What is Programming Languages Research?

Michael Hicks
University of Maryland

PLUM

A Conversation, circa 2014

We need to hire in PL this year!

… I have a nagging concern: Isn’t PL a solved problem?

Um, no, there’s lots to do.

Really? What is it that you PL people are working on?

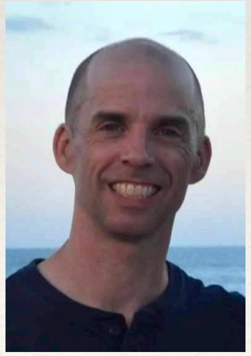
We work on Programming Languages!

OK, but …

Don't modern languages work pretty well? And aren't they often developed by non-academics?

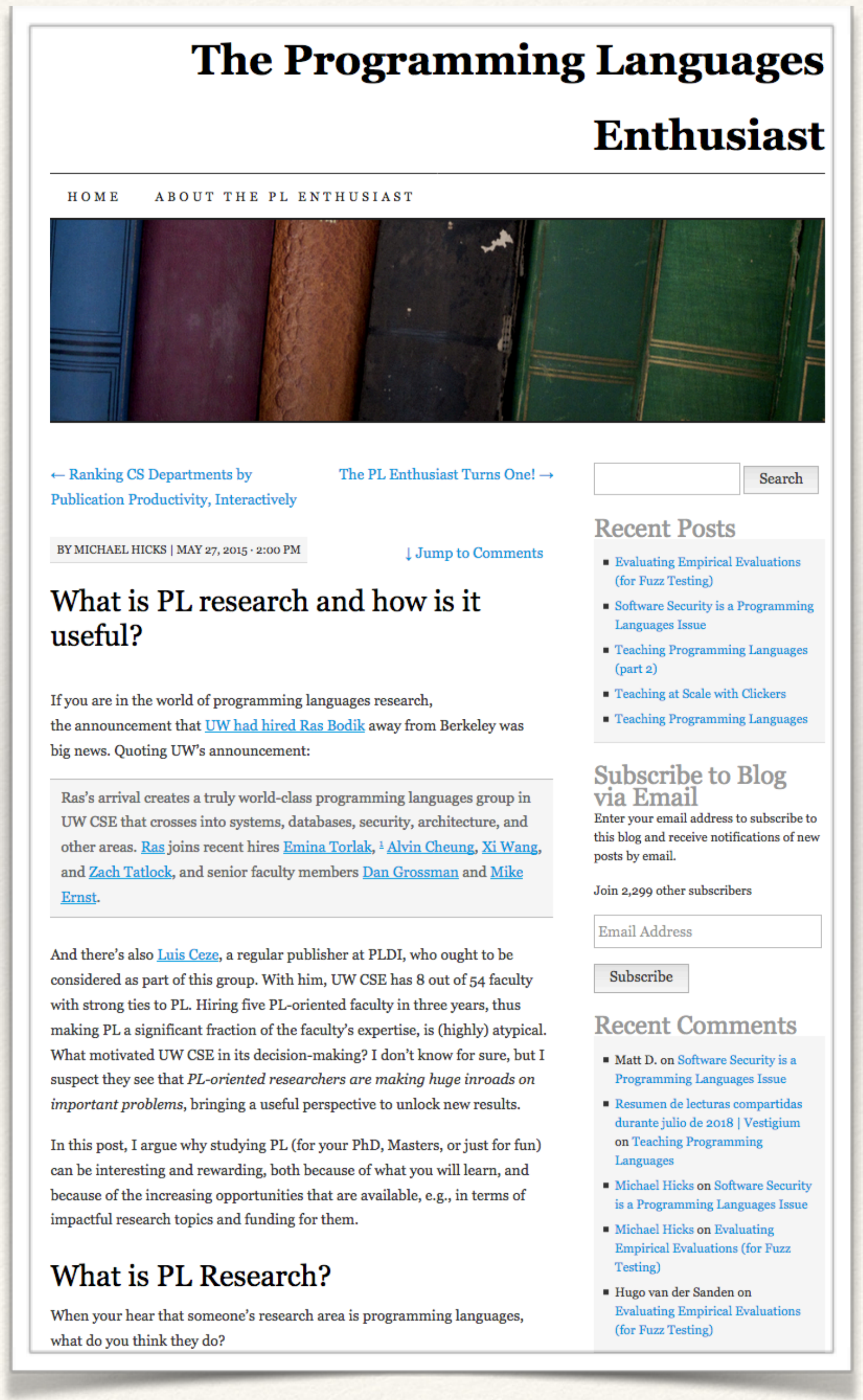
Yes, but there are still big research contributions still to make.

Doing what?



I should start a blog …

What is PL Research?



The Programming Languages Enthusiast

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The PL Enthusiast Turns One! →

BY MICHAEL HICKS | MAY 27, 2015 · 2:00 PM

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What is PL research and how is it useful?

If you are in the world of programming languages research, the announcement that UW had hired Ras Bodik away from Berkeley was big news. Quoting UW's announcement:

> Ras's arrival creates a truly world-class programming languages group in UW CSE that crosses into systems, databases, security, architecture, and other areas. Ras joins recent hires Emina Torlak, [1] Alvin Cheung, Xi Wang, and Zach Tatlock, and senior faculty members Dan Grossman and Mike Ernst.

And there's also Luis Ceze, a regular publisher at PLDI, who ought to be considered as part of this group. With him, UW CSE has 8 out of 54 faculty with strong ties to PL. Hiring five PL-oriented faculty in three years, thus making PL a significant fraction of the faculty's expertise, is (highly) atypical. What motivated UW CSE in its decision-making? I don't know for sure, but I suspect they see that *PL-oriented researchers are making huge inroads on important problems*, bringing a useful perspective to unlock new results.

In this post, I argue why studying PL (for your PhD, Masters, or just for fun) can be interesting and rewarding, both because of what you will learn, and because of the increasing opportunities that are available, e.g., in terms of impactful research topics and funding for them.

What is PL Research?

When your hear that someone's research area is programming languages, what do you think they do?

