" for PCC proof checking?
  - LF type reconstruction [Necula/Lee 96]
  - Oracle-based theorem proving [Necula/Rahul 01]
  - Verifiable logic programs

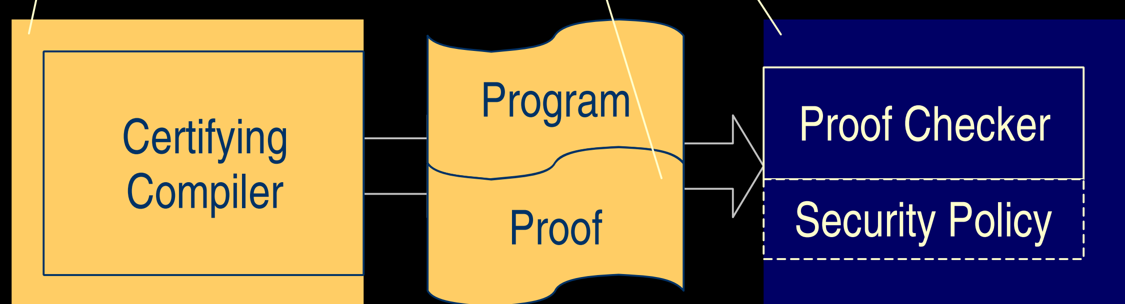
# *Thesis Statement*

- It is practical to engineer a system for proof-carrying code in which policy is separated from mechanism.

- In particular, I examine a generic implementation of the PCC infrastructure that accepts a wide variety of security properties encoded in a formal specification language.

# *The Rest of this Talk*

- Framework
- Code Consumer
- Code Producer
- Proof Engineering



# *Framework*

Temporal Logic

Machine Model

# *Temporal Logic*

- Truth is relative to a specific *time*
  - Propositions hold over finite or infinite intervals
- Excellent representation for security properties
  - *How* the program computes a result

# *Temporal Logic Syntax*

- Linear-time 1st-order temporal logic [Manna/Pnueli 80]
  - Identify time with CPU clock
- Expressions $e ::= a \mid x \mid c \mid f(e_1, \ldots, e_k)$
  - Parameters *a* refer to the machine state (*e.g.*, **`pc`**)
- Propositions $p ::= R(e_1, \ldots, e_k)$

$$\mid p_1 \wedge p_2 \mid p_1 \vee p_2 \mid p_1 \supset p_2$$
$$\mid \forall x.\, p_1 \mid \exists x.\, p_1 \mid \bigcirc p_1 \mid \Box p_1 \mid p_1 \,\mathcal{U}\, p_2$$

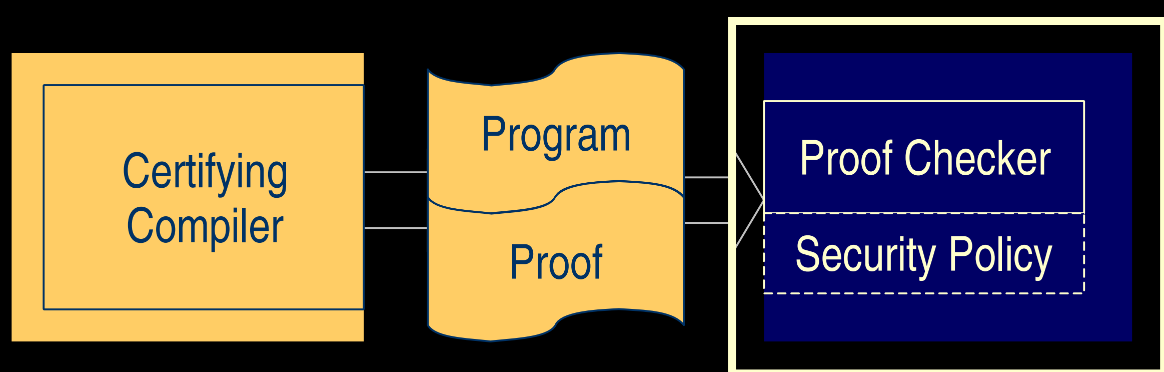
# *Temporal Logic as a Security-Policy Language*

