How tests and proofs impede one another:

The need for always-on static and dynamic feedback

Michael Ernst
joint work with Michael Bayne
University of Washington

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Tests and proofs

Tests and proofs are synergistic

[…, ISSTA 2006, SCP 2007, PLDI 2008, ECOOP 2008, ISSTA 2008, ASE 2009, …]

- Problem: attitudes and implementations put them at odds
- Goal: reconcile them

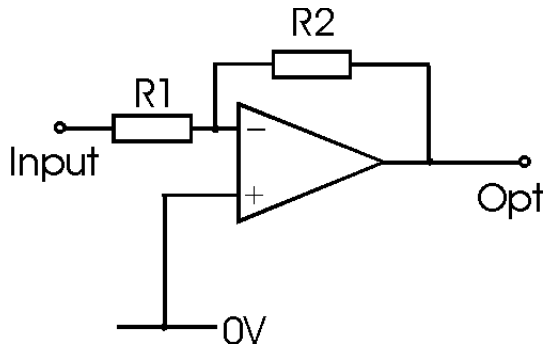
This talk: philosophy, lay of the land, problems, technical nugget, challenges

A theme: putting the developer in charge

Feedback is the essence of engineering

Software developers
get feedback from:

- dynamic analysis ("tests")
- static analysis ("proofs")
  - prime example: type systems



How do you choose a type system?

- Dynamically-typed scripting languages:
  - Faster and more flexible program development and modification
- Statically-typed programming languages:
  - More reliable and maintainable applications

You shouldn't have to choose!

Can we give programmers the benefits of both?

A type system checks some properties

Language designer chooses checks to address development needs

- Static checks
- Dynamic checks (early or late)

Later, tool developers add more checks

- Static: LCLint [Evans 94]
- Dynamic: Purify [Hastings 92]

Why don't tool developers remove checks?

Why we ♥ static typing (proofs)

- Documentation (machine-checked)
- Correctness/reliability
- Refactoring
- Performance (optimizations)
- Faster development? Yes [Gannon 77, Prechelt 98], no [Hannenberg 09, 10]

Why we ♥ dynamic typing (= Why we  static typing)

- Suited to rapidly-changing requirements
- More flexible code
  - Meta-programming: dynamic program behavior, add fields, change class
- No false positive warnings
  - Every static type system rejects some correct programs
- More interactive, more fun
- Ability to run tests at any time

```
Object now = new Date();
now.getMonth();   // illegal!
```

Other reasons we ♥ dynamic languages (besides the dynamic type system)

- Libraries (e.g., Rails)
- Conciseness (type inference, collection literals)
- Read-eval-print loop; no edit-compile-test cycle

Neither tests nor proofs dominates the other

- Tests:
  - Reveals emergent behavior
  - Quickly builds insight
  - Type system captures only a few properties
    - Not: user satisfaction, algorithmic properties
- Proofs:
  - Ensures consistency throughout the whole program
  - Guarantees absence of errors
  - Encourages good design
    - Caveat: some good designs are untypable

Two verification technologies that help programmers

Programmer should be able to choose the best one

Your programming language imposes a development model

Dynamically-typed languages favor testing

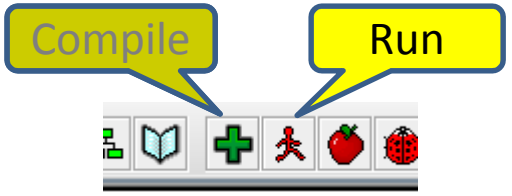
Dynamically-typed languages inhibit proofs

Statically-typed languages favor type-checking

Statically-typed languages inhibit testing

Problem: the programmer is not in charge

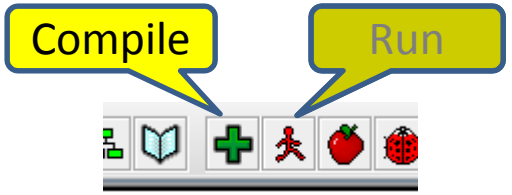
Dynamic languages inhibit proofs



- Good support for testing, at any moment
  - No fuss and bother of appeasing the type checker
- No possibility of static type checking
  - …and most other static analyses are also very hard
  - Programmers attempt to emulate a type system
    - Naming conventions, comments, extra assertions, tests
    - Inevitably, hard-to-debug type errors remain

