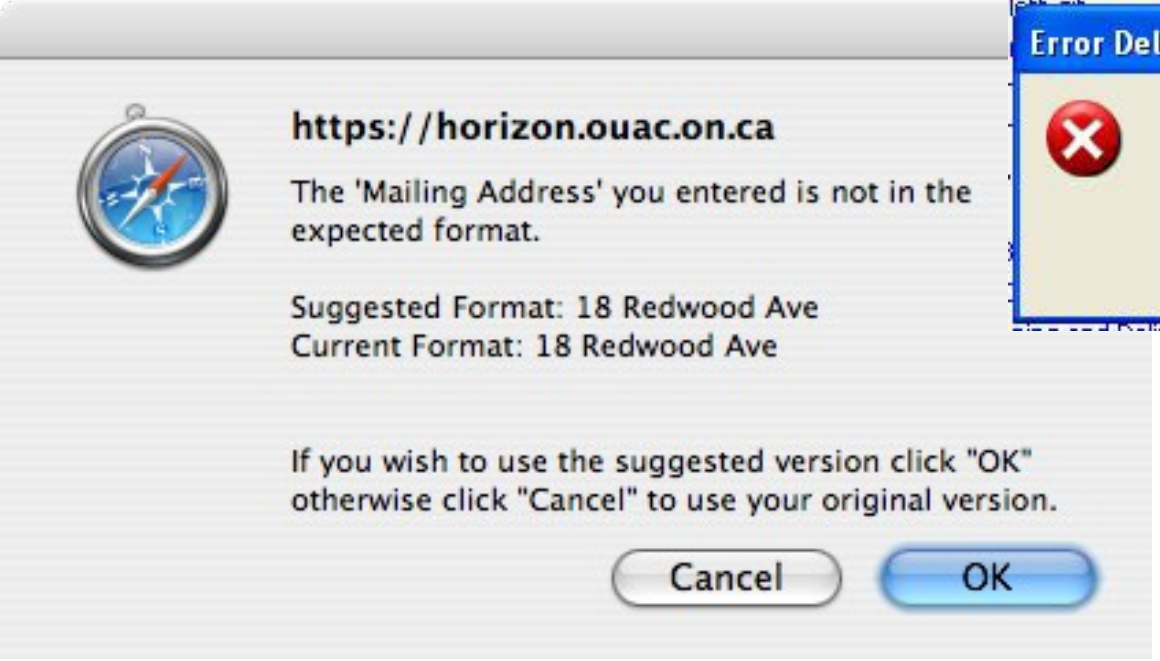

https://horizon.ouac.on.ca
The 'Mailing Address' you entered is not in the expected format.
Suggested Format: 18 Redwood Ave
Current Format: 18 Redwood Ave
If you wish to use the suggested version click "OK" otherwise click "Cancel" to use your original version.
Cancel
OK


Error Deleting File or Folder
Cannot delete FilePicker: There is not enough free disk space.
Delete one or more files to free disk space, and then try again.
OK

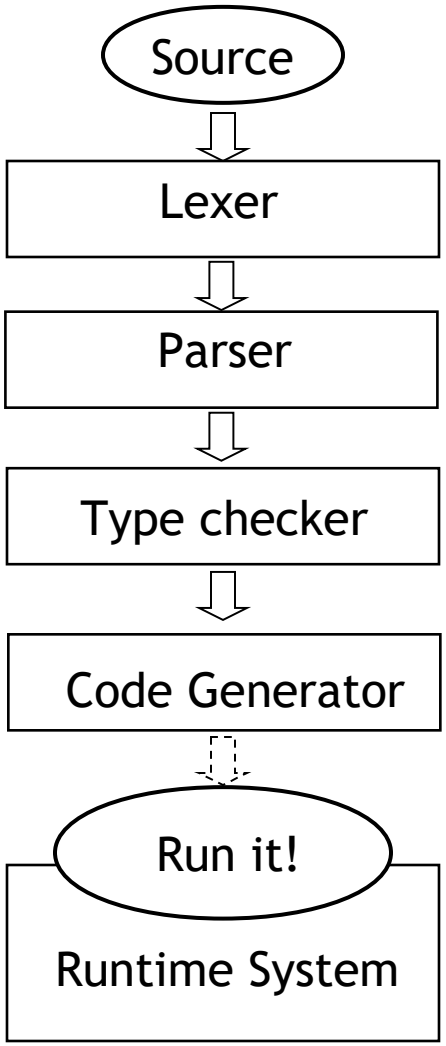
Exceptions


NO! - Bad User!!!
You've been warned 3 times that this file does not exist.
Now you've made us catch this worthless exception and we're upset.
Do not do this again.
OK

One-Slide Summary

- Real-world programs must have **error-handling** code. Errors can be handled where they are detected or the error can be **propagated** to a caller.
- Passing special error return codes is itself error-prone.
- Exceptions are a formal and automated way of reporting and handling errors. Exceptions can be implemented efficiently and described formally.
- It is possible to optimize quality properties other than speed. Power and accuracy are common.

Language System Structure



- We looked at each stage in turn
- A new language feature affects many stages
- We will add exceptions

