Tutorial on Exception Handling

"Preventing to fail
by preparing to fail"

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Why Programs Fail

- Specification is in error:
  - does not capture the user's intent
  - incomplete, inconsistent
- Design is in error:
  - logical error, e.g. forgotten case
  - idealized hypotheses, e.g. about integer range, available memory, processing speed
  - incorrect assumptions about other components
- Underlying machine fails:
  - incorrect compilation
  - error in library implementation
  - hardware failure

inv2_8: $ml\_tl = red \Rightarrow ml\_pass = \mathrm{TRUE}$

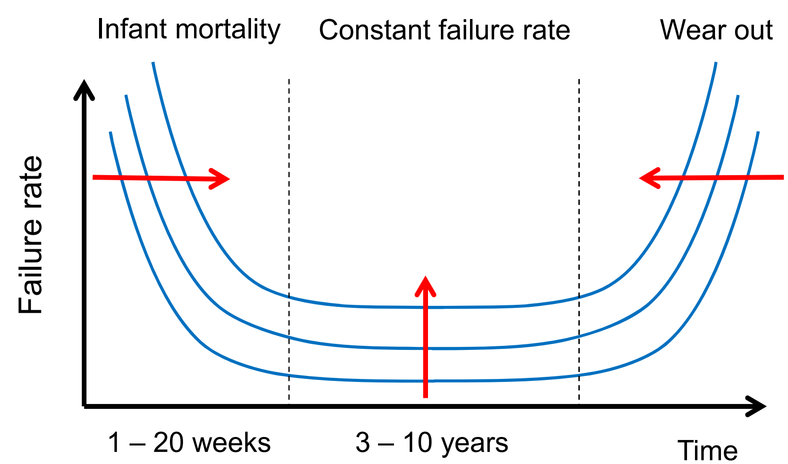
inv2_9: $il\_tl = red \Rightarrow il\_pass = \mathrm{TRUE}$

variant_2: $b\_2\_n(ml\_pass) + b\_2\_n(il\_pass)$

H_2 \ H_1	$y = 10$	$y > 10$	$y < 10$
$x \geq 0$	0	y^2	$-y^2$
$x < 0$	x	$x + y$	$x - y$

G

ML_out_2
when
$ml\_tl = green$
$a + b + 1 = d$
then
$a := a + 1$
$ml\_tl := red$
$ml\_pass := \mathrm{TRUE}$
end



Design Error: Microsoft Zune Bug ...

from techcruch.com:

30GB Zunes all over the world fail en masse

MATT BURNS | Wednesday, December 31st, 2008 | **0 Comments**

It seems that a random bug is affecting a bunch, if not every, 30GB **Zunes**. Real early this morning, a bunch of Zune 30s just stopped working. No official word from Redmond on this one yet but we might have a gadget Y2K going on here. **Fan boards** and **support forums** all have the same mantra saying that at 2:00 AM this morning, the Zune 30s reset on their own and doesn't fully reboot. We're sure Microsoft will get flooded with angry Zune owners as soon as the phone lines open up for the last time in 2008. More as we get it.

Update 2: **The solution** is … kind of weak: let your Zune run out of battery and it'll be fixed when you wake up tomorrow and charge it.

Zune.net, **ZuneBoards**, **ZuneScene**, **Gizmodo**

Update: Reddit **adds**:

... Design Error: Microsoft Zune Bug

Zune bug explained in detail

DEVIN COLDEWEY | Wednesday, December 31st, 2008 | **0 Comments**

Earlier today, the sound of **thousands of Zune owners crying out in terror** made ripples across the blogosphere. The response from Microsoft is to **wait until tomorrow** and all will be well. You're probably wondering, what kind of bug fixes itself?