- Combining security policies
  - Conjunction: $p_1 \wedge p_2$
  - Disjunction: $p_1 \vee p_2$
- Tracking execution history (security automata)
  - History parameters: $\Box(\mathtt{q} = e \supset \bigcirc(\mathtt{q} = e')) \supset \Box p(\mathtt{q})$
- Modular security policies
  - Private histories: $\forall y.\ \Box(y = e \supset \bigcirc(y = e')) \supset \Box p(y)$

# *Abstract Machine Model*

- Simplified machine model for this talk
- Three parameters for machine state
  - **`pc`**: program counter
  - **`g`**: general-purpose register file
  - **`m`**: memory
- Instruction set is unimportant

# *Code Consumer*



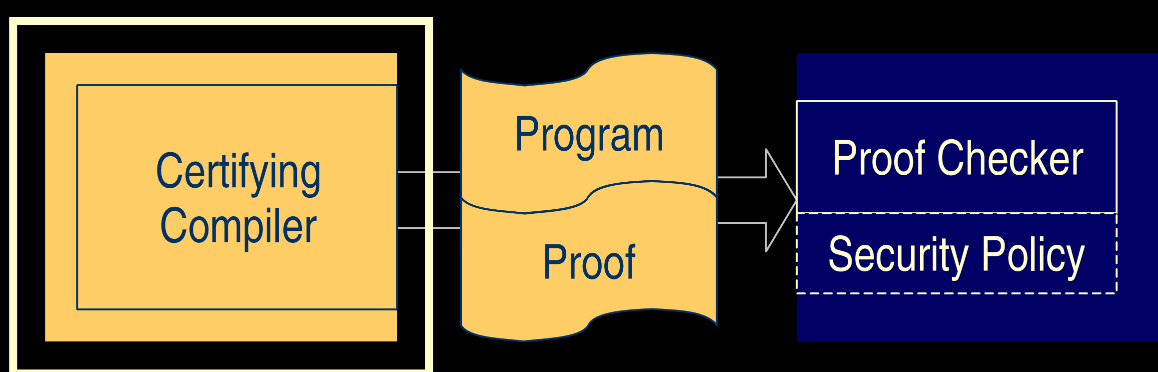
# *Formal Machine Semantics*

- Provides a basis for proof checking
  - Security policy must follow from machine semantics
- The transition relation
  - Effect of an instruction on a state [Pnueli 77]
  - Syntactic rather than semantic (*e.g.*, model checking)
- Theorem: soundness
  - Follows directly from operational semantics

# *Proof Checking*

- Enforces *all* temporal-logic security properties
  - All safety properties (*e.g.*, memory safety, resource bounds, access control, Java security manager)
  - Most familiar liveness properties (*e.g.*, termination)
  - Can’t express noninterference (*e.g.*, information flow)
- Proof checker has a logic-program interpreter
  - Reconstructs omitted proof fragments
- Handwritten proofs are possible, but…

# *Code Producer*



# *Strategy*

- Proof construction is harder than proof checking
  - We can *enforce* more properties than we can *certify*
    - This may be inevitable
- Decouple enforcement from certification
  - Many approaches to certification
  - Get enforcement right "once and for all"
- Focus on certifying type safety
  - Needed for many applications
  - First test case for automatic certification

# *Automatic Proof Construction*

- Build an *adapter* for the SpecialJ compiler
  - Automatic proofs of type safety
  - Experiment with larger examples
- Use a *logic of programs* for safety properties
  - Derive from temporal logic [Gordon 89]
  - Instantiate for SpecialJ type safety
- How does SpecialJ work?