Lecture Summary

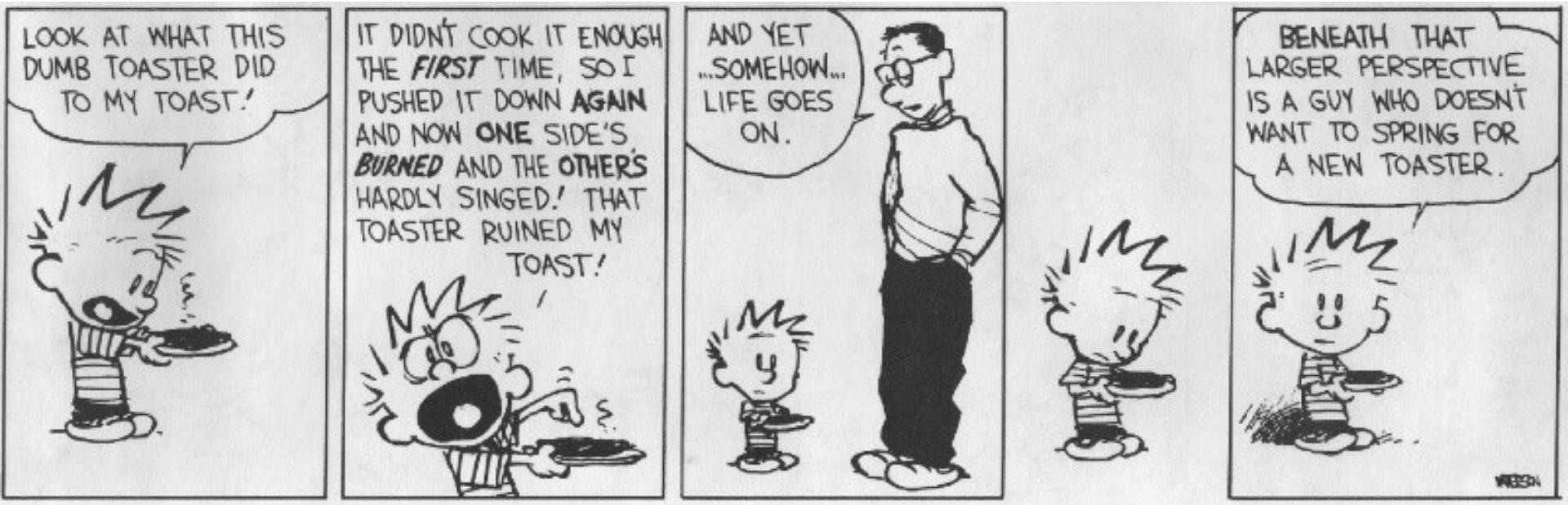
- Why exceptions ?
- Syntax and informal semantics
- Semantic analysis (i.e., type checking rules)
- Operational semantics
- Code generation
- Runtime system support

Exceptional Motivation

- "Classroom" programs are written with optimistic assumptions
- Real-world programs must consider "exceptional" situations:
  - Resource exhaustion (disk full, out of memory, network packet collision, …)
  - Invalid input
  - Errors in the program (null pointer dereference)
- It is usual for code to contain 1-5% error handling code (figures for modern Java open source code)
  - With 3-46% of the program text transitively reachable

Why do we care?

- Are there any implications if software makes mistakes?



Approaches To Error Handling

Two ways of dealing with errors:

- Handle them where you detect them
  - e.g., null pointer dereference → stop execution

- Let the caller handle the errors:
  - The caller has more contextual information

    e.g., an error when opening a file:

    a) In the context of opening /etc/passwd

    b) In the context of opening a log file
  - But we must tell the caller about the error!

Error Return Codes

- The callee can signal the error by returning a special return value or **error code**:
  - Must not be one of the valid inputs
  - Must be agreed upon beforehand (i.e., in API)
    - What's an example?
- The caller promises to check the error return and either:
  - Correct the error, or
  - Pass it on to its own caller

Error Return Codes

- It is sometimes hard to select return codes
  - What is a good error code for:
    - divide(num: Double, denom: Double) : Double { … }
- How many of you always check errors for:
  - malloc(int) ?
  - open(char *) ?
  - close(int) ?
  - time(struct time_t *) ?
- Easy to forget to check error return codes

Example: Automated Grade Assignment

```
float getGrade(int sid) { return dbget(gradesdb, sid); }

void setGrade(int sid, float grade) {
    dbset(gradesdb, sid, grade);
}
void extraCredit(int sid) {
    setGrade(sid, 0.33 + getGrade(sid));
}
void grade_inflator() {
    while(gpa() < 3.0) {  extraCredit(random());  }
}
```

- What errors are we ignoring here?

Example: Automated Grade Assignment

```
float getGrade(int sid) {
    float res; int err = dbget(gradesdb, sid, &res);
    if(err < 0) { return -1.0;}
    return res;
}

int extraCredit(int sid) {
    int err;  float g = getGrade(sid);
    if(g < 0.0) { return 1; }
    err = setGrade(sid, 0.33 + g));
    return (err < 0);
}
```

Example: Automated Grade Assignment

A lot of extra code

```
float getGrade(int sid) {
    float res; int err = dbget(gradesdb, sid, &res);
    if(err < 0) { return -1.0;}
    return res;
}

int extraCredit(int sid) {
    int err;  float g = getGrade(sid);
    if(g < 0.0) { return 1; }
    err = setGrade(sid, 0.33 + g));
    return (err < 0);
}
```

Example: Automated Grade Assignment

A lot of extra code

```
float getGrade(int sid) {
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    int err;  float g = getGrade(sid);
    if(g < 0.0) { return 1; }
    err = setGrade(sid, 0.33 + g));
    return (err < 0);
}
```

Some functions change their type

Example: Automated Grade Assignment

A lot of extra code

```
float getGrade(int sid) {
    float res; int err = dbget(gradesdb, sid, &res);
    if(err < 0) { return -1.0;}
    return res;
}

int extraCredit(int sid) {
    int err;  float g = getGrade(sid);
    if(g < 0.0) { return 1; }
    err = setGrade(sid, 0.33 + g));
    return (err < 0);
}
```

Some functions change their type

Error codes are sometimes arbitrary

Exceptions

- **Exceptions** are a language mechanism designed to allow:
  - Deferral of error handling to a caller
  - Without (explicit) error codes
  - And without (explicit) error return code checking

Adding Exceptions to Cool

- We extend the language of expressions:

  e ::= throw e | try e catch x : T $\Rightarrow$ e_2

- (Informal) semantics of throw e
  - Signals an exception
  - Interrupts the current evaluation and searches for an exception handler up the activation tree
  - The value of e is an exception parameter and can be used to communicate details about the exception

Adding Exceptions to Cool

(Informal) semantics of try e catch x : T $\Rightarrow$ e_2

- e is evaluated first
- If e's evaluation terminates normally with v

  then v is the result of the entire expression

  Else (e's evaluation terminates exceptionally)