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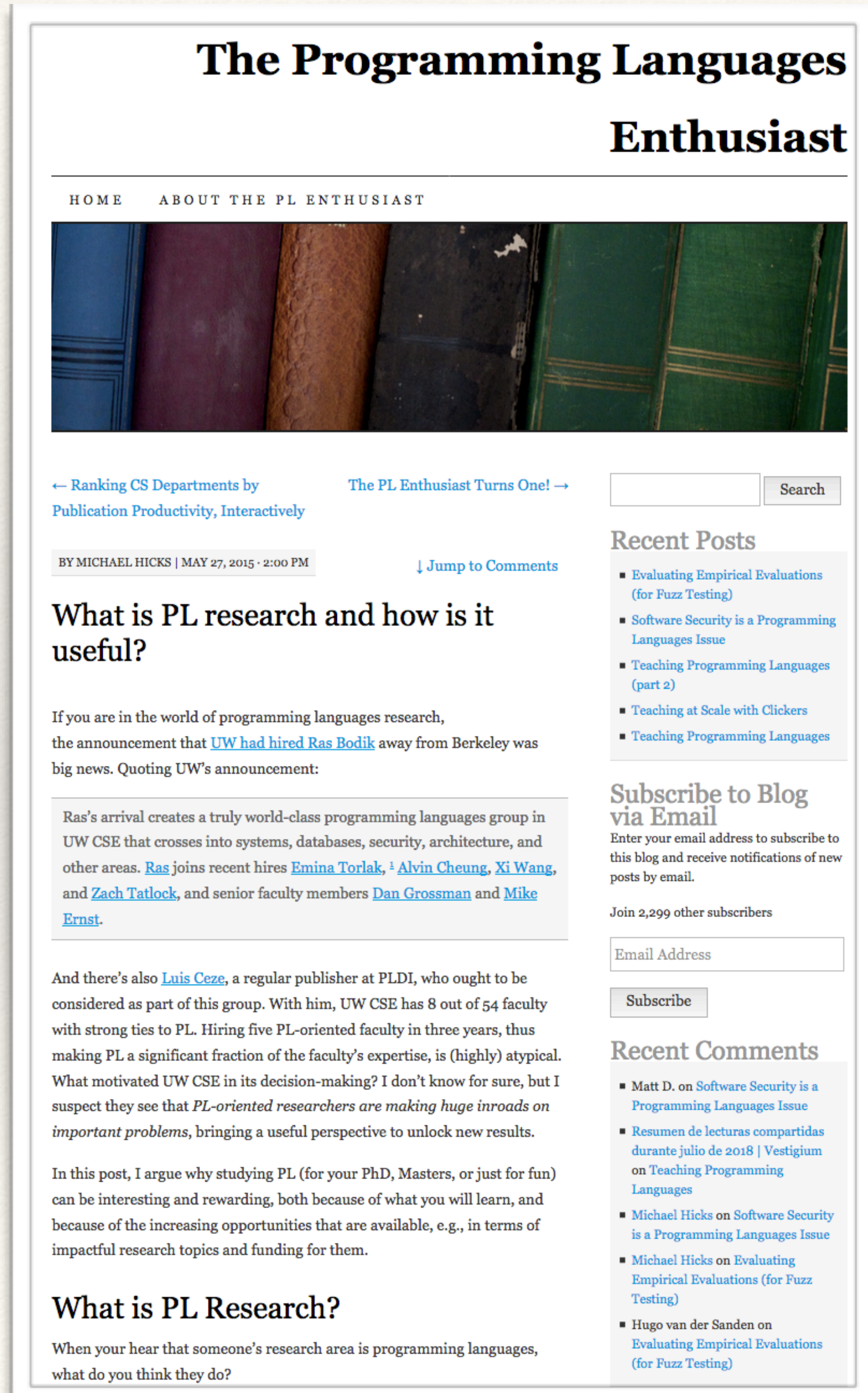
PL research views the programming language as having a central place in solving computing problems.

A PL researcher:

- develops *general abstractions*, or *building blocks*, for solving problems, or classes of problems,
- considers software *behavior* in a *rigorous and general way*, e.g., to prove that (classes of) programs enjoy properties we want, and/or eschew properties we don't.

What is PL Research?



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- The ethos of PL research is to not just find solutions to important problems, but to find the *best expression of those solutions*, typically in the form of a kind of language, language extension, library, program analysis, or transformation.
- The hope is for *simple, understandable solutions* that are also *general*: By being part of (or acting at the level of) a language, they apply to many (and many sorts of) programs, and possibly many sorts of problems.

Example: Improving Program Efficiency

- Quicksort in Haskell

```haskell
sort :: (Ord a) => [a] -> [a]
sort (x:xs) = lesser ++ x:greater
    where lesser  = sort [y | y <- xs, y <  x]
          greater = sort [y | y <- xs, y >= x]
sort _ = []
```

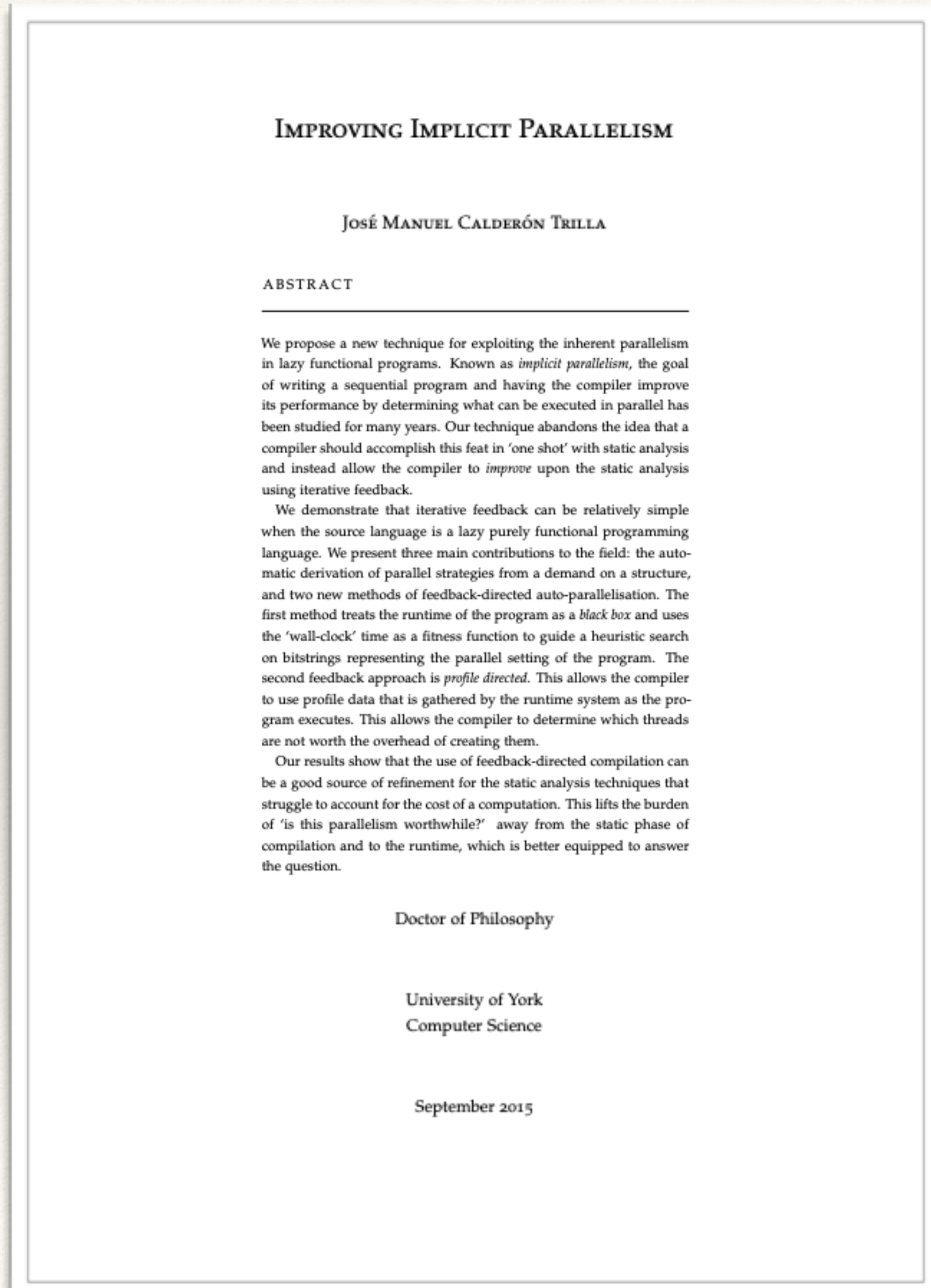
- Parallelize it

```haskell
sort :: (Ord a) => [a] -> [a]
sort (x:xs) = force greater `par`
  (force lesser `pseq`  (lesser ++ x:greater))
    where lesser  = sort [y | y <- xs, y <  x]
          greater = sort [y | y <- xs, y >= x]
sort _ = []
```

Thought Process

- Two halves of input list can be constructed in parallel
- OK because each activity is independent
- This should be a win for small `xs` on *n>1* cores assuming `par` and `pseq` manage parallel resources efficiently

Thought Process, Generalized


Improving Implicit Parallelism

José Manuel Calderón Trilla

ABSTRACT

We propose a new technique for exploiting the inherent parallelism in lazy functional programs. Known as *implicit parallelism*, the goal of writing a sequential program and having the compiler improve its performance by determining what can be executed in parallel has been studied for many years. Our technique abandons the idea that a compiler should accomplish this feat in 'one shot' with static analysis and instead allow the compiler to *improve* upon the static analysis using iterative feedback.