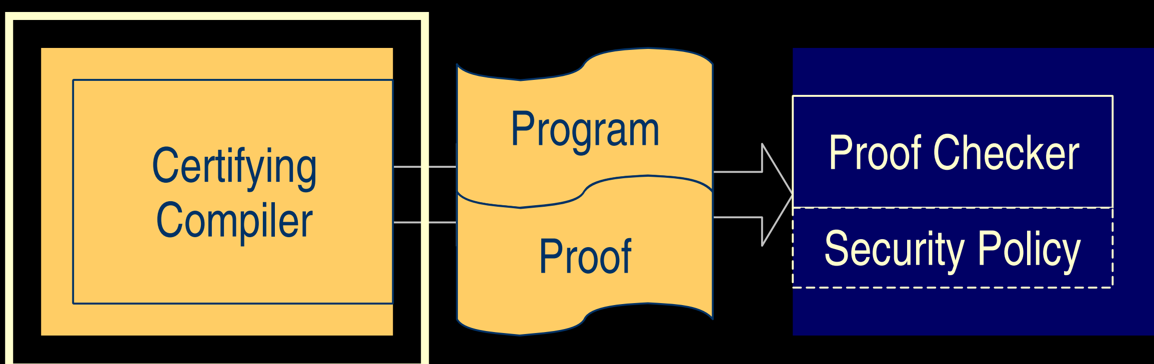
# *SpecialJ Symbolic Evaluation*

- Interpret program using machine semantics
  - Symbolic machine state is a formal expression
  - Unknown values are variables
  - Based on an implicit program logic
- Emit proof obligations for dangerous instructions
- Handle loops using *recurring loop invariants*
  - Each invariant leads to another invariant, and we're safe in the meantime

# *Proof Generation*

- Generate a “skeleton” of program-logic rules that simulate the SpecialJ symbolic evaluator
  - Safety proofs from SpecialJ discharge premises of program-logic rules
- The code producer supplies the *untrusted* program logic [Appel/Felty 00]

# *Program Logic*



# *A Logic of Programs for Invariance Properties*

- A specialized logic for reasoning about programs
  - Proves invariance in addition to partial correctness
  - Verifies each procedure independently
- Shows that an invariance property holds until a specific *goal property* is reached
  - Goal is initially a procedure postcondition
- An *invariance property* is a property of individual machine states

# *Conventions*

- $e$ is a symbolic machine-state tuple $(e_{\mathtt{pc}}, e_{\mathtt{g}}, e_{\mathtt{m}})$
  - Parameters for unknown values
  - Example: $(25, \mathtt{upd}(a_{\mathtt{g}}, \mathtt{r}_0, 5), a_{\mathtt{m}})$
- $\mathtt{s}$ is a parameter always equal to $(\mathtt{pc}, \mathtt{g}, \mathtt{m})$
- $p_{\mathtt{safe}}$ is an invariance property (*e.g.*, type safety)
- $p_{\mathtt{gl}}$ is the current goal property

# *Specifications*

- Specifications on **s** (no temporal operators)
  - $p_{\mathtt{i}}$ is a loop invariant
  - $p_{\mathtt{p}}$ is a procedure precondition
  - $p_{\mathtt{q}}$ is a procedure postcondition
  - $x_0$ is free: instantiated with *reference* machine state
- Example loop invariant (for code address 25):

$$\pi_{\mathtt{pc}}(\mathtt{s}) = 25 \wedge \mathtt{r}_0(\pi_{\mathtt{g}}(\mathtt{s})) : \mathtt{int} \wedge \pi_{\mathtt{m}}(\mathtt{s}) = \pi_{\mathtt{m}}(x_0)$$

$$\mathtt{pc} = 25 \wedge \mathtt{r}_0(\mathtt{g}) : \mathtt{int} \wedge \mathtt{m} = \pi_{\mathtt{m}}(x_0)$$