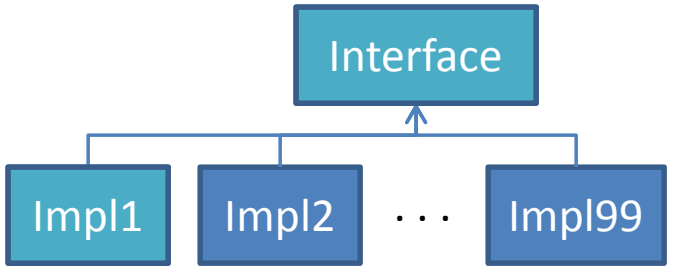
Example: a field crash after hours of execution

Static languages inhibit testing

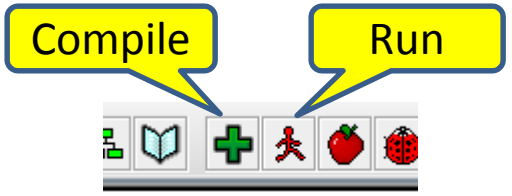


- Support *both* testing and type-checking
  - … in a specific order
- No tests are permitted until types are perfect
  - Delays learning from experimentation
  - Not all properties are captured by types
  - Assumption: what errors are important?

Example: change an interface & 1 implementation, then test



Putting the developer in charge



Each language-imposed approach leads to frustration and wasted effort

The developer should be able to get feedback from tests *or* proofs (or both!) at any time

- Knows the biggest risks or uncertainties
- Knows how to address them

Open research questions

1. When is static feedback (types, proofs) most useful?
2. When is dynamic feedback (testing) most useful?

- Not: "When does lack of *X* get most in the way?"

3. What language model or toolset gives the benefits of both approaches?

Enabling tests and proofs

- Workarounds: emulate dynamic typing
- Prototype in dynamic language, deliver in static
- Each program is half-static, half-dynamic
  - Add types to a dynamic language
  - Add `Dynamic` type to a static language
  - Result is unsafe and inflexible

- Full static and dynamic views of the program, at any moment during development

Outline

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Workarounds: emulate dynamic typing in a statically-typed language

1. Partial compilation or execution

   Don't compile code with type errors

   Comment out; modify build file; unexecuted casts

2. Explicit dynamic typing

   `Dynamic`, `Object`, `void*`

   No documentation benefits

   Prone to untypeable, confusing design

Problems with workarounds

- Reasoning burden
  - Identify boundary between checked & unchecked
- Transformation burden
  - Represent the boundary (coarsely) to the type system
  - Later, undo work (in an order dictated by the type system)
- Boundary changes with time

Workarounds indicate a need for better mechanisms!