We demonstrate that iterative feedback can be relatively simple when the source language is a lazy purely functional programming language. We present three main contributions to the field: the automatic derivation of parallel strategies from a demand on a structure, and two new methods of feedback-directed auto-parallelisation. The first method treats the runtime of the program as a *black box* and uses the 'wall-clock' time as a fitness function to guide a heuristic search on bitstrings representing the parallel setting of the program. The second feedback approach is *profile directed*. This allows the compiler to use profile data that is gathered by the runtime system as the program executes. This allows the compiler to determine which threads are not worth the overhead of creating them.

Our results show that the use of feedback-directed compilation can be a good source of refinement for the static analysis techniques that struggle to account for the cost of a computation. This lifts the burden of 'is this parallelism worthwhile?' away from the static phase of compilation and to the runtime, which is better equipped to answer the question.

Doctor of Philosophy

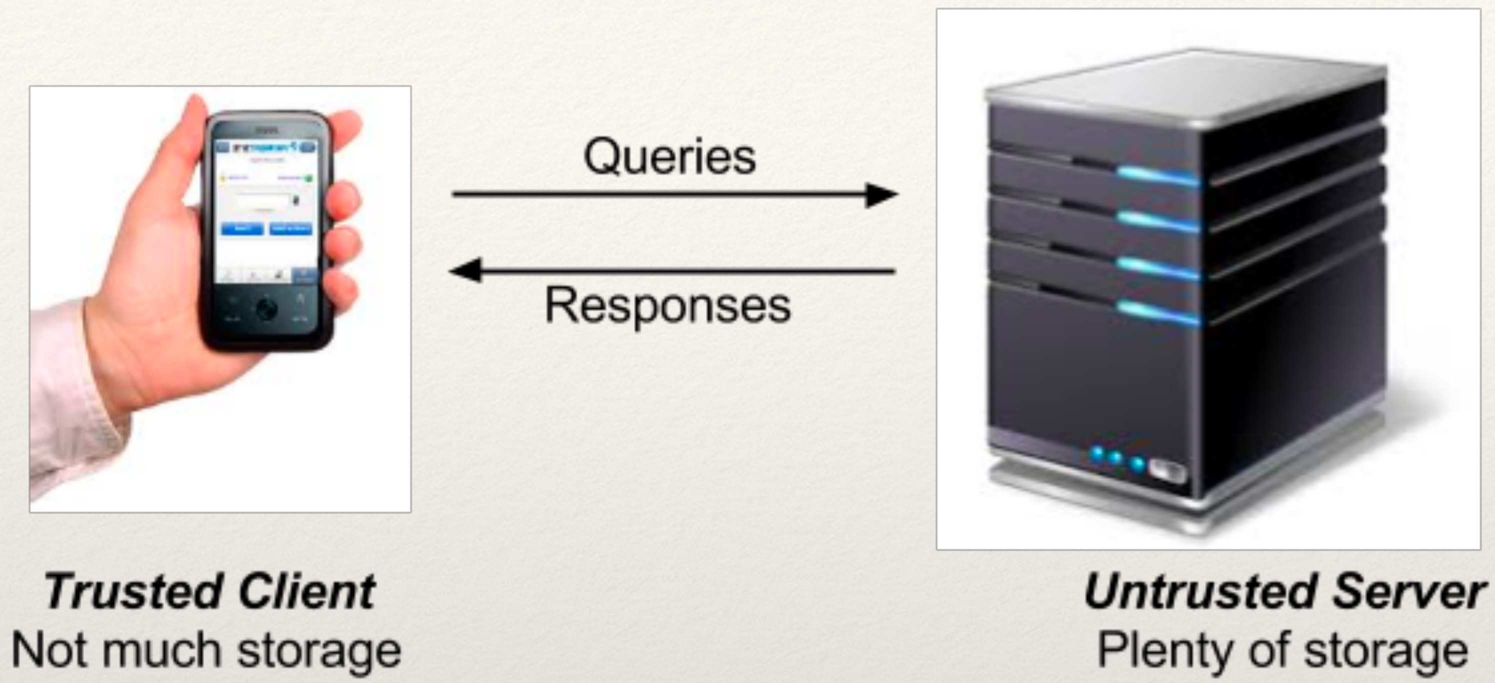
University of York
Computer Science

September 2015

- Automatically pick components of a program to parallelize
- Choose those such that the meaning of the program is preserved, and the performance is likely to improve.

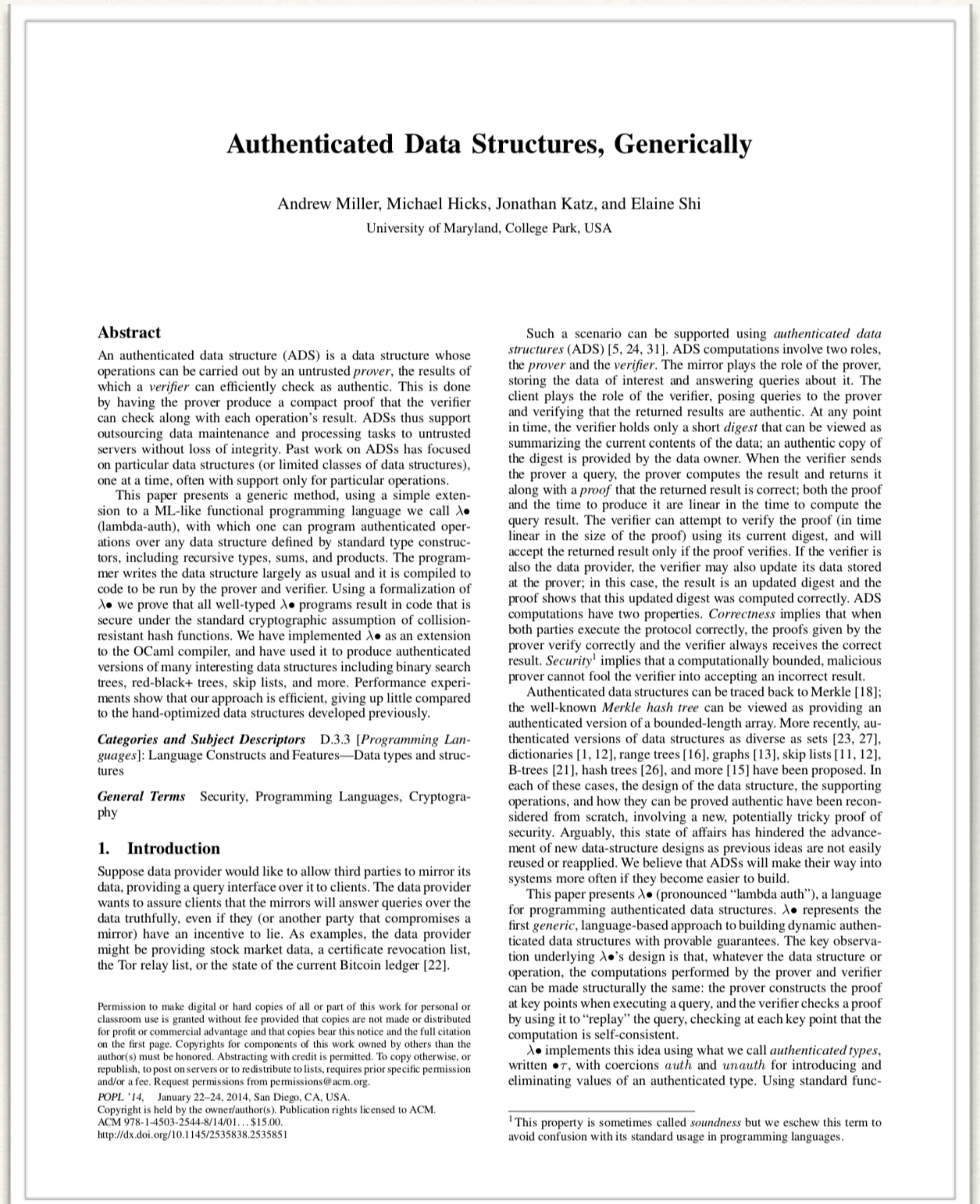
PL research lifts problems to the level of the language, turning a one-off solution into a general one