  If the exception parameter is of type $\leq$ T then
  - Evaluate e_2 with x bound to the exception parameter
  - The (normal or exceptional) result of evaluating e_2 becomes the result of the entire expression

  Else
  - The entire expression terminates exceptionally

Example: Automated Grade Assignment

```
float getGrade(int sid) {   return dbget(gradesdb, sid); }

void setGrade(int sid, float grade) {
    if(grade < 0.0 || grade > 4.0) { throw (new NaG); }
    dbset(gradesdb, sid, grade); }

void extraCredit(int sid) {
    setGrade(sid, 0.33 + getGrade(sid)) }

void grade_inflator() {
    while(gpa < 3.0) {
        try extraCredit(random())
        catch x : Object ⇒ print “oh noes!?\n”; }
    }
```

Example Notes

- Only error handling code remains
- But no error propagation code
  - The compiler handles the error propagation
  - No way to forget about it
  - And also much more efficient (we'll see)
- Two kinds of evaluation outcomes:
  - Normal return (with a return value)
  - Exceptional "return" (with an exception parameter)
  - No way to get confused which is which

Where do exceptions come from?

Overview

- ✓ Why exceptions ?
- ✓ Syntax and informal semantics
- Semantic analysis (i.e. type checking rules)
- Operational semantics
- Code generation
- Runtime system support

Typing Exceptions

- We must extend the Cool typing judgment

$$O, M, C \vdash e : T$$

  - Type T refers to the normal return value!

- We'll start with the rule for try:
  - Parameter "x" is bound in the catch expression
  - try is like a conditional

$$\frac{O, M, C \vdash e : T_1 \qquad O[T/x], M, C \vdash e' : T_2}{O, M, C \vdash \text{try } e \text{ catch } x : T \Rightarrow e' : T_1 \sqcup T_2}$$

Typing Exceptions

- What is the type of "throw e" ?
- The type of an expression:
  - Is a description of the possible return values, and
  - Is used to decide in what contexts we can use the expression
- "throw" does not return to its immediate context but directly to the exception handler!
- The same "throw e" is valid in any context:

  if throw e then (throw e) + 1 else (throw e).foo()
- As if "throw e" has *any type*!

Typing Exceptions

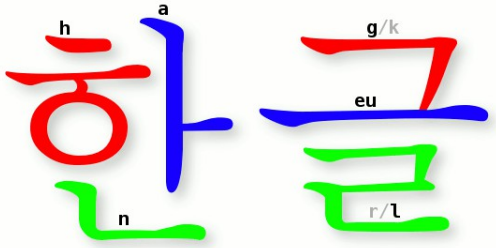
$$\frac{O, M, C \vdash e : T_1}{O, M, C \vdash \text{throw } e : T_2}$$

- As long as "e" is well typed, "throw e" is well typed with *any type needed* in the context
  - T_2 is unbound!

- This is convenient because we want to be able to signal errors from any context

Real-World Languages

- Hangul is the recently-constructed (well, 15th century) alphabet for *this* language. It contains 24 constants and vowels, but is written in syllable *blocks* of two to five letters. For example, 한 looks like a single character but is composed of three distinct letters: ㅎ h, ㅏ a, and ㄴ n. The shapes of the letters are related to the *features* of the sounds they represent.



Fictional Magicians

- In Arthurian legend, this magician often serves as an antagonist to Arthur and Guinevere (who discovers her infidelity). Her actions include healing, studying under Merlin, plotting against Lancelot, and other various convoluted schemes. A complex type of superior image mirage bears her name.

Real-World Languages

- This language group has more native speakers (almost one billion) than any other language. Dialects are typically tonal, analytic languages with word order and particles used instead of inflection or affixes. The standard word order is S-V-O. Its rich literary history includes Four Great Classical Novels: Water Margin (水滸傳), Romance of the Three Kingdoms (三國演義), Journey to the West (西遊記), and Dream of the Red Chamber (紅樓夢).

World History

- This Roman general and seven-time consul reformed the army (107 BC), defeated Germanic invaders, and has been called the third founder of Rome (transitioning it from a Republic to an Empire). In addition to allowing all citizens (regardless of land ownership) to join the army, he is often credited with a new spear (*pilum*) in which one of two nails holding the blade to the shaft was replaced with a weak wooden pin.

Overview

- ✓ Why exceptions ?
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Operational Semantics of Exceptions

- Several ways to model the behavior of exceptions
- A **generalized value** is
  - Either a normal termination value, or
  - An exception with a parameter value

g ::= Norm(v) | Exc(v)

- Thus given a generalized value we can:
  - Tell if it is normal or exceptional return, and
  - Extract the return value or the exception parameter

Operational Semantics of Exceptions (1)

- The existing rules change to use Norm(v) :

$$\frac{so, E, S \vdash e_1 : Norm(Int(n_1)), S_1 \quad so, E, S_1 \vdash e_2 : Norm(Int(n_2)), S_2}{so, E, S \vdash e_1 + e_2 : Norm(Int(n_1 + n_2)), S_2}$$

$$\frac{E(id) = l_{id} \quad S(l_{id}) = v}{so, E, S \vdash id : Norm(v), S}$$

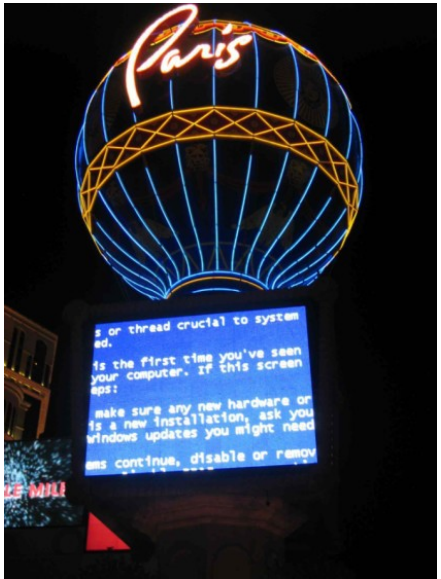
$$\frac{}{so, E, S \vdash self : Norm(so), S}$$

Operational Semantics of Exceptions (2)

- "throw" returns exceptionally:

$$\frac{so, E, S \vdash e : v, S_1}{so, E, S \vdash \text{throw } e : Exc(v), S_1}$$

  - The rule above is *not well formed*! Why?