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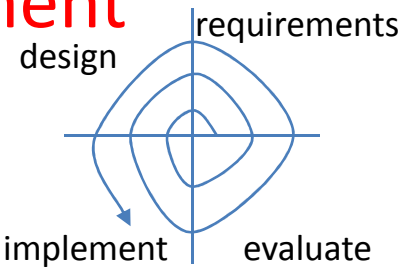
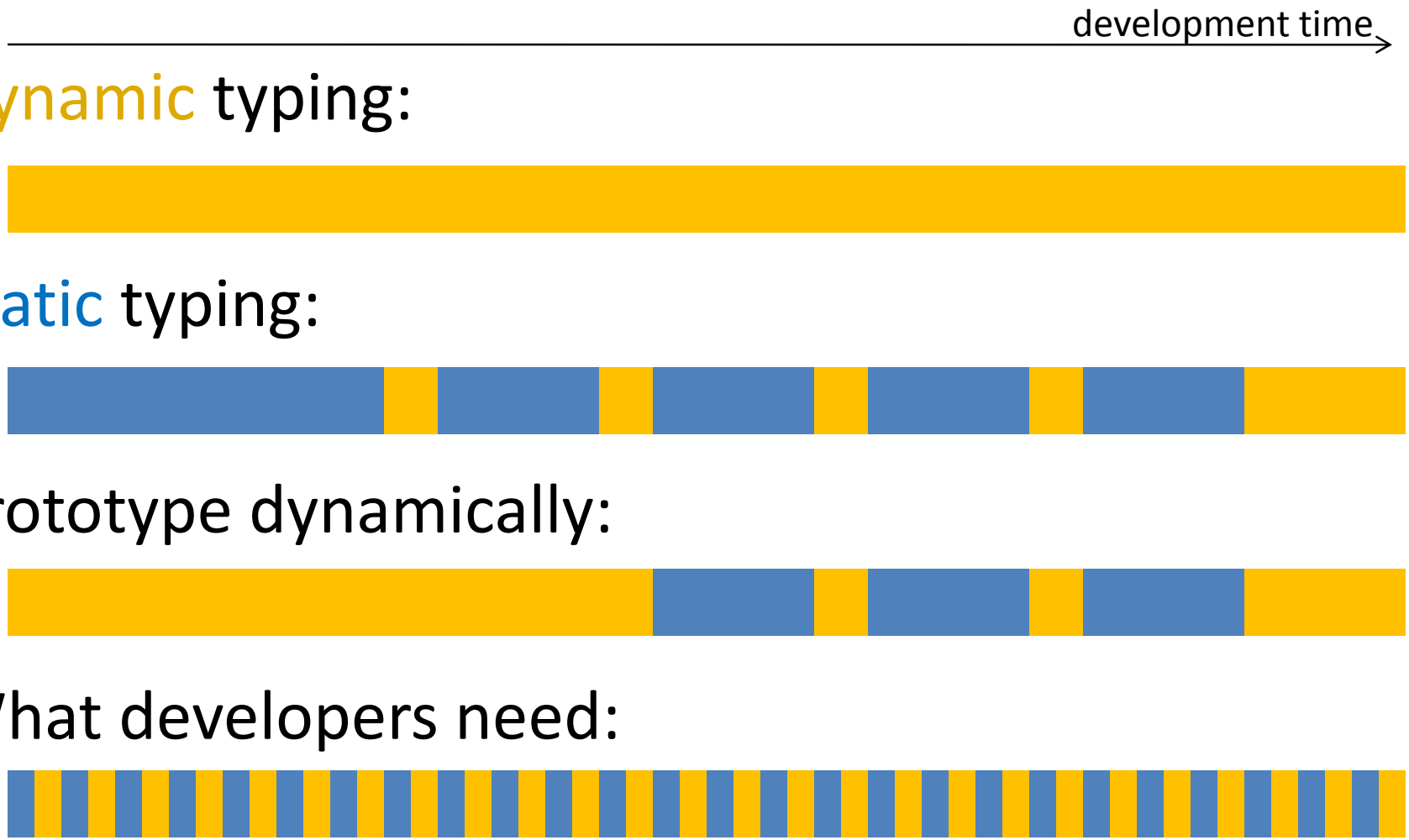
Dynamic prototype ⇒ static product

1. Start coding in a dynamic language
2. Throw away the prototype
3. Rewrite in a static language
4. Ship the statically-typed version

The great fallacy of hybrid static/dynamic typing:
A transition from testing to proving exists
Programmers need early static checking
Programmers need late dynamic development
(Consider spiral [Boehm 86],
agile [Beck 01] development)



Switching between dynamic and static feedback



The need for early static feedback

- Documentation
  - Provisional type
  - Types are more inviting than comments
  - Type-checker shows where `Dynamic` is needed
- Correctness
  - Aids in debugging
  - Some aspects of the code can be finalized early
- Improves program design
  - Keeps type-checking in the developer's mind
  - Encourages statically-typeable design
  - Indicates divergence quickly, when changes are easier

The need for early dynamism

- Prototyping
  - Structure changes quickly
  - Code is written quickly and thrown away
    - Wasteful to create separate implementations and interfaces
  - Code fits “in the developer’s head”
  - Code becomes obsolete, inconsistent
- API sketching
  - Iterate on interface, implementation, and client
  - Developer can focus on vertical slices of functionality

The need for late dynamism in software evolution

- Programmer wants to make and test a change
  - Doesn't want to delay the tests
- Representation or interface changes
  - Change `String` to a data structure
- Library replacement
  - Test parts of the client
- Exploratory changes
  - Restructuring may require many type changes and workarounds before determining viability
  - Likely to be wasted work

Problems with prototyping in a dynamic language

- No benefit of early static checking
- No benefit of late dynamic development

- Design may not be implementable in the static language
  - Due to features of the dynamic language
- Forced to throw away the prototype
  - The freedom to throw it away is good
  - Being forced to throw it away is bad
  - The developer should decide what to discard
- Prototyping approach is inefficient
- We need seamless integration in a single language