Example: Authenticated Data Structure



- **Merkle tree** (1988): Complete tree, where server answers queries with evidence the answer is correct
- Since then, separate papers on: **sets**, **dictionaries**, **range trees**, **graphs**, **skip lists**, **B-trees**, **hash trees**, …

ADS Construction, Generalized



Authenticated Data Structures, Generically

Andrew Miller, Michael Hicks, Jonathan Katz, and Elaine Shi

University of Maryland, College Park, USA

Abstract

An authenticated data structure (ADS) is a data structure whose operations can be carried out by an untrusted *prover*, the results of which a *verifier* can efficiently check as authentic. This is done by having the prover produce a compact proof that the verifier can check along with each operation's result. ADSs thus support outsourcing data maintenance and processing tasks to untrusted servers without loss of integrity. Past work on ADSs has focused on particular data structures (or limited classes of data structures), one at a time, often with support only for particular operations.

This paper presents a generic method, using a simple extension to a ML-like functional programming language we call λ• (lambda-auth), with which one can program authenticated operations over any data structure defined by standard type constructors, including recursive types, sums, and products. The programmer writes the data structure largely as usual and it is compiled to code to be run by the prover and verifier. Using a formalization of λ• we prove that all well-typed λ• programs result in code that is secure under the standard cryptographic assumption of collision-resistant hash functions. We have implemented λ• as an extension to the OCaml compiler, and have used it to produce authenticated versions of many interesting data structures including binary search trees, red-black+ trees, skip lists, and more. Performance experiments show that our approach is efficient, giving up little compared to the hand-optimized data structures developed previously.

Categories and Subject Descriptors D.3.3 [*Programming Languages*]: Language Constructs and Features—Data types and structures

General Terms Security, Programming Languages, Cryptography

1. Introduction

Suppose data provider would like to allow third parties to mirror its data, providing a query interface over it to clients. The data provider wants to assure clients that the mirrors will answer queries over the data truthfully, even if they (or another party that compromises a mirror) have an incentive to lie. As examples, the data provider might be providing stock market data, a certificate revocation list, the Tor relay list, or the state of the current Bitcoin ledger [22].

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ACM 978-1-4503-2544-8/14/01…$15.00.
http://dx.doi.org/10.1145/2535838.2535851

Such a scenario can be supported using *authenticated data structures* (ADS) [5, 24, 31]. ADS computations involve two roles, the *prover* and the *verifier*. The mirror plays the role of the prover, storing the data of interest and answering queries about it. The client plays the role of the verifier, posing queries to the prover and verifying that the returned results are authentic. At any point in time, the verifier holds only a short *digest* that can be viewed as summarizing the current contents of the data; an authentic copy of the digest is provided by the data owner. When the verifier sends the prover a query, the prover computes the result and returns it along with a *proof* that the returned result is correct; both the proof and the time to produce it are linear in the time to compute the query result. The verifier can attempt to verify the proof (in time linear in the size of the proof) using its current digest, and will accept the returned result only if the proof verifies. If the verifier is also the data provider, the verifier may also update its data stored at the prover; in this case, the result is an updated digest and the proof shows that this updated digest was computed correctly. ADS computations have two properties. *Correctness* implies that when both parties execute the protocol correctly, the proofs given by the prover verify correctly and the verifier always receives the correct result. *Security*[1] implies that a computationally bounded, malicious prover cannot fool the verifier into accepting an incorrect result.

Authenticated data structures can be traced back to Merkle [18]; the well-known *Merkle hash tree* can be viewed as providing an authenticated version of a bounded-length array. More recently, authenticated versions of data structures as diverse as sets [23, 27], dictionaries [1, 12], range trees [16], graphs [13], skip lists [11, 12], B-trees [21], hash trees [26], and more [15] have been proposed. In each of these cases, the design of the data structure, the supporting operations, and how they can be proved authentic have been reconsidered from scratch, involving a new, potentially tricky proof of security. Arguably, this state of affairs has hindered the advancement of new data-structure designs as previous ideas are not easily reused or reapplied. We believe that ADSs will make their way into systems more often if they become easier to build.

This paper presents λ• (pronounced "lambda auth"), a language for programming authenticated data structures. λ• represents the first *generic*, language-based approach to building dynamic authenticated data structures with provable guarantees. The key observation underlying λ•'s design is that, whatever the data structure or operation, the computations performed by the prover and verifier can be made structurally the same: the prover constructs the proof at key points when executing a query, and the verifier checks a proof by using it to "replay" the query, checking at each key point that the computation is self-consistent.

λ• implements this idea using what we call *authenticated types*, written $\bullet\tau$, with coercions $auth$ and $unauth$ for introducing and eliminating values of an authenticated type. Using standard func-

[1] This property is sometimes called *soundness* but we eschew this term to avoid confusion with its standard usage in programming languages.

- **Simple language extension,** data structure written mostly as usual. Different code generated for client and server
  - Expresses many prior ADSs
- Proved that **type correctness** implies **authenticity**
  - Adversary can only fool client by inverting one-way hash
  - One proof for all!

Elements of PL Research

- ***Design***: What feature, analysis, transformation, etc.?
- ***Mathematics** and **proof***: What does it mean? Why is what you are doing correct?
- ***Implementation***: How do you implement this language, analysis, transformation ... ?
- ***Empirical evaluation***: Does the design/implementation work (most of the time)?