Operational Semantics of Exceptions (2)

- "throw" returns exceptionally:

$$\frac{so, E, S \vdash e : v, S_1}{so, E, S \vdash \text{throw } e : Exc(v), S_1}$$

  - The rule above is *not well formed*! Why?

$$\frac{so, E, S \vdash e : Norm(v), S_1}{so, E, S \vdash \text{throw } e : Exc(v), S_1}$$

Operational Semantics of Exceptions (3)

- "throw e" always returns exceptionally:

$$\frac{so, E, S \vdash e : Norm(v), S_1}{so, E, S \vdash throw\ e : Exc(v), S_1}$$

  - What if the evaluation of e itself throws an exception?
    - e.g. "throw (1 + (throw 2))" is like "throw 2"
    - Formally:

$$\frac{so, E, S \vdash e : Exc(v), S_1}{so, E, S \vdash throw\ e : Exc(v), S_1}$$

Operational Semantics of Exceptions (4)

- All existing rules are changed to propagate the exception:

$$\frac{so, E, S \vdash e_1 : Exc(v), S_1}{so, E, S \vdash e_1 + e_2 : Exc(v), S_1}$$

  - Note: the evaluation of e_2 is aborted

$$\frac{so, E, S \vdash e_1 : Norm(Int(n_1)), S_1 \quad so, E, S_1 \vdash e_2 : Exc(v), S_2}{so, E, S \vdash e_1 + e_2 : Exc(v), S_2}$$

Operational Semantics of Exceptions (5)

- The rules for “try” expressions:
  - Multiple rules (just like for a conditional)

$$\frac{so, E, S \vdash e : Norm(v), S_1}{so, E, S \vdash try\ e\ catch\ x : T \Rightarrow e' : Norm(v), S_1}$$

  - What if e terminates exceptionally?
    - We must check whether it terminates with an exception parameter of type T or not

Operational Semantics for Exceptions (6)

- If e does not throw the expected exception

$$\frac{so, E, S \vdash e : Exc(v), S_1 \quad v = X(\ldots) \quad \text{not } (X \leq T)}{so, E, S \vdash \text{try } e \text{ catch } x : T \Rightarrow e' : Exc(v), S_1}$$

- If e does throw the expected exception

$$\frac{so, E, S \vdash e : Exc(v), S_1 \quad v = X(\ldots) \quad X \leq T \quad l_{new} = newloc(S_1) \quad so, E[l_{new}/x], S_1[v/l_{new}] \vdash e' : g, S_2}{so, E, S \vdash \text{try } e \text{ catch } x : T \Rightarrow e' : g, S_2}$$

Operational Semantics of Exceptions. Notes

- Our semantics is precise
- But is not very clean
  - It has two or more versions of each original rule
- It is not a good recipe for implementation
  - It models exceptions as “compiler-inserted propagation of error return codes”
  - There are much better ways of implementing exceptions
- There are other semantics that are cleaner and model better implementations (qv. 590)

Overview

- ✓ Why exceptions ?
- ✓ Syntax and informal semantics
- ✓ Semantic analysis (i.e. type checking rules)
- ✓ Operational semantics
- Code generation
- Runtime system support

Code Generation for Exceptions

- One method is suggested by the operational semantics
- Simple to implement
- But not very good
  - We pay a cost at each call/return (i.e., often)
  - Even though exceptions are rare (i.e., exceptional)
- A good engineering principle:
  - Don't pay often for something that you use rarely!
    - *What is **Amdahl's Law**?*
  - Optimize the common case!

Solutions?

Long Jumps

- A long jump is a *non-local* goto:
  - In one shot you can jump back to a function in the caller chain (bypassing many intermediate frames)
  - A long jump can “return” from many frames at once

- Long jumps are a commonly used implementation scheme for exceptions
  - See **`setjmp(3)`**, **`longjmp(3)`**

- Disadvantage:
  - (Minor) performance penalty at each try

Implementing Exceptions with Tables (1)

- We do not want to pay for exceptions when executing a “try”
  - Only when executing a “throw”

```
cgen(try e catch e') =
    cgen(e)                    ; Code for the try block
    goto end_try
L_catch:
    cgen(e')                   ; Code for the catch block
end_try:
     …
cgen(throw) =
    jmp runtime_throw          ; <- this is the trick!
```

Implementing Exceptions with Tables (2)

- The normal execution proceeds at full speed
- When a throw is executed we use a runtime function that finds the right catch block
- For this to be possible the compiler produces a table saying, for each catch block, which instructions it corresponds to
  - Check table, walk up call stack, check table, check type conformance, walk up call stack ...

Implementing Exceptions with Tables. Notes

- runtime_throw looks at the table and figures which catch handler to invoke

- Advantage:
  - No cost, except if an exception is thrown
- Disadvantage:
  - Tables take space (even 30% of binary size)
  - But at least they can be placed out of the way

- Java Virtual Machine uses this scheme

try … finally …

- Another exception-related construct:

  try e_1 finally e_2

  - After the evaluation of e_1 terminates (either normally or exceptionally) it evaluates e_2
  - The whole expression then terminates like e_1

- Used for cleanup code:

```
try
    f = fopen("treasure.directions", "w");
    … compute … fprintf(f, "Go %d paces to the west", paces); …
finally
    fclose(f);
```

Try-Finally Semantics

- Typing rule:

$$\frac{O, M, C \vdash e_1 : T_1 \qquad O, M, C \vdash e_2 : T_2}{O, M , C \vdash \text{try } e_1 \text{ finally } e_2 : T_2}$$