# *Judgments*

- Transition
  - The successor of state $e$ is $e$' $\qquad e \longrightarrow e'$
- Evaluation
  - From state $e$, $p_{\mathtt{safe}}$ holds until $p_{\mathtt{gl}}$ holds $\qquad e \overset{p_{\mathsf{safe}}}{\rightsquigarrow} p_{\mathsf{gl}}$
- Strict Evaluation
  - $p_{\mathtt{safe}}$ must also hold for at least one step $\qquad e \overset{p_{\mathsf{safe}}}{\rightsquigarrow}{}^{+} p_{\mathsf{gl}}$
- Procedure Call
  - Once $p_{\mathtt{p}}$ holds, $p_{\mathtt{safe}}$ holds until $p_{\mathtt{q}}$ holds $\qquad p_{\mathsf{p}} \overset{p_{\mathsf{safe}}}{\rightsquigarrow}{}^{\star} p_{\mathsf{q}}$
  - Derive this for initial entry point

# *Strict Evaluation Rules*

$$\frac{\vdash [e/\mathsf{s}]\, p_{\mathtt{safe}} \qquad \vdash e \longrightarrow e' \qquad \vdash e' \overset{p_{\mathtt{safe}}}{\rightsquigarrow} p_{\mathsf{gl}}}{\vdash e \overset{p_{\mathtt{safe}}}{\rightsquigarrow}{}^{+} p_{\mathsf{gl}}} \rightsquigarrow^{+}\mathsf{i}_1$$

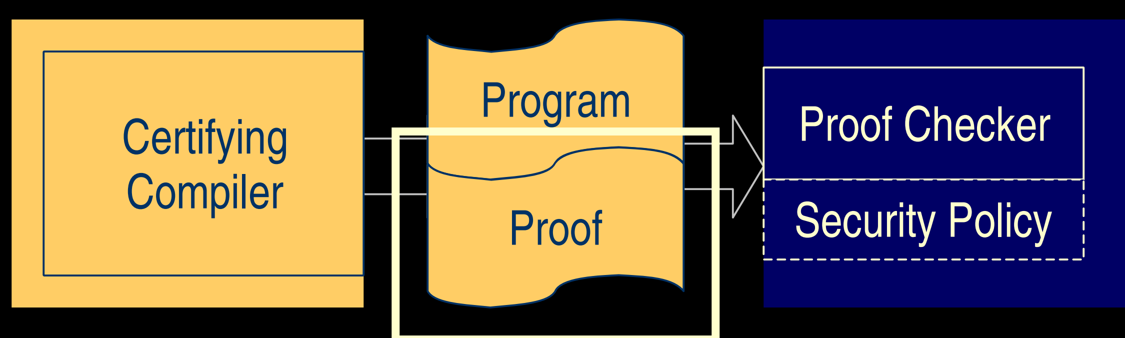
$$\frac{\vdash e \overset{p_{\mathtt{safe}}}{\rightsquigarrow}{}^{+} p_{\mathsf{gl}}}{\vdash e \overset{p_{\mathtt{safe}}}{\rightsquigarrow} p_{\mathsf{gl}}} \rightsquigarrow^{+}\mathsf{e}$$

# *Evaluation Rules*

$$\frac{\vdash [e/\mathsf{s}]\, p_{\mathsf{gl}}}{\vdash e \overset{p_{\mathtt{safe}}}{\rightsquigarrow} p_{\mathsf{gl}}} \rightsquigarrow \mathsf{i}_0$$

$$\frac{\vdash e \overset{p_{\mathtt{safe}}}{\rightsquigarrow} [e/x_0]\, p_{\mathsf{i}} \vee p_{\mathsf{gl}} \qquad \begin{array}{c} \overline{\vdash [e/x_0]\,[a/\mathsf{s}]\, p_{\mathsf{i}}}^{\,u} \\ \vdots \\ \vdash a \overset{p_{\mathtt{safe}}}{\rightsquigarrow} + [e/x_0]\, p_{\mathsf{i}} \vee p_{\mathsf{gl}} \end{array}}{\vdash e \overset{p_{\mathtt{safe}}}{\rightsquigarrow} p_{\mathsf{gl}}} \rightsquigarrow \mathsf{loop}^{a,u}$$