PL Research Toolbox

- *Language specification* (what features, syntax)
- *Semantics* (operational, denotational)
- *Static reasoning* (logics, types, static analysis)
- *Dynamic reasoning* (tests, monitors, profiles)
- *Implementation* (compilation, interpretation, services)

What's Next: A Tour

- Disclaimer: This is my perspective
  - It is not comprehensive
  - It is probably wrong (hopefully only a little)
- But it will give you some sense of the field

Implementation

Machines Don’t Run our Programs

```
8B542408 83FA0077 06B80000 0000C383
FA027706 B8010000 00C353BB 01000000
B9010000 008D0419 83FA0376 078BD989
C14AEBF1 5BC3
```


```
fib:
    mov edx, [esp+8]
    cmp edx, 0
    ja @f
    mov eax, 0
    ret

    @@:
    cmp edx, 2
    ja @f
    mov eax, 1
    ret

    @@:
    push ebx
    mov ebx, 1
    mov ecx, 1

    @@:
        lea eax, [ebx+ecx]
        cmp edx, 3
        jbe @f
        mov ebx, ecx
        mov ecx, eax
        dec edx
    jmp @b

    @@:
    pop ebx
    ret
```

Other Programs Make it Possible

Three main implementation strategies:

- **Interpreter**: Runs any program in language *Q*
- **Compiler**: Converts a program in language *Q* to one in language *L*, for which you have a machine or interpreter
  - Hybrid: A just-in-time (**JIT**) **compiler** compiles the program as it interprets it

Run-time Services

- Various components support language abstractions
  - **Garbage collector** frees unneeded memory
  - **Thread system** runs different threads
- **Libraries** implement key (parts of) language abstractions (e.g., strings, numbers, networking)

Research Directions

- Compiler/interpreter **optimization**: Register allocation, memory hierarchy optimization, use of special hardware (e.g., GPUs), partial evaluation, …
- **Garbage collection** algorithms: Parallel, concurrent, incremental, space-efficient, real-time, hybrid, …
- **JIT implementation** & optimization: fast tracing/profiling, on-stack replacement, …
- **Domain-specific techniques**: Probabilistic programming, neural nets, …
- *The* POPL'19 paper (language implementation not POPL's main theme):
  - **Efficient parameterized algorithms for data packing**, Krishnendu Chatterjee, Amir Kafshdar Goharshady, Nastaran Okati, Andreas Pavlogiannis

Semantics

Formal Semantics

- To work with programs, we must know what they mean
  - *Semantics* comes from the Greek *semaino*, “to mean”
- Most language semantics are *informal*. But we can do better by making them *formal*. Two main styles:
  - **Operational semantics** (like an interpreter)
  - **Denotational semantics** (like a compiler)

Formal semantics is a key PL tool

Operational Semantics

- Evaluation is described as *transitions* (aka *reductions*) in some *abstract machine;* a **definitional interpreter**
  - The *meaning* of a program is its fully reduced form
  - `let x=2 in x+3` $\longrightarrow$ `2+3` $\longrightarrow$ `5`
- Can model *many* programming language features
  - Concurrency, non-determinism, run-time cost, higher-order functions, probabilistic choice, …
- This is the most popular style of semantics

Denotational Semantics

- The meaning of a program is defined as a **mathematical object**, e.g., a function or number
- Typically define an *interpretation function* $[\![\ ]\!]$
  - Meaning of program fragment given by meaning of its components; $[\![e1+e2]\!] = [\![e1]\!] + [\![e2]\!]$
  - Gets interesting when we try to find denotations of loops or recursive functions, cyclic heap state
- Particularly useful for *equational reasoning*

Research Directions

- PL researchers frequently use operational semantics to model new languages and language features
  - Or model features in a new way, to facilitate some other advance (e.g., proof of a property)
- Also, new techniques for semantics modeling, particularly for domain-specific computations

Some POPL'19 Papers

- **Skeletal semantics and their interpretations**, Martin Bodin, Philippa Gardner, Thomas Jensen, Alan Schmitt
- **A calculus for Esterel: if can, can. if no can, no can.** Spencer P. Florence, ShuHung You, Jesse A. Tov, Robert Bruce Findler
- **Familial monads and structural operational semantics**, Tom Hirschowitz
- **Game semantics for quantum programming,** Pierre Clairambault, Marc De Visme, Glynn Winskel
- **Exploring C semantics and pointer provenance**, Kayvan Memarian, Victor B. F. Gomes, Brooks Davis, Stephen Kell, Alexander Richardson, Robert N. M. Watson, Peter Sewell
- **ISA semantics for ARMv8a, RISCv, and CHERIMIPS**, Alasdair Armstrong, Thomas Bauereiss, Brian Campbell, Alastair Reid, Kathryn E. Gray, Robert M. Norton, Prashanth Mundkur, Mark Wassell, Jon French, Christopher Pulte, Shaked Flur, Ian Stark, Neel Krishnaswami, Peter Sewell

Static Reasoning

Static Analysis

- Goal: establish **property** R of (all of) a **program** P's executions. Examples:
    - R = *no run-time failures*, or R = *always terminates*
- But: Reasoning via the semantics directly — **testing** — is infeasible (i.e., infinite number of runs)
- Many static analysis algorithms/techniques: **type systems**, dataflow analysis, **abstract interpretation**, symbolic execution, constraint-based analysis, …

Soundness and Completeness

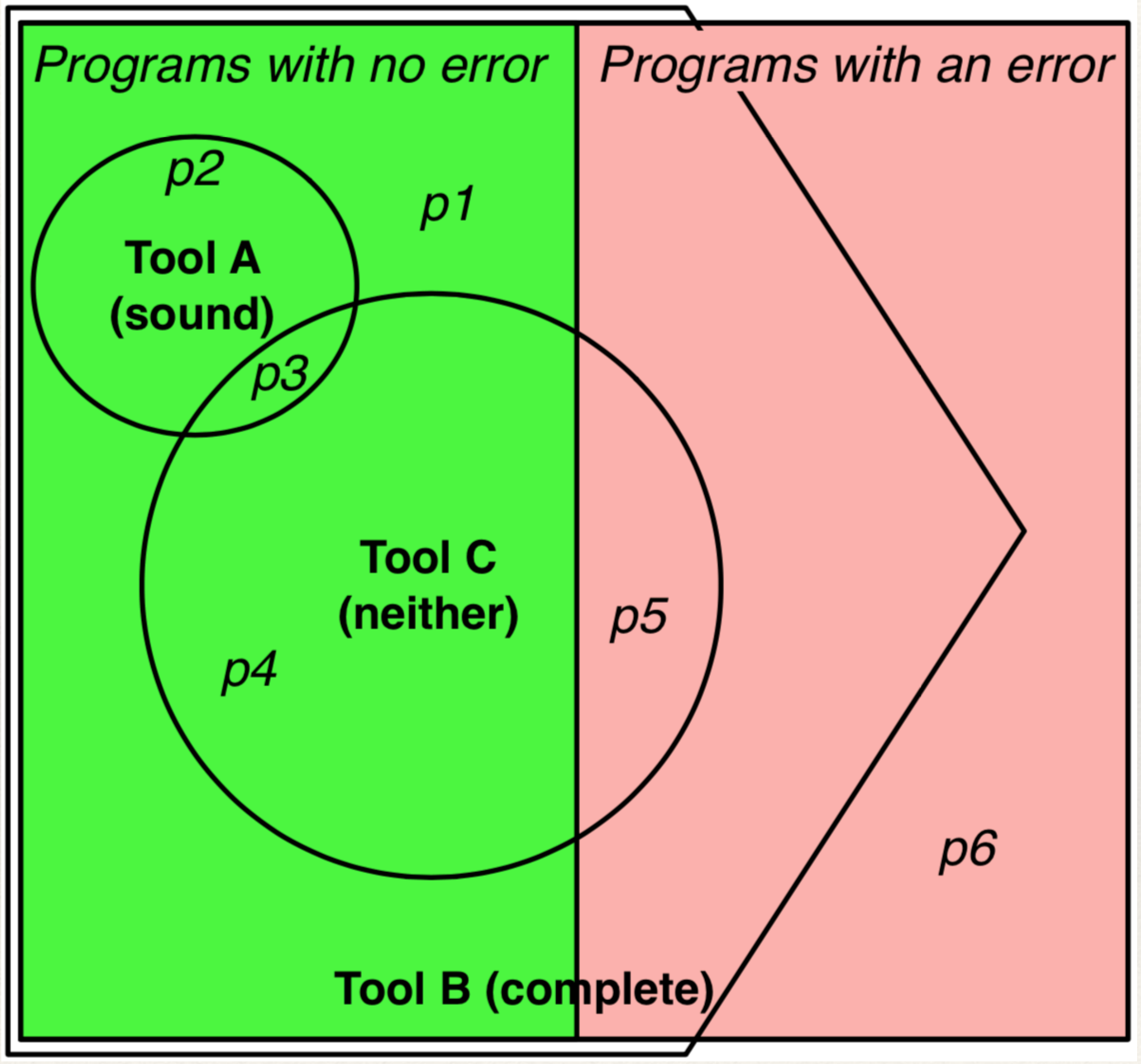
- Suppose a static analysis *S* attempts to prove property *R* of program *P*. For example,
  - *R = program has no run-time errors (e.g., div-by-zero)*
  - *S(P) = true* implies *P* has no run-time errors