- Operational semantics:

$$\frac{so, E, S \vdash e_1 : \text{Norm}(v), S_1 \qquad so, E, S_1 \vdash e_2 : \mathbf{g}, S_2}{so, E, S \vdash \text{try } e_1 \text{ finally } e_2 : \mathbf{g}, S_2}$$

$$\frac{so, E, S \vdash e_1 : \mathbf{Exc(v_1)}, S_1 \qquad so, E, S_1 \vdash e_2 : \text{Norm}(v_2), S_2}{so, E, S \vdash \text{try } e_1 \text{ finally } e_2 : \mathbf{Exc(v_1)}, S_2}$$

Obscure Corner Case

- Operational Semantics

$$\frac{so, E, S \vdash e_1 : \mathbf{Exc(v_1)}, S_1 \quad so, E, S_1 \vdash e_2 : \mathbf{Exc(v_2)}, S_2}{so, E, S \vdash \text{try } e_1 \text{ finally } e_2 : \mathbf{???}, S_2}$$

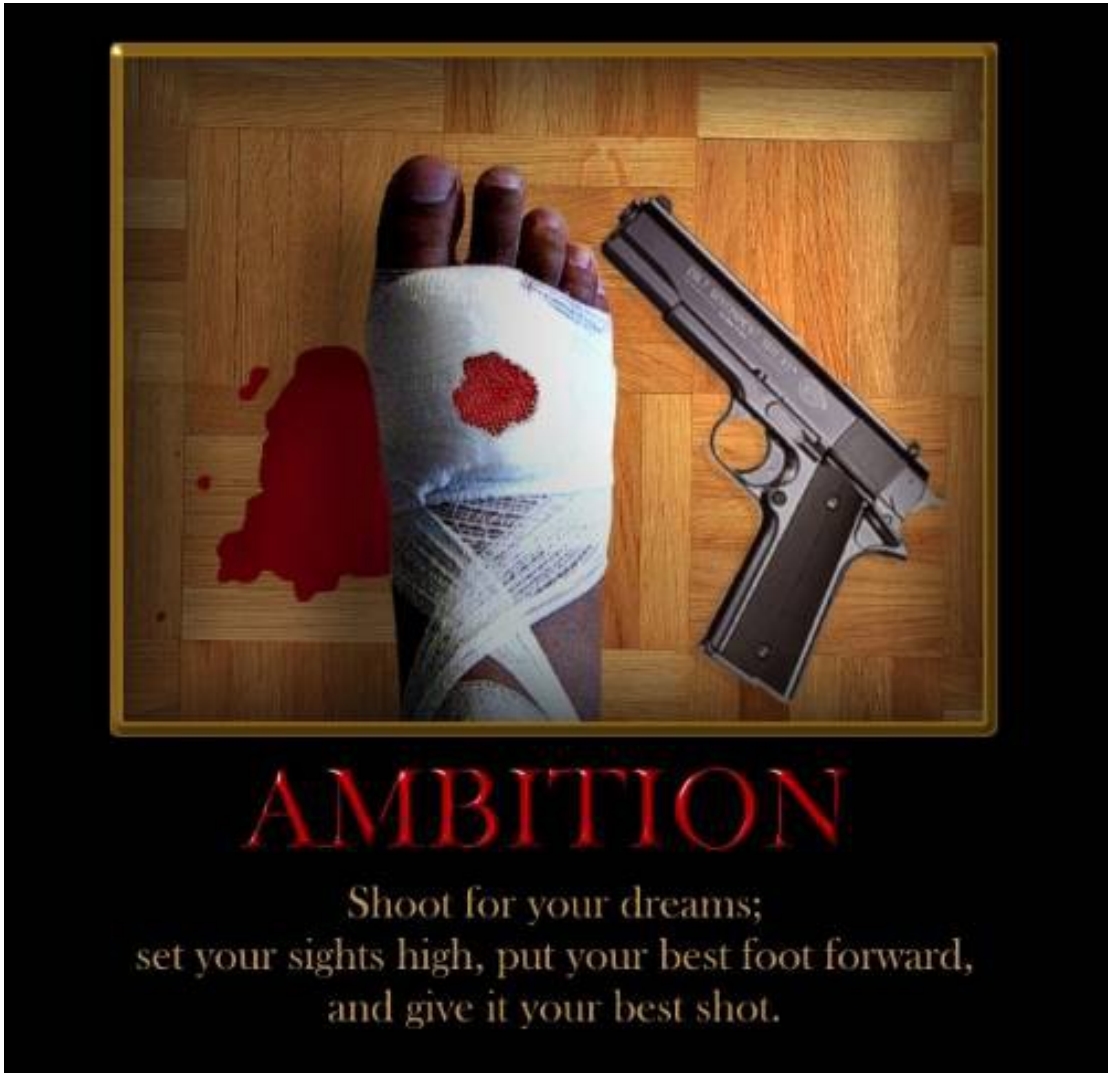
- Difficulty in understanding try-finally is one reason why Java programmers tend to make at least 200 exception handling mistakes per million lines of code

14.20.2 Execution of try-catch-finally

- A try statement with a finally block is executed by first executing the try block. Then there is a choice:
- If execution of the try block completes normally, then the finally block is executed, and then there is a choice:
  - If the finally block completes normally, then the try statement completes normally.
  - If the finally block completes abruptly for reason *S*, then the try statement completes abruptly for reason *S*.
- If execution of the try block completes abruptly because of a throw of a value *V*, then there is a choice:
  - If the run-time type of *V* is assignable to the parameter of any catch clause of the try statement, then the first (leftmost) such catch clause is selected. The value *V* is assigned to the parameter of the selected catch clause, and the *Block* of that catch clause is executed. Then there is a choice:
    - If the catch block completes normally, then the finally block is executed. Then there is a choice:
      - If the finally block completes normally, then the try statement completes normally.
      - If the finally block completes abruptly for any reason, then the try statement completes abruptly for the same reason.
    - If the catch block completes abruptly for reason *R*, then the finally block is executed. Then there is a choice:
      - If the finally block completes normally, then the try statement completes abruptly for reason *R*.
      - If the finally block completes abruptly for reason *S*, then the try statement completes abruptly for reason *S* (and reason *R* is discarded).
  - If the run-time type of *V* is not assignable to the parameter of any catch clause of the try statement, then the finally block is executed. Then there is a choice:
    - If the finally block completes normally, then the try statement completes abruptly because of a throw of the value *V*.
    - If the finally block completes abruptly for reason *S*, then the try statement completes abruptly for reason *S* (and the throw of value *V* is discarded and forgotten).
- If execution of the try block completes abruptly for any other reason *R*, then the finally block is executed. Then there is a choice:
  - If the finally block completes normally, then the try statement completes abruptly for reason *R*.
  - If the finally block completes abruptly for reason *S*, then the try statement completes abruptly for reason *S* (and reason *R* is discarded).