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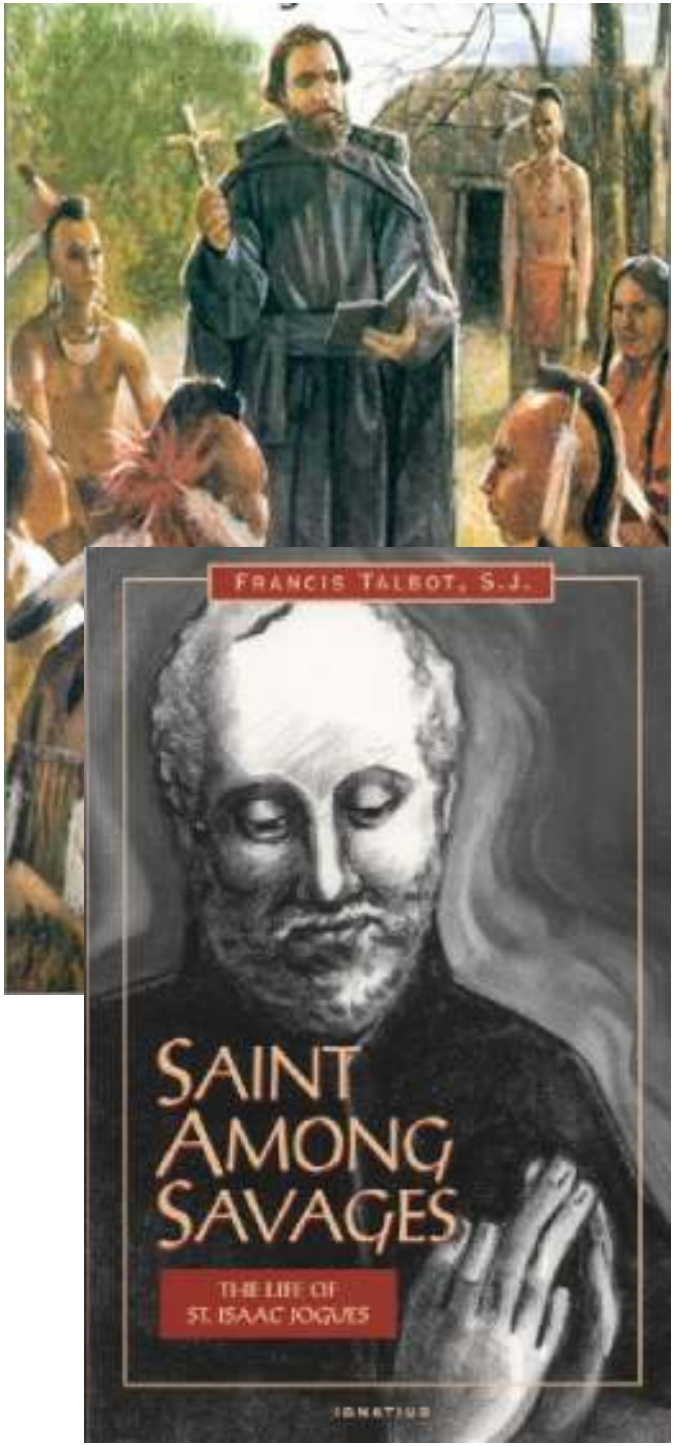
Add types to a dynamic language

Popular among academics

Less popular among practitioners

Realities:

- Dynamism is a key selling point, not incidental
- Types cannot handle all language features
  - Programming paradigms do not translate
- Poor cost/benefit



Upgrading your type system

- For untyped programs:
  - Add types to Scheme [Cartwright 91] , Erlang [Nyström 03], Python [Ancona 2007], Java [Lagorio 07], Ruby [Furr 09], PHP [Camphuijsen 09], …
- For typed programs:
  - Immutability: C/C++ **`const`**
  - Generics (parametric polymorphism): Java 5, C# 2
  - Haskell type classes
  - Information flow: Jif [Myers 97]
  - Pluggable types [Bracha 04, ISSTA 08]: nullness, immutability, …
- For even stronger properties:
  - Extended Static Checking: array bounds [Leino 98, Flanagan 02]
  - Discharge arbitrary assertions: theorem proving [Ou 04, Flanagan 06]

Java Generics

Convert Java 1.4 code to Java 5 code

Key benefit: type-safe containers

[OOPSLA 04, ECOOP 05, ICSE 07]

- Instantiation problem:

```
List myList = ...;
```

⇒

```
List<String> myList = ...;
```

- Parameterization problem

```
class Map {
  Object get(Object key) { … }
}
```

⇒

```
class Map<K,V> {
  V get(K key) { … }
}
```

Adding parameters changes the type constraints

Java standard libraries

The JDK libraries are not generics-correct

- Most signatures use generic types
- The implementations do not type-check
  - Retained from Java 1.4, usually without change

Why?