# *Proof Engineering*



# *Proof Representation*

| Decoding | Prelude | Body |
| --- | --- | --- |
| `[96] P1 P2 ==>`<br>`P1 and P2.`<br>… | `prl/sk_safe: …`<br>`= [d_r] [d_s] …`<br>… | `6e 06 90 0d 0d 8f 89 0e`<br>`60 78 60 60 7c 34 23 7d`<br>… |

- Minimize total proof size for large programs
  - *Decoding* specifies binary-to-LF translation
  - *Prelude* provides derived rules
    - Includes the derived program logic, logic program
  - *Body* is a binary proof encoding

# *Proof Reconstruction*

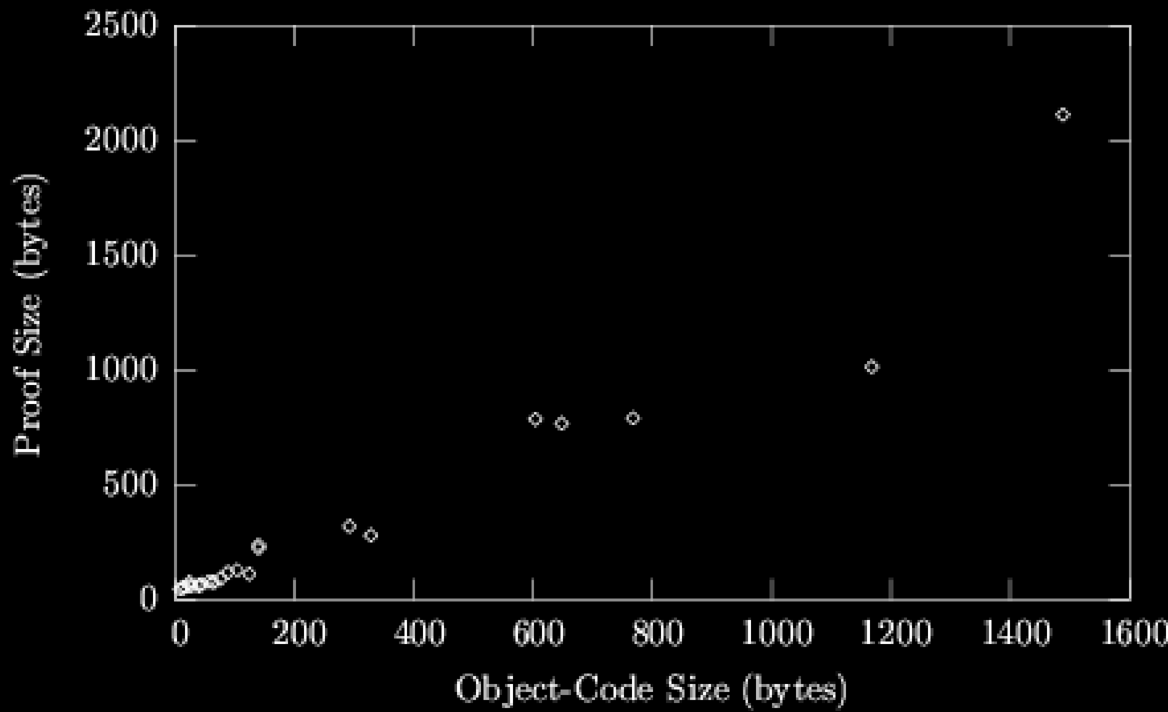
- An explicit proof is too large, even in binary
- Use the logic interpreter: reconstruct most of the proof on demand
  - Omit decidable fragments entirely
  - Map undecidable fragments onto minimal outlines
    - Explicitly constrain possible clauses [Pfenning 01]
    - Resembles “oracle” checking [Necula/Rahul 01]
  - Code *producer* chooses which parts to omit

# *Verifiable Logic Programs*

- Only search over derived rules
  - Each derived rule has an explicit proof in the prelude
  - Code producer writes the logic program
    - Based on program logic
  - Optimize for the certification strategy