Avoiding Code Duplication for try … finally

- The Java Virtual Machine designers wanted to avoid this code duplication



Avoiding Code Duplication for try … finally

- The Java Virtual Machine designers wanted to avoid this code duplication

- So they invented a *new* notion of *subroutine*
  - Executes within the stack frame of a method
  - Has access to and can modify local variables
  - One of the few true innovations in the JVM

JVML Subroutines Are Complicated

- Subroutines are the most difficult part of the JVML

- And account for the several bugs and inconsistencies in the bytecode verifier
  - And are used in practice for code obfuscation!

- Complicate the formal proof of correctness:
  - 14 or 26 proof invariants due to subroutines
  - 50 of 120 lemmas due to subroutines
  - 70 of 150 pages of proof due to subroutines

Are JVML Subroutines Worth the Trouble ?

- Subroutines save space?
  - About 200 subroutines in 650,000 lines of Java (mostly in JDK)
  - No subroutines calling other subroutines
  - Subroutines save 2427 bytes of 8.7 Mbytes (0.02%)!

- Changing the name of the language from Java back to Oak would save 13 times more space!

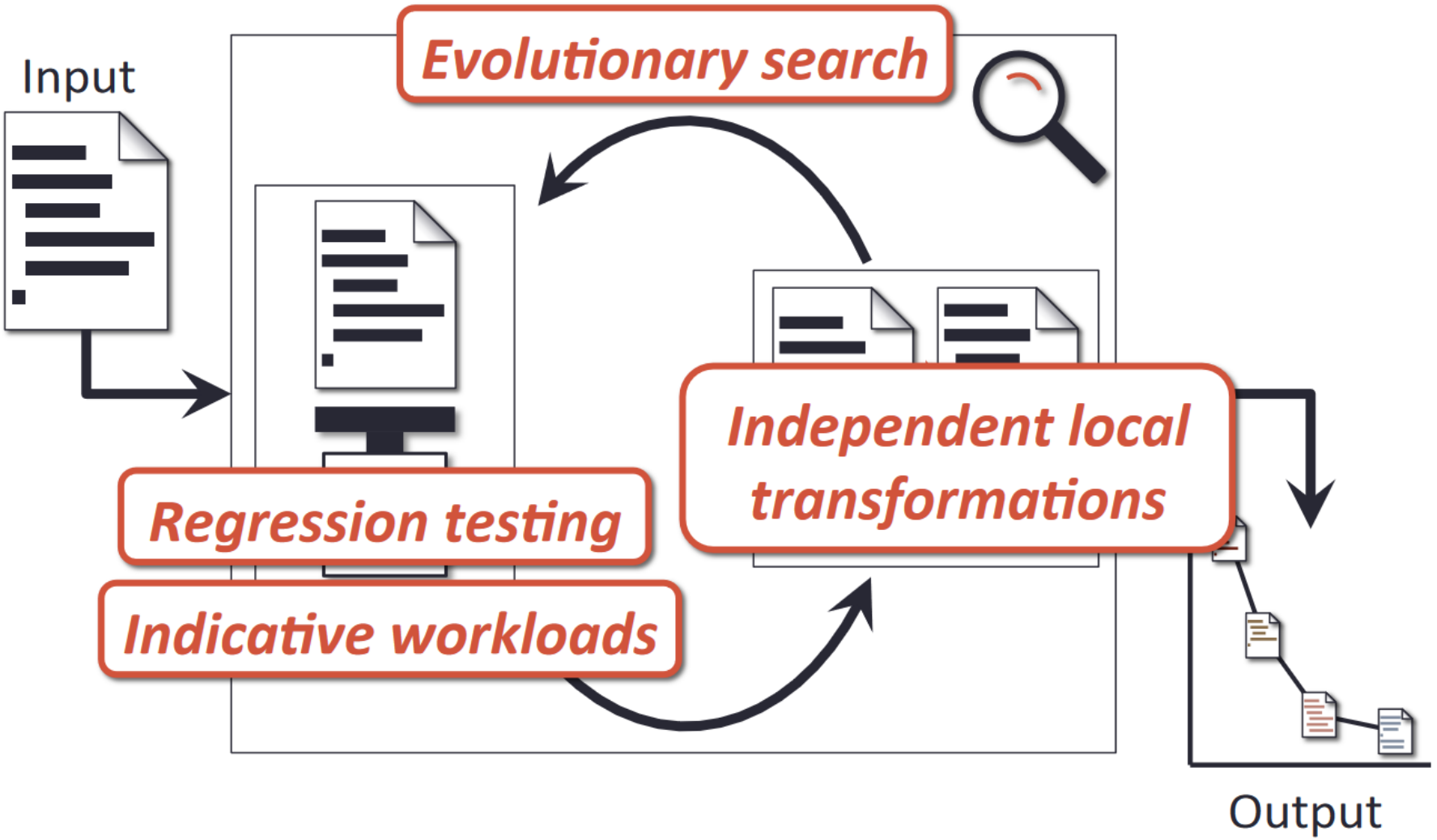
Exceptions. Conclusion

- Exceptions are a very useful construct
- A good **programming language solution** to an important **software engineering problem**
- But exceptions are complicated:
  - Hard to implement
  - Complicate the optimizer
  - Very hard to debug the implementation (exceptions are exceptionally rare in code)