Soundness and Completeness

- Analysis S is **sound** *iff* for all P,
  - $S(P) = true \implies P$ exhibits R
- Analysis S is **complete** *iff* for all P,
  - P exhibits $R \implies S(P) = true$

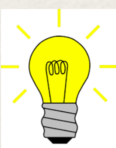
Exhibit R

Do not exhibit R



Abstract Interpretation

- Rice's Theorem: Any **non-trivial property** R is **undecidable** (not both sound and complete)



Abstract the behavior of the program, so that

  - Proof about abstraction $\Longrightarrow$ proof about real thing

- Seminal papers: Cousot and Cousot, 1977, 1979

Abstract interpretation: a unified lattice model for static analysis of programs by construction or approximation of fixpoints: Most cited POPL paper ever!

Example

$e ::= n \mid e + e$

$$\alpha(n) = \begin{cases} - & n < 0 \\ 0 & n = 0 \\ + & n > 0 \end{cases}$$

Abstraction function

Abstract semantics

+	-	0	+
-	-	-	?
0	-	0	+
+	?	+	+

- *Abstract domain* = {-,0,+,?}
  - Need for ? arises because of the abstraction

Abstract Domains, and Semantics

- Many abstract domains developed
  - **Signs** (previous slide), **intervals** $[l,u]$ where $l \leq n \leq u$, **convex polyhedra**, **octagons**, **pentagons**, …
- Abstract semantics for language constructs
  - Basic constructs (sequence, assignment, etc.) easy
  - Key **challenge** is **loops**: Need to ensure their analysis terminates (idea: “widening”)

It's All AI, but Details Matter

- All static analyses can be view as abstract interpretation
  - Easy to relate to **data flow analysis**, **symbolic execution**, **typing** (later), etc.
- But
  - precise setup can differ significantly, with
  - different precision/performance tradeoffs

Research Directions: Static Analysis

- Analyses for **new properties**
  - Side-channel freedom, data-race freedom, proper resource use, tainting, bias-freedom in ML-inferred algorithms, …
- **Implementation methods**,
  - often to better trade off performance and precision: new/faster abstract domains, new heuristics/search, connections to machine learning methods, …
- Analyses for **new applications**

Some POPL'19 papers

- **A true positives theorem for a static race detector**, Nikos Gorogiannis, Peter W. O'Hearn, Ilya Sergey
- **Concerto: a framework for combined concrete and abstract interpretation**, John Toman, Dan Grossman
- **A^2I: abstract^2 interpretation**, Patrick Cousot, Roberto Giacobazzi, Francesco Ranzato
- **An abstract domain for certifying neural networks**, Gagandeep Singh, Timon Gehr, Markus Püschel, Martin Vechev
- **Context-, flow-, and field-sensitive dataflow analysis using synchronized Pushdown systems**, Johannes Späth, Karim Ali, Eric Bodden
- **Fast and exact analysis for LRU caches**, Valentin Touzeau, Claire Maïza, David Monniaux, Jan Reineke
- **Refinement of path expressions for static analysis,** John Cyphert, Jason Breck, Zachary Kincaid, Thomas Reps

Formal Verification

- This is a static analysis with a very specific property — **functional correctness**
  - Given program P and a spec ϕ relating inputs to outputs. **Prove that P meets the spec**, ie $\forall x.\ \phi(x,P(x))$
- Lots of approaches to do this based on ideas like verification condition generation, weakest preconditions, dependent types, etc.
  - Differ in details. Notable: What logic used.

Program Synthesis

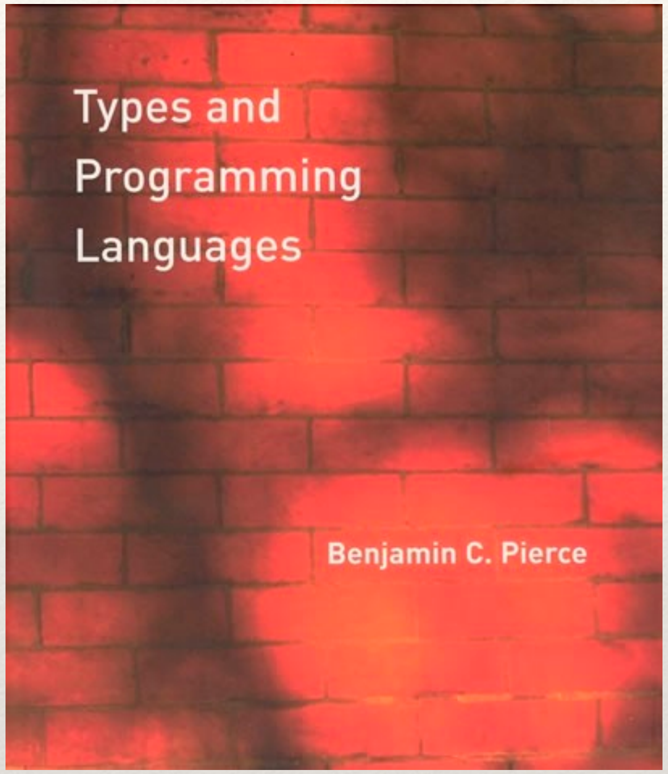
- Don't prove the program — construct it automatically!
  - Given a spec ϕ relating inputs to outputs. **Find a program P that meets the spec**, ie $\forall x.\ \phi(x, P(x))$
- Many methods being explored
  - explicit search, symbolic search, hybrid search, type-directed search, derivational synthesis, domain-specific synthesis, …