Well, I've got the code here and it's very simple, really; if you've taken an introductory programming class, you'll see the error right away.

```
year = ORIGINYEAR; /* = 1980 */

while (days > 365)
{
    if (IsLeapYear(year))
    {
        if (days > 366)
        {
            days -= 366;
            year += 1;
        }
    }
    else
    {
        days -= 365;
        year += 1;
    }
}
```

Detected Faults

- Some errors are always detected by the underlying machine:
  - indexing an array out of bounds
  - allocating memory when none is available
  - reading a file beyond its end
- Some errors can be detected by instrumenting programs:

```
class STACK
   capacity: INTEGER
   count: INTEGER
invariant
   count <= capacity
push is ...
```

- Some faults are “unfeasible” to detect:
  - only a single pointer to an object exists
  - validity of precondition and invariant of binary search
  - termination

Responding to Detected Faults

- Even with best effort, possibility of fault in a complex system remains.

  S_1 ; S_2 ; S_3 ; S_4 where S_1, S_3 may detect an error
  in case of error, execute T instead

- Explicit testing a priori or a posteriori:

```
if S1 possible then
  S1 ; S2 ;
  if S3 possible then
    S3 ; S4
  else T
else T
```

```
S1 ;
if S1 successful then
  S2 ; S3
  if S3 successful then
    S4
  else T
else T
```

- Dedicated exception handling:

```
try
  S1 ; S2 ; S3 ; S4
catch
  T
```

body

handler

Exception Handling

- no additional variables and control structures interspersed; original program structure remains visible

```
f = fopen(filename, "r");
if (f == NULL) {
   ... error
} else {
   ... read file (possibly failing)
   fclose(f);
}
```

```
try {
   f = fopen(filename, "r");
   ... read file (possibly failing)
   fclose(f);
} catch {
   ... error
}
```

- useful for rare or undesired cases

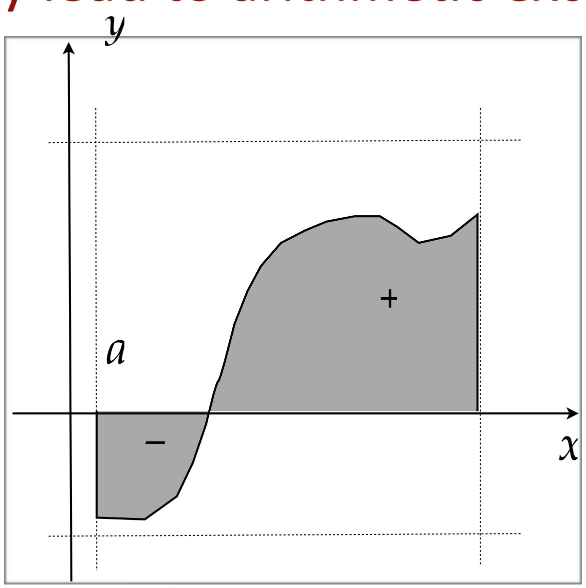
- allows for imperfections during design process supporting extension and contraction

```
static void FutureFeature()
{
   // Not developed yet.
   throw new NotImplementedException();
}
```

[MS Developer Documentation for .NET]

Example: Monte Carlo Integration in Python

- Function f evaluated randomly: may lead to arithmetic exception




```python
def area(f, a, b, l, u, n):
    c = 0
    for i in range(n):
        try:
            x = random.uniform(a, b)
            y = random.uniform(l, u)
            if 0 <= y <= f(x):
                c = c + 1
            elif f(x) <= y <= 0:
                c = c - 1
        except:
            pass
    return (u - l) * (b - a) * c / n
```

- "Rare and undesired", but possible.
- Here exception handler does nothing, but quality of result affected.

Further Examples for Exception Handling

- Some a priori tests cannot be performed efficiently, e.g. testing arithmetic addition for possible overflow requires a subtraction, which means doubling the number of operations, e.g. in a matrix multiplication.

- A priori tests like for arithmetic overflow of floating point numbers cannot be performed reliably at all due to rounding errors.

- Errors like stack overflow on a procedure call are difficult to test for because programming languages do not offer any means.

- Transient hardware failures may occur at any time, so there is no place to test for them.