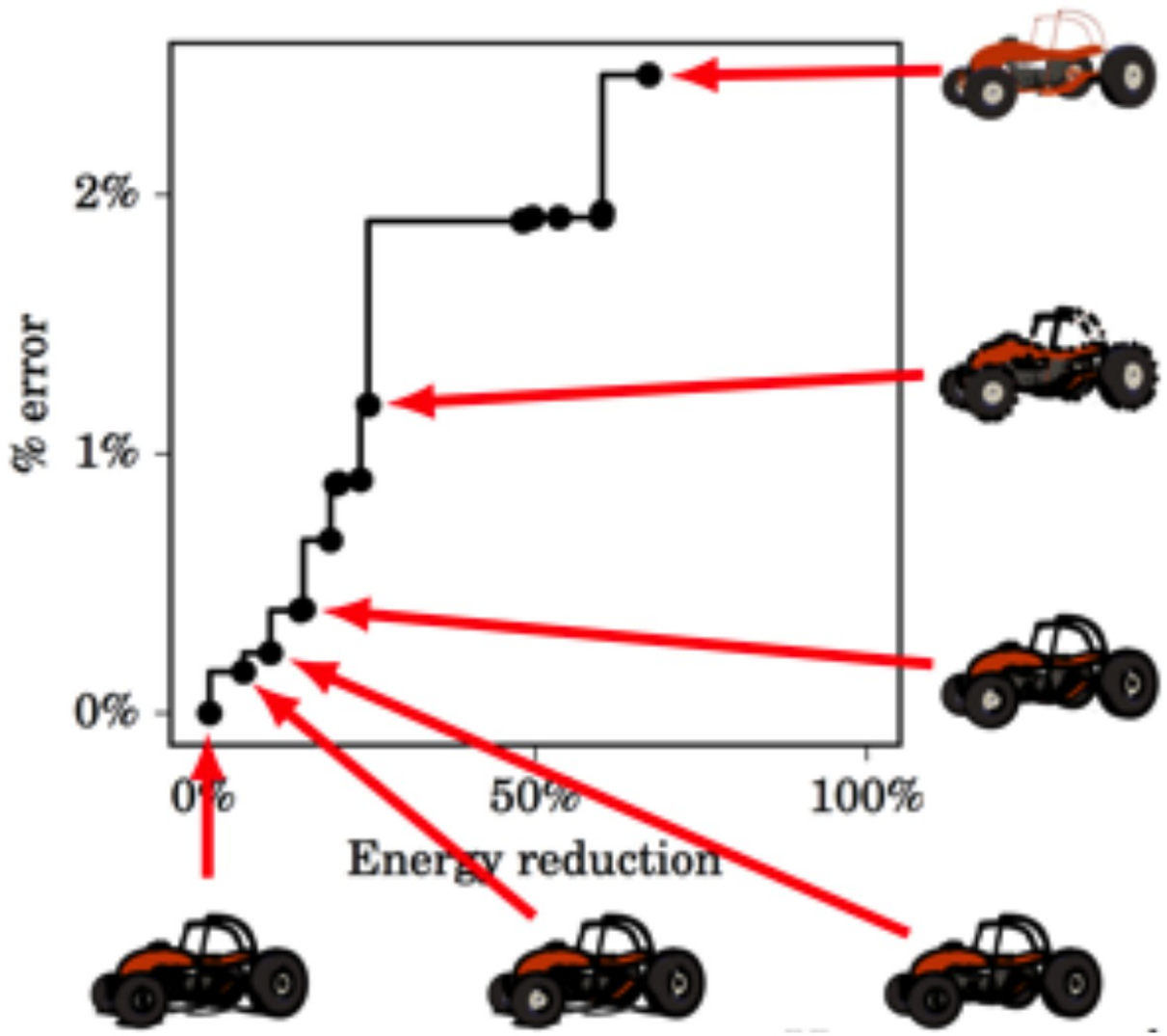
Optimizing Quality Properties

- Normal (speed) optimization:
  - “Don't break the build”
  - Use an analysis to determine, in advance, that a known-beneficial transformation can be applied without changing the semantics
- Post-compiler search-based optimization:
  - Use tests to determine, post hoc, if a transformation can be applied with acceptable changes to the semantics – and measure whether it is beneficial or not (cf. `mp3` or `jpg`)