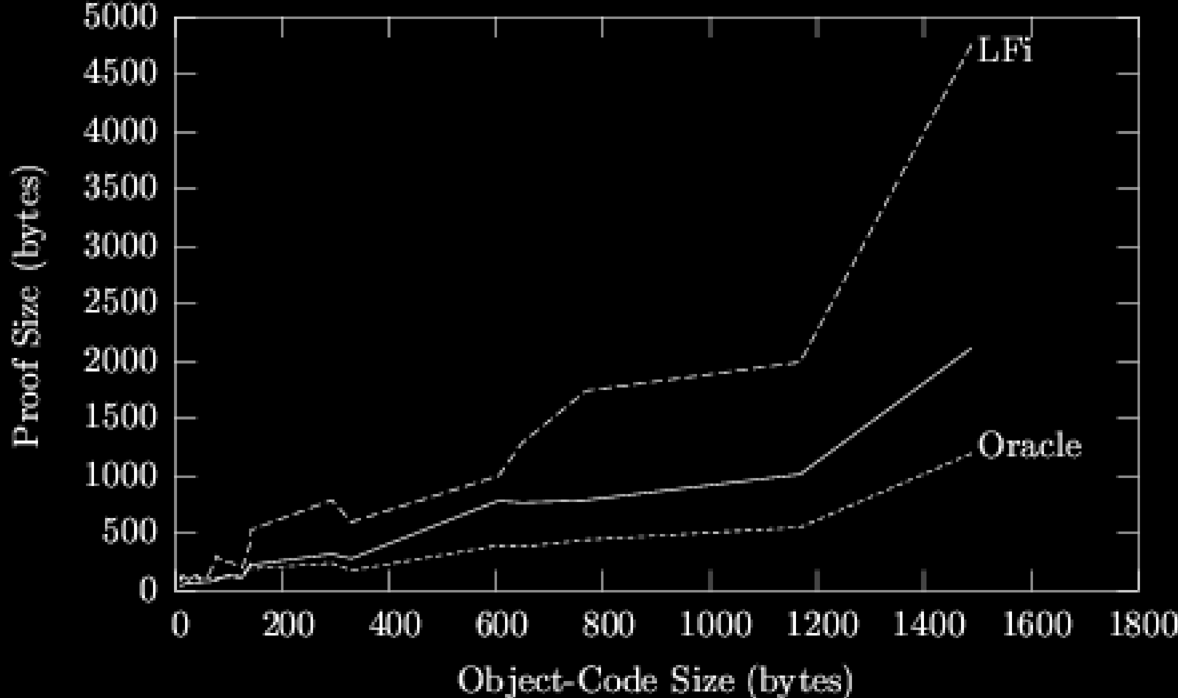
# *Experimental Results*

# *Proof Size*

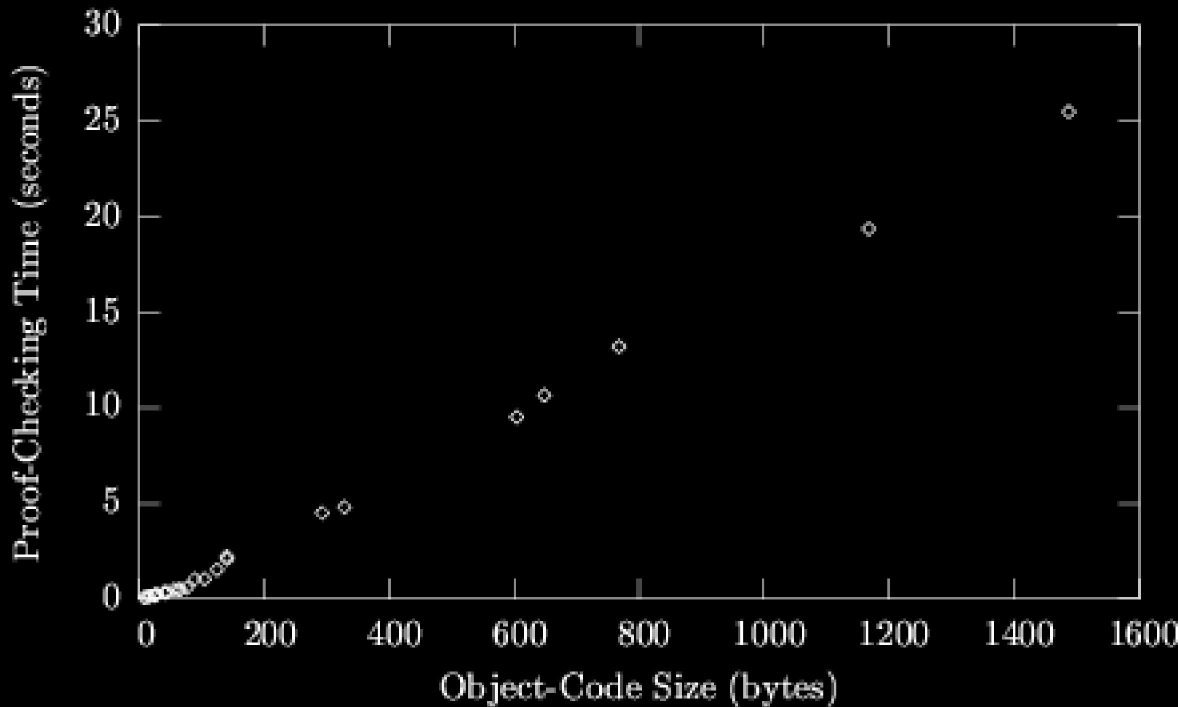



- Doesn’t include prelude or decoding

# *Relative Proof Size*



# *Proof-Checking Time*




- Measured on a 1.6GHz Athlon PC

# Related Work

# *Foundational PCC*

- *Foundational PCC* [Appel/Felty 00; Hamid, *et al.* 02] reconstructs PCC on higher-order logic
  - No trusted type system: derive in higher-order logic
- I want explicit security policies
  - Work with an existing compiler and safety proofs
  - Attack VC generator: less trustworthy than type system
    - 16,000 lines of C vs. 200 lines of LF
- *Foundational typed assembly language* [Crary 03; Crary/Sarkar 04]

# *Expressive Security Policies*

- Proof-carrying Code
  - Resource bounds [Necula/Lee 98]
- Typed Assembly Language (TAL)
  - Security automata [Walker 00]
  - Capabilities [Crary, *et al*. 99]
  - Resource bounds [Crary/Weirich 00]
  - TALT-R [Vanderwaart/Crary 04]
- Software Fault Isolation
  - Security automata [Erlingsson/Schneider 99]
  - Edit automata [Walker 02]

# Future Work

# *Future Work*

- Speed up proof checking
  - Where is the “sweet spot?”
- Automatic certification for more safety properties
  - Advanced type systems
  - Instrumentation
- Temporal logic is a particular choice of notation
  - Measure effect of other choices

# *Automatic Certification: Advanced Type Systems*

- Type systems can check many safety properties
- Programmer provides the proof
  - Source code must be written such that it type checks
  - A typing derivation is a proof of safety
- Two approaches for PCC
  - Code consumer adopts another type system (easier)
  - Map typing derivations onto derived rules (harder)

# *Automatic Certification: Instrumentation*

- Inline reference monitors (IRM) [Erlingsson/ Schneider 99]
  - Security automaton threaded through program
  - Run-time checks ensure program is safe
  - Tools exist to instrument Java bytecode (SASI, Naccio, Polymer)
- Code producer can also do this
  - Straightforward loop invariants and proofs
  - No IRM tool in the TCB

# *Conclusion*

- Contributions
  - Enforcement for Temporal-Logic Properties
  - A Derived Program Logic for Safety Properties
  - Proof Engineering for Foundational Proofs
  - A Temporal-Logic Framework for PCC
  - A Foundation for SpecialJ
- Thanks: Michael Donohue, Stephen Magill