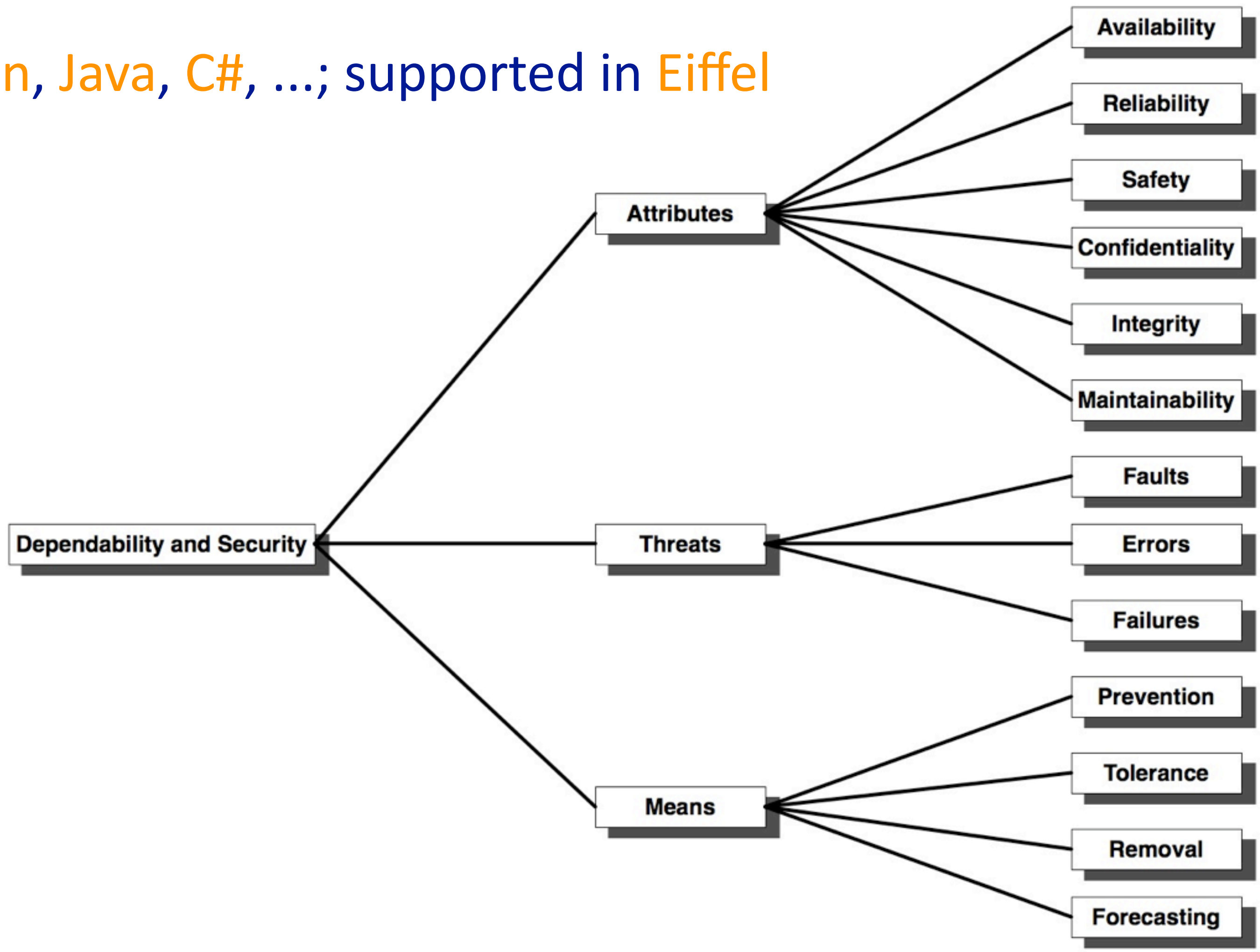
Overview

What should an exception handler do in general?

Where is an exception handler best placed?

- we give a theory based on weakest preconditions
- applicable to python, Java, C#, ...; supported in Eiffel

Where does this fit in?