Search-Based Optimization

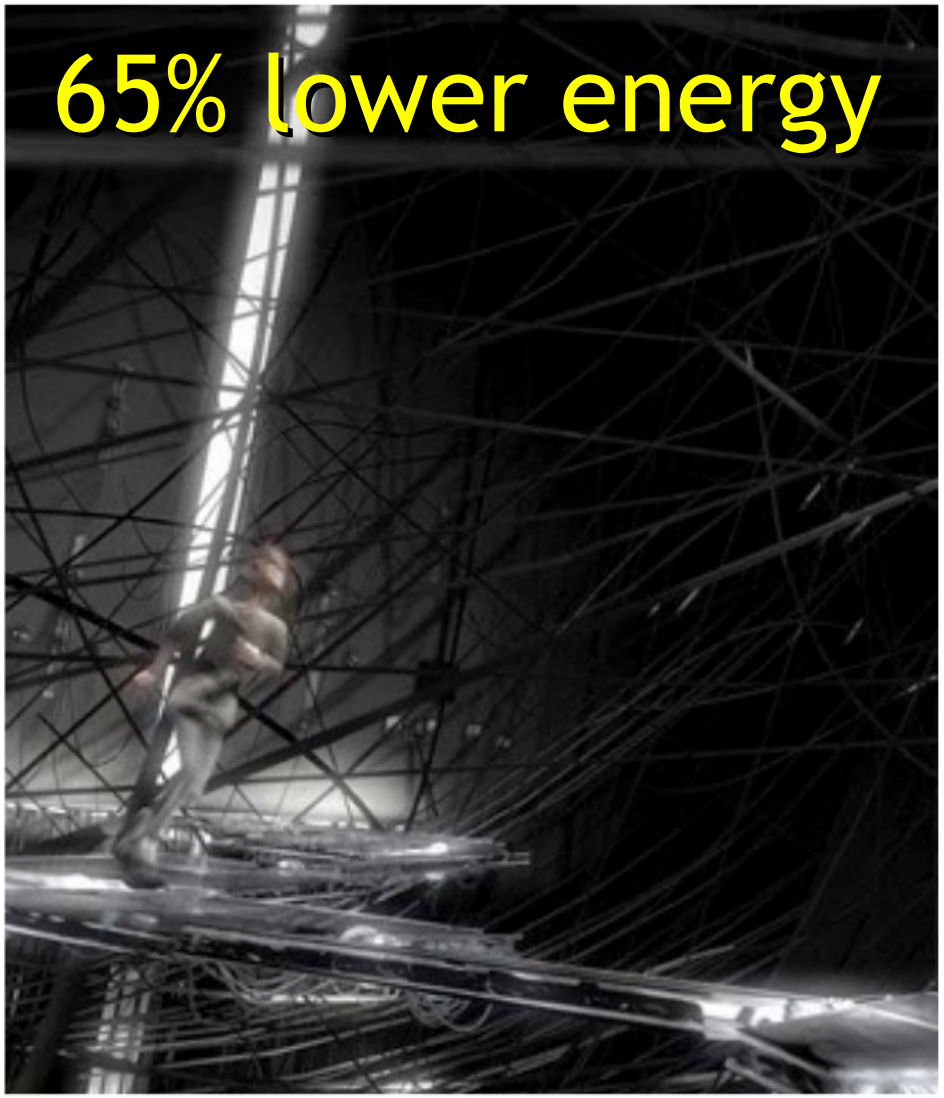


Optimizations Explore Tradeoffs

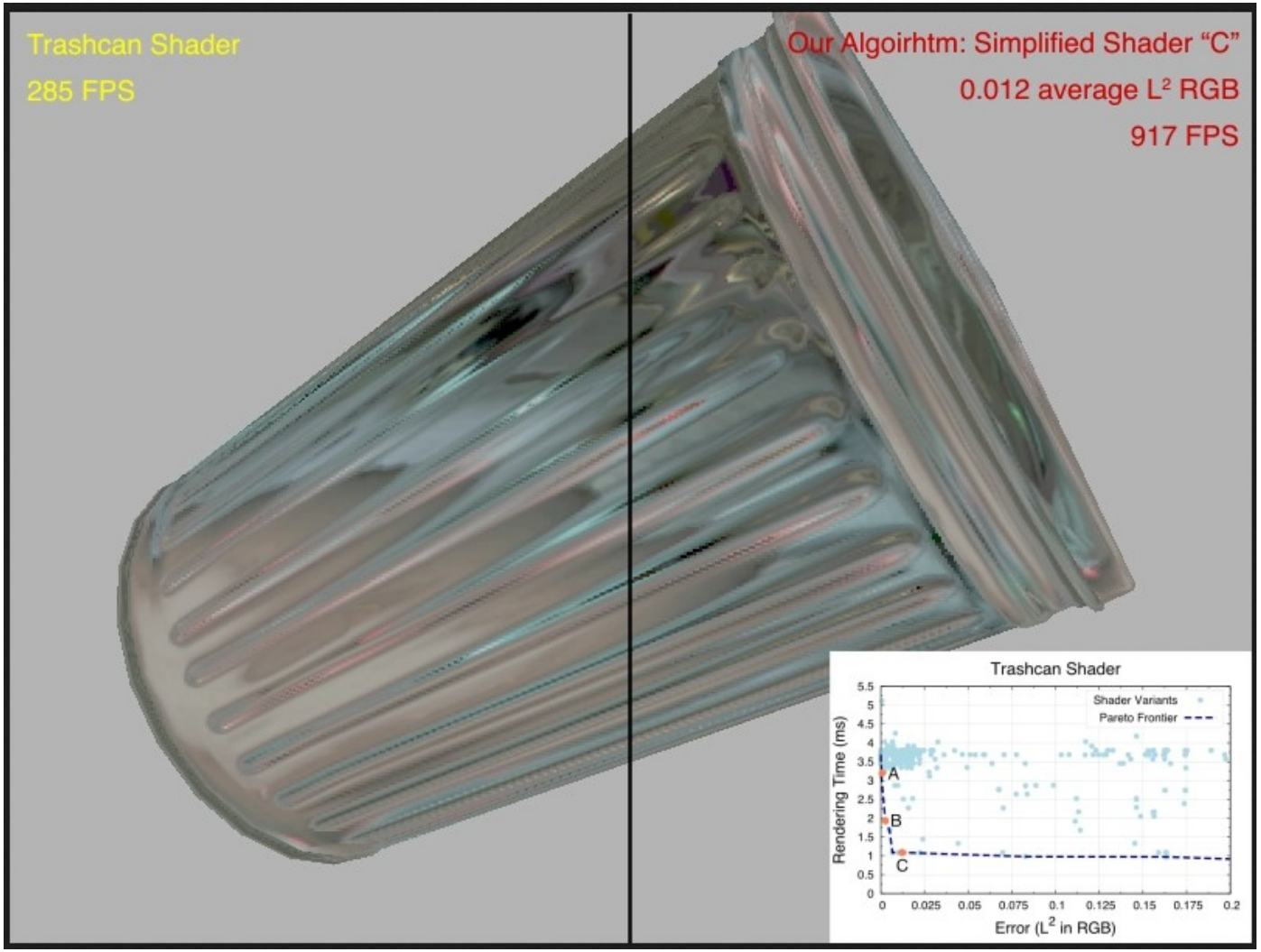


Can you spot the difference?

Can you spot the difference?



Time Permitting: Video Demo?



Quality Optimization Conclusion

- In many domains users are interested in trading off one property for another
  - Speed, energy consumption, space, visual fidelity, mathematical accuracy, etc.
- Search-based approaches try out “exotic” transformations that could not be proved correct in advance
  - Testing on indicative workloads replaces analysis
  - Requires use case that can accept slight errors

Questions