- Old design flaws were revealed
- Danger of refactoring was too great
- The code already worked
- It wasn't worth it

Immutability

Goal: avoid unintended side effects

- in the context of an imperative language

Dozens of papers proposing type systems

Little empirical evaluation

- Javari: 160KLOC case studies [OOPSLA 05]
- IGJ: 106KLOC case studies [FSE 07]

Building a type checker is hard

- Solution: Checker Framework [ISSTA 08]

What bugs can you find & prevent?

	The annotation you write:
• Null dereferences	`@NonNull`
• Mutation and side-effects	`@Immutable`
• Concurrency: locking	`@GuardedBy`
• Security: encryption, tainting	`@Encrypted` `@Untainted`
• Aliasing	`@Linear`
• Equality tests	`@Interned`
• Strings: localization, regular expression syntax	`@Localized` `@Regex`
• Typestate (e.g., open/closed files)	`@State`
• You can write your own checker!	

Pluggable type-checking

Untyped legacy language: Java
Typed language: Java with type qualifiers

Checker Framework eases type system construction

- Previous frameworks were unsatisfactory
- Academics built dozens of type-checkers
- Teaching: usable in first class in the major
- Industry: in daily use
- Influenced the design of Java 7 (type annotations)

Cost/benefit: A mixed success

+ Final design is clearer, better, documented, checked
+ You can ignore the type-checking when you want to
– It takes a lot of time
  - Annotation burden: minor
  - Understanding & improving design: major
– Adds no new features
– You already fixed the worst bugs
– May introduce new errors

It's hard to add stronger types

- The design is inherently not type-safe
  - Uses dynamic typing, dynamic checks, heterogeneity
  - Requires many loopholes (casts, suppressed warnings)
- This instantiation of the design is not type-safe
  - Programmer had no pressure to make the program type-safe
  - The type-safe version is better, but you learn that in retrospect
  - Another implementation would have been easy at the start
  - Design decisions proliferate and ossify
- Design is too hard to understand
- There are too many errors to correct or suppress
  - Every change carries a risk; cost may outweigh benefits
- Problem: type-checking is too late (not: too much of it)
  - Late changes are costly

Write and check types from the beginning

- Adding types after the fact is doomed
  - Whole-program type inference probably is, too
- New code is a good testing ground for new type systems
  - But, most development effort is maintenance
- We can't ignore legacy code
  - Evaluation
  - Practicality and impact

Another stymied project: Eliminating null pointer exceptions

- Goal: prove all dereferences safe in an existing program
  - NPEs are pervasive and important
  - Problem is simple to express

[Barnett 04, Spoto 08]

- Suppose: 99% success rate, 200 KLOC program
  - 1000 dereferences to check manually!
  - Program changes will be necessary

Analysis power vs. transparency

- A powerful analysis can prove many facts
  - Example: analysis that considers all possible execution flows in your program
  - Pointer analysis, type inference
- A transparent analysis has comprehensible behavior and results
  - Results depend on local information only
  - Small change to program $\Rightarrow$ small change in analysis results

To make an analysis more transparent:

- Concrete error cases & counterexamples, …
- User-supplied annotations & restructuring

Open question: Do programmers need more power or transparency? When?

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Incremental/gradual/hybrid typing

Statically-typed portion is safe

Run-time type errors are the fault of the dynamic code or the boundary

Programmer must:

- Decide the boundary
- Indicate it with type annotations

Research challenge: behavior at the boundary

- Correctness
- Blame control
- Efficiency

Correctness

- Retain all assertions that may fail [Ou 04, Flanagan 06]
- Objects may need to carry types [Siek 07, Herman 07]
- Contracts at the boundary [Findler 02, Gray 05]

Blame assignment

- A run-time error might arise in typed code
- Find the root cause in untyped code
- Usually located at the boundary
- Stop the program as soon as detected

[Findler 01, Tobin-Hochstadt 06,08, Furr 09, Wadler 09]

Efficiency

- Statically discharge assertions
  - Omit run-time checks
  - Remove wrappers
  - Smaller representations
- Permit tail recursion
- Extension to higher-order functions
- Omit blame assignment [Bloom 09]