Some POPL'19 papers

- Verification
  - **Decoupling lock-free data structures from memory reclamation for static analysis**, Roland Meyer, Sebastian Wolff
  - **Pretend synchrony: synchronous verification of asynchronous distributed programs**, Klaus v. Gleissenthall, Rami Gökhan Kıcı, Alexander Bakst, Deian Stefan, Ranjit Jhala
- Synthesis
  - **Bayesian synthesis of probabilistic programs for automatic data modeling**, Feras A. Saad, Marco F. CusumanoTowner, Ulrich Schaechtle, Martin C. Rinard, Vikash K. Mansinghka
  - **Structuring the synthesis of heap-manipulating programs**, Nadia Polikarpova, Ilya Sergey
  - **Hamsaz: replication coordination analysis and synthesis**, Farzin Houshmand, Mohsen Lesani

Type Systems

- A **type system** is
  - a *tractable syntactic method* for *proving* the *absence* of certain program *behaviors* by *classifying* phrases according to the *kinds of values* they compute. —*Pierce*



- They are good for
  - **Detecting errors** (don't add an integer and a string)
  - **Abstraction** (hiding representation details)
  - **Documentation** (tersely summarize an API)
- Designs trade off precision, efficiency, readability

Example Type System

$e ::= n \mid e + e$
$\quad \mid \text{true} \mid \text{false} \mid e = e$
$\quad \mid \text{if } e \text{ then } e \text{ else } e$

$\tau ::= \text{int} \mid \text{bool}$

Judgment $\boxed{\vdash e : \tau}$

means

"expression e has type τ"

<u>Examples</u>

$\vdash \text{true} : \text{bool}$ "true has type bool"

$\vdash 1 + 2 : \text{int}$

$\vdash \text{if } 1 = 1 \text{ then true else false} : \text{bool}$

$\vdash \text{if} \ldots \text{then } 1 \text{ else false} : ?$ *error*

$\vdash \text{if true then } 1 \text{ else false} : ?$ ***doesn't check***

Rules of Inference

$\boxed{\vdash e : \tau}$ means "expression e has type τ"

$$\frac{}{\vdash n : \text{int}} \qquad \frac{}{\vdash \text{true} : \text{bool}} \qquad \frac{}{\vdash \text{false} : \text{bool}}$$

Axioms

Premise

Conclusion

$$\frac{\vdash e1 : \text{int} \qquad \vdash e2 : \text{int}}{\vdash e1 + e2 : \text{int}} \qquad \frac{\vdash e1 : \tau \qquad \vdash e2 : \tau}{\vdash e1 = e2 : \text{bool}}$$

e1 and *e2* must have **same** type τ

$$\frac{\vdash e : \text{bool} \qquad \vdash e1 : \tau \qquad \vdash e2 : \tau}{\vdash \text{if } e \text{ then } e1 \text{ else } e2 : \tau}$$

NB: Operational semantics often also expressed using rules of inference

Soundness

- If $\vdash e : \tau$ then either
  - e reduces to a *value* v of type τ, or e diverges*
    - (for our example, values v are n, true, false)
    - Reduction often defined as operational semantics
- Corollary: e will never get "stuck"
  - i.e., never fails to reduce a non-value
    - which constitutes a "run-time error"
- Proof by induction on typing derivation

*Divergence not possible in this simple language, but is for real ones!

Types and Static Analysis

- Relating to AI, a type is an abstract domain
  - Proving *P* is well-typed is a static analysis of *P*
  - By type safety, analysis is **sound** (but **not complete**)
- Viewed as a static analysis, types need not be present in (or even defined by) the language
  - Analysis becomes a kind of *type inference*

Properties by Typing

- Idea: Formulate an operational semantics for which violation of a property *R* results in a stuck program. Eg,
  - The program **divides by zero**, dereferences a **null pointer**, or accesses an **array out of bounds**
  - A thread attempts to **dereference a pointer without holding a lock**
  - The program **uses tainted data** (i.e., from an adversary) where untainted data expected
  - A program **dereferences a dangling pointer**
- Formulate a type system to enforce *R*; prove type safety

Example: ADS

$$\begin{array}{lll} \text{Exprs } e & ::= & v \mid \textbf{let } x = e_1 \textbf{ in } e_2 \mid v_1\ v_2 \mid \textbf{case } v\ v_0\ v_1 \\ & \mid & \textbf{prj}_1\ v \mid \textbf{prj}_2\ v \mid \textbf{unroll}\ v \mid \mathit{auth}\ v \mid \mathit{unauth}\ v \end{array}$$

$$\begin{array}{lll} \ll \pi, \mathit{auth}\ v \gg & \rightarrow_I & \ll \pi, v \gg \\ \ll \pi, \mathit{unauth}\ v \gg & \rightarrow_I & \ll \pi, v \gg \\ \ll \pi, \mathit{auth}\ v \gg & \rightarrow_P & \ll \pi, \langle \mathsf{hash}\ (\![v]\!), v \rangle \gg \\ \ll \pi, \mathit{unauth}\ \langle h, v \rangle \gg & \rightarrow_P & \ll \pi\ @\ [\ (\![v]\!)\ ],\ v \gg \\ \ll \pi, \mathit{auth}\ v \gg & \rightarrow_V & \ll \pi, \mathsf{hash}\ v \gg \end{array}$$

$$\frac{\mathsf{hash}\ s_0 = h}{\ll [s_0]\ @\ \pi, \mathit{unauth}\ h \gg \rightarrow_V \ll \pi, s_0 \gg}$$

$$\frac{\Gamma \vdash v : \tau_1}{\Gamma \vdash \textbf{inj}_1\ v : \tau_1 + \tau_2} \qquad \frac{\Gamma \vdash v : \tau_2}{\Gamma \vdash \textbf{inj}_2\ v : \tau_1 + \tau_2}$$

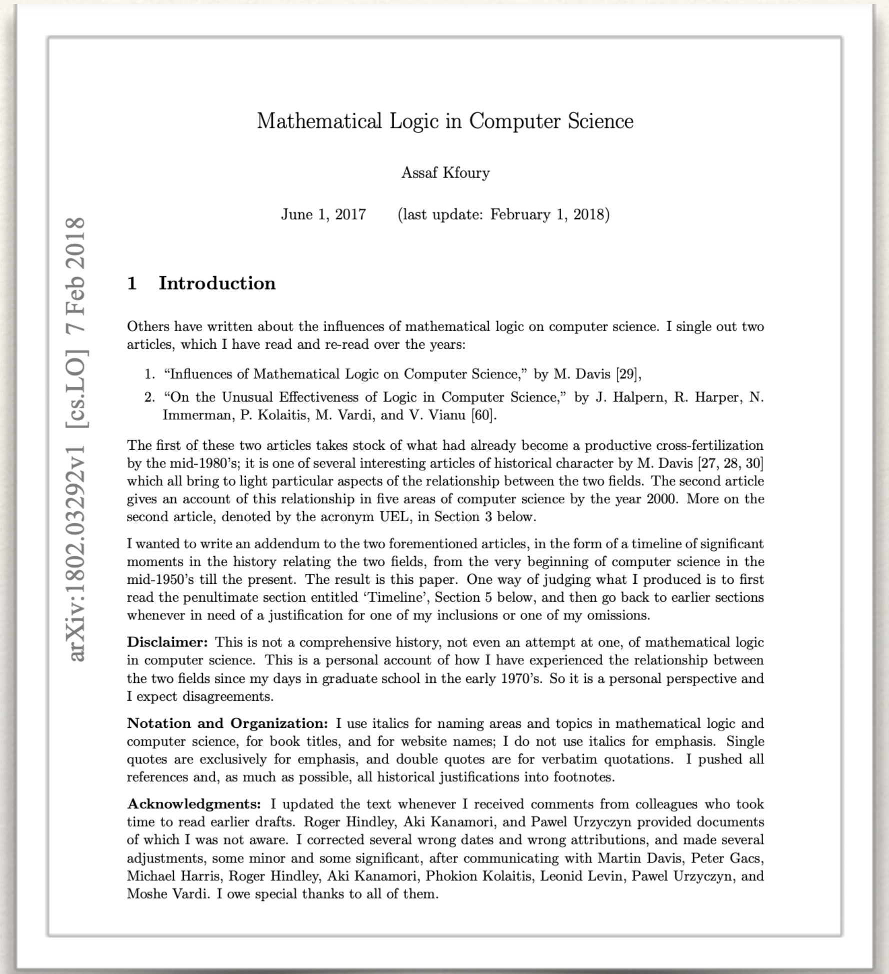
$$\frac{\Gamma \vdash v : \tau_1 + \tau_2 \qquad \Gamma \vdash v_1 : \tau_1 \rightarrow \tau \qquad \Gamma \vdash v_2 : \tau_2 \rightarrow \tau}{\Gamma \vdash \textbf{case}\ v\ v_1\ v_2 : \tau}$$