[Herman 09, Siek 09,10]

Disadvantages

- Mostly starts from a dynamic mindset
  - But, programmers are more likely to accept
- Little encouragement for good design
  - Types not required, type checker errors assumed
- Few run-time guarantees
- Programmer must manage boundary
- Evaluation needed

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Dynamic interpretation of static code

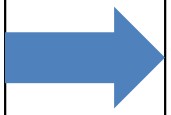
Write in a statically-typed language

The developer may always execute the code

To execute, ignore the types (mostly)

Convert every type to **`Dynamic`**

```
class MyClass {
 List<String> names;
 int indexOf(String name) {
  …
 }
}
```



```
class MyClass {
 Object names;
 Object indexOf(Object name) {
  …
 }
}
```

Type-removing transformation

- Primitive operations (`+`, `>`, `[]`, `if`) dynamically check their argument types
- Method invocations and field accesses are performed reflectively
  - Run-time system re-implements dynamic dispatch, etc.

- Compilation always succeeds
  - Code must be syntactically correct
- Code can be run

Why wasn't this done before?

- Rigid attitudes about the "best" feedback
- Divide between static and dynamic researchers
- Aping of developer workarounds
- Choices made for the convenience of tools
- Difficult to get right

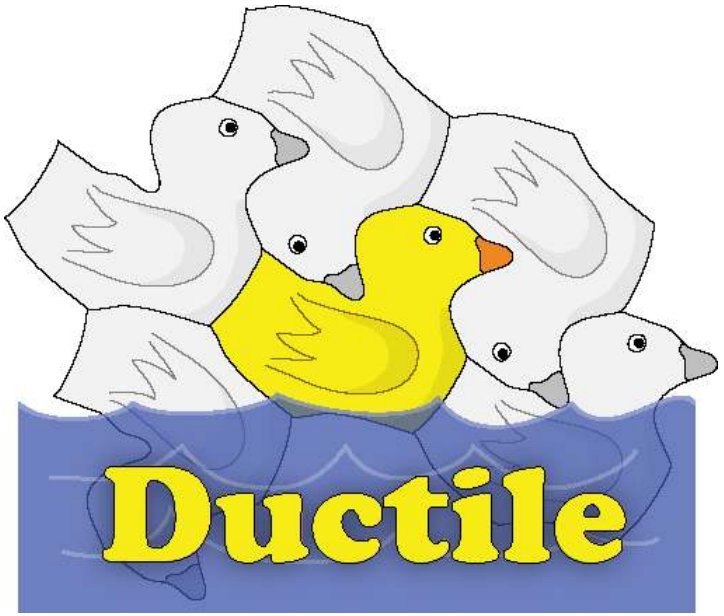
Question: What other problems have this feel?

Challenges to dynamic interpretation

1. Preserve semantics for type-correct programs
2. Useful semantics for type-incorrect programs

- Exploration of these challenges: Ductile
  - DuctileJ is a dialect of Java

http://code.google.com/p/ductilej/



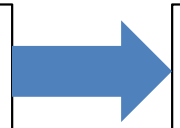
Preserve semantics of well-typed programs

1. Static types affect semantics (e.g., overloading)
2. Reflective calls yield different exceptions
3. Interoperation with un-transformed code
4. Meta-programming model limitations

Method overloading

Transformed declarations have same signature

```
void foo(int x) { … }
void foo(Date x) { … }
```



```
void foo(Object x) { … }
void foo(Object x) { … }
```

Overload resolution depends on static types

- Do not implement multi-method dispatch!

Solution:

- Dummy type-carrying arguments to disambiguate
- Resolution at run time if necessary

Exceptions

Reflective calls have different checked exceptions

- Compiler error
- Different run-time behavior

Solution:

- Wrap exceptions
- Catch, unwrap, and re-throw with correct type

Interfacing with non-transformed code

- Tool must operate on source code
  - Because the code doesn't compile!
- Bytecode transformation is possible
  - Libraries are usually general enough already
- Solution: untransformed code is treated like a primitive operation
  - Signatures inherited from libraries remain un-transformed – e.g., **`hashCode()`**

Reflection

Reflection results reflect transformed program

Solution: Un-transform signatures in results

Cannot reflectively call:

- `super` constructor
- `super` method call
- Chained constructor call
- Anonymous inner class constructor

Solution: Fight magic with more magic

Useful semantics for ill-typed programs

Give a semantics to ill-typed programs

- Formalization is a research challenge

Best-effort interpretation of the program

Accommodations for ill-typed programs

Each of these accommodations could be disabled:

- Assignment: permitted, regardless of declared and actual types
- Missing fields: add new field
- Method invocation
  - Search for closest matching signature in run-time type ("duck typing")
  - If none, generalize or refine type

Leave these on even in code that type-checks

Example code paradigms:

- Interface declarations: no **`implements`** is needed
- Type sketching: make up a name, or use **`var`**

Debugging and blame assignment

At each assignment and pseudo-assignment:

- Check against static type and record the result

If the program fails:

- Show relevant type failures (true positives)

If the program succeeds:

- User can choose to ignore or examine the log

Blame assignment as late as possible

- Contrasts with other work: as early as possible

Feedback vs. action

A user has a choice to interact with, or to ignore:

- tests
- version control conflicts
- performance tuning
- lint
- theorem-proving

Why doesn't the type-checker provide this choice?

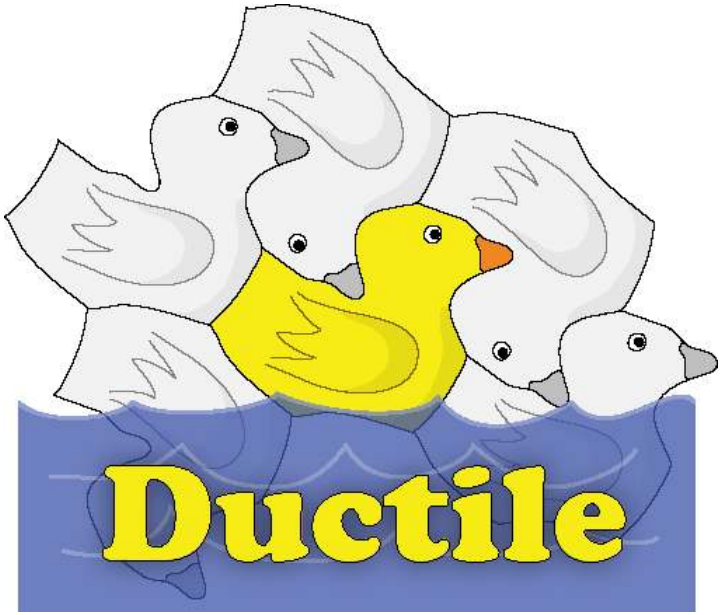
- Tool builder convenience and doctrine

Should separate when feedback is discovered and acted upon

Weekend release for type systems

- Goal is a statically-typed program
  - Occasionally, the type-checker gets in the way
- Disable type-checker temporarily
  - Continue thinking about types!
- Write a slice of a correctly-typed program
  - Missing branches, exception handling, etc.
- If you need **`Dynamic`**, use it
  - Or design a better type system!
- Efficiency is not a major concern
  - Human attention is the scarce resource

Prototype implementation



DuctileJ: a dialect of Java

Publicly available at
http://code.google.com/p/ductilej/

To use: add **`detyper.jar`** to your classpath

Try it and give us feedback

Assessment: Preserving semantics

Program	sLOC	Tests
Google Collections	51,000	44,760
HSQLDB	76,000	3,783
JODA Time	79,000	3,688

Assessment: Usefulness for prototyping

Prototyping an address book manager

Delayed specification of:

- Interfaces
  - After implementation complete, defined the interface
- Checked exceptions
  - No dummy **`try`** or **`throws`** constructs
- Access control
  - Didn't make members **`public`** unless necessary

Partial implementation of:

- Interfaces
  - Object that implemented only **`add`** acted as a **`List`**
  - **`Iterable`**
- Exception handling
  - Missing **`catch`** clauses

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Static ♥ dynamic

Synergy and duality between tests and proofs [PASTE 04]

- Type-checking
- Slicing: what computations can affect a value
- Memory safety: Purify, LCLint
- Atomicity checking [Flanagan 03]
- Specification checking
- Specification generation [Cousot 77, ICSE 99]

Look for more analogies and gaps!

Lessons

- Put the programmer in control
  - Separate feedback from action
  - Programmer workarounds $\Rightarrow$ new solutions
- Scratch your own itches
- Complement existing analyses
  - Characterize strengths, needs
  - Blend two lines of research
- Power/transparency tradeoff
- Change tool design based on insights