$$\frac{\Gamma \vdash v : \tau}{\Gamma \vdash \mathit{auth}\ v : \bullet\tau} \qquad \frac{\Gamma \vdash v : \bullet\tau}{\Gamma \vdash \mathit{unauth}\ v : \tau}$$

- Define **language extension** for using recursive hashes, the key ADS feature
- Define **operational semantics** that models one-way nature of hashes, with variants for verifier (client), prover (server), and "ideal"
- Define **type system** that ensures proper use of hashed values
- Prove security (in the style of **type safety**): Only by finding a hash collision can the server fool the client

Research Directions: Types

- Type systems have a strong connection to **formal logic**: Ideas go back and forth
- Type system development is a central PL activity
  - add **precision** (e.g., dependent and refinement types),
  - prove **new properties** (e.g., abstraction, free theorems),
  - support **new language constructs** and / or domain-specific properties



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Mathematical Logic in Computer Science

Assaf Kfoury

June 1, 2017 (last update: February 1, 2018)

1 Introduction

Others have written about the influences of mathematical logic on computer science. I single out two articles, which I have read and re-read over the years:

1. "Influences of Mathematical Logic on Computer Science," by M. Davis [29],
2. "On the Unusual Effectiveness of Logic in Computer Science," by J. Halpern, R. Harper, N. Immerman, P. Kolaitis, M. Vardi, and V. Vianu [60].

The first of these two articles takes stock of what had already become a productive cross-fertilization by the mid-1980's; it is one of several interesting articles of historical character by M. Davis [27, 28, 30] which all bring to light particular aspects of the relationship between the two fields. The second article gives an account of this relationship in five areas of computer science by the year 2000. More on the second article, denoted by the acronym UEL, in Section 3 below.

I wanted to write an addendum to the two forementioned articles, in the form of a timeline of significant moments in the history relating the two fields, from the very beginning of computer science in the mid-1950's till the present. The result is this paper. One way of judging what I produced is to first read the penultimate section entitled 'Timeline', Section 5 below, and then go back to earlier sections whenever in need of a justification for one of my inclusions or one of my omissions.

Disclaimer: This is not a comprehensive history, not even an attempt at one, of mathematical logic in computer science. This is a personal account of how I have experienced the relationship between the two fields since my days in graduate school in the early 1970's. So it is a personal perspective and I expect disagreements.

Notation and Organization: I use italics for naming areas and topics in mathematical logic and computer science, for book titles, and for website names; I do not use italics for emphasis. Single quotes are exclusively for emphasis, and double quotes are for verbatim quotations. I pushed all references and, as much as possible, all historical justifications into footnotes.

Acknowledgments: I updated the text whenever I received comments from colleagues who took time to read earlier drafts. Roger Hindley, Aki Kanamori, and Pawel Urzyczyn provided documents of which I was not aware. I corrected several wrong dates and wrong attributions, and made several adjustments, some minor and some significant, after communicating with Martin Davis, Peter Gacs, Michael Harris, Roger Hindley, Aki Kanamori, Phokion Kolaitis, Leonid Levin, Pawel Urzyczyn, and Moshe Vardi. I owe special thanks to all of them.

Some POPL'19 Papers

- **Intersection types and runtime errors in the pi-calculus**, Ugo Dal Lago, Marc de Visme, Damiano Mazza, Akira Yoshimizu
- **Sound and complete bidirectional type-checking for higher-rank polymorphism with existentials and indexed types**, Joshua Dunfield, Neelakantan R. Krishnaswami
- **Exceptional asynchronous session types: session types without tiers**, Simon Fowler, Sam Lindley, J. Garrett Morris, Sára Decova
- **Polymorphic symmetric multiple dispatch with variance**, Gyunghee Park, Jaemin Hong, Guy L. Steele Jr., Sukyoung Ryu
- **Abstracting extensible data types: or, rows by any other name**, J. Garrett Morris, James McKinna

Dynamic Reasoning

Dealing with False Alarms

- Recall Rice's theorem: no sound and complete static analysis (for interesting properties/languages)
  - Type systems reject safe programs; static analyses emit false alarms
- Idea: Alarm if property R is **violated during execution**
  - Do so during testing, and/or during deployment (e.g., dynamic typing)

Hybrid Reasoning

- Most type systems do not try to prove that an index to an array is always within its bounds
  - Compiler adds a **dynamic check** (monitor) if unsure
  - Trades added precision with run-time overhead (and chance of failure)
  - Such type systems ***combine*** **static** *and* **dynamic reasoning**
- **Gradual typing**: Hybrid support for static types (proved once and for all) and dynamic types (checked at run-time)

Gradual Typing is Popular

Dart

Typed

flow-typed

TS

Reticulated

Some POPL'19 Papers

- **Adventures in monitorability: from branching to linear time and back again**, Luca Aceto, Antonis Achilleos, Adrian Francalanza, Anna Ingólfsdóttir, Karoliina Lehtinen
- **Modular quantitative monitoring**, Rajeev Alur, Konstantinos Mamouras, Caleb Stanford
- **Gradual type theory**, Max S. New, Daniel R. Licata, Amal Ahmed
- **Gradual typing: a new perspective**, Giuseppe Castagna, Victor Lanvin, Tommaso Petrucciani, Jeremy G. Siek
- **LWeb: information flow security for multitier web applications**, James Parker, Niki Vazou, Michael Hicks
- **From fine- to coarse-grained dynamic information flow control and back**, Marco Vassena, Alejandro Russo, Deepak Garg, Vineet Rajani, Deian Stefan

So as you can see …

PL has a substantial toolbox of **mathematics** and **implementation techniques** that are widely applicable

With these: We can make **it** more **general**, more **elegant**, more **direct**, more **efficient**, more **reliable**, more **secure** …

Wow! Thanks for getting me up to date…

Recap: What is PL Research?

PL research views the programming language as having a central place in solving computing problems.

A PL researcher:

- develops *general abstractions*, or *building blocks*, for solving problems, or classes of problems,
- considers software *behavior* in a *rigorous and general way*, e.g., to prove that (classes of) programs enjoy properties we want, and/or eschew properties we don't.