(Avizienis et al 2004)

Outline

- Prelude: undefinedness of expressions
- Review: weakest preconditions
- Theory: weakest exceptional preconditions
- Theory: domain properties
- Discussion: “Java vs. Eiffel” style exceptions
- Patterns: masking, propagating, flagging, rollback, degraded service, recovery block, repeated attempts, conditional retry
- Theory: total and “partial” correctness assertions
- Application: Eiffel
- Theory: Algebraic Laws

The Problem of Undefinedness

- If E = E is true, then is x div y = x div y also true, as in:

```
b := (x div y = x div y)
```

- If $P \land Q \equiv Q \land P$ is true, then are the following the same:

```
var a : array N of T ;
var n := 0 ;
while a(n) ≠ key and n < N do
    n := n + 1
```

```
...
...
while n < N and a(n) ≠ key do
    n := n + 1
```

- Our solution is to distinguish

  terms in the logic ↔ expressions in programs

  and in particular:

  predicates (boolean terms) ↔ boolean expressions

Terms vs Expressions

- Terms in the logic, here higher-order logic:
  - used to reason about programs
  - all familiar laws hold: $P = P \quad P \wedge Q \equiv Q \wedge P \quad P \vee \neg P$
- Expressions in programs:
  - "look like terms", but may be undefined
  - ΔE: the definedness of E
  - 'E': the value of E
  - include conditional and, or as well as strict &, |

Definedness and Value of Expressions ...

Let c be a constant, x a variable, and assume a : array N of T:

Δc	$\equiv$ <u>true</u>	‘c’	$=$ c
Δx	$\equiv$ <u>true</u>	‘x’	$=$ x
$\Delta a(E)$	$\equiv \Delta E \wedge 0 \leq$ ‘E’ $< N$	‘a(E)’	$=$ a(E)
Δ-E	$\equiv \Delta E$	‘-E’	$=$ -E
$\Delta\neg E$	$\equiv \Delta E$	‘¬E’	$= \neg E$
$\Delta(E \cdot F)$	$\equiv \Delta E \wedge \Delta F$	‘E · F’	$= E \cdot F$
Δ(E <u>div</u> F)	$\equiv \Delta E \wedge \Delta F \wedge$ ‘F’ $\neq 0$	‘E <u>div</u> F’	$=$ E <u>div</u> F
Δ(E <u>mod</u> F)	$\equiv \Delta E \wedge \Delta F \wedge$ ‘F’ $\neq 0$	‘E <u>mod</u> F’	$=$ E <u>mod</u> F
$\Delta(E + F)$	$\equiv \Delta E \wedge \Delta F$	‘E + F’	$= E + F$
$\Delta(E - F)$	$\equiv \Delta E \wedge \Delta F$	‘E – F’	$= E - F$
$\Delta(E = F)$	$\equiv \Delta E \wedge \Delta F$	‘E = F’	$= E = F$
...			

we will leave out the ‘quotes’ as structure is preserved

With bounded arithmetic:

$$\Delta(E \cdot F) \equiv \Delta E \wedge \Delta F \wedge \text{minint} \leq E \cdot F \leq \text{maxint}$$

... Definedness and Value of Expressions

Let c be a constant, x a variable, and assume a : array N of T:

$\Delta(E \text{ \underline{and} } F)$	$\equiv \Delta E \wedge (E \Rightarrow \Delta F)$	‘E and F’	$= E \wedge F$	conditional
$\Delta(E \text{ \underline{or} } F)$	$\equiv \Delta E \wedge (\neg E \Rightarrow \Delta F)$	‘E or F’	$= E \vee F$	operators
$\Delta(E \,\&\, F)$	$\equiv \Delta E \wedge \Delta F$	‘E & F’	$= E \wedge F$	strict
$\Delta(E \mid F)$	$\equiv \Delta E \wedge \Delta F$	‘E | F’	$= E \vee F$	operators

Some laws:

$\neg(E \text{ \underline{and} } F) = \neg E \text{ \underline{or} } \neg F$

$\neg(E \text{ \underline{or} } F) = \neg E \text{ \underline{and} } \neg F$

	Dijkstra	Eiffel	Java
and	cand	and then	&&
or	cor	or else	||

Weakest Preconditions

$\underline{wp}(S, Q) \equiv$ weakest precondition such that S terminates with postcondition Q

Let Q be a predicate, $\underline{x}$ a list of variables, $\underline{E}$ a list of expressions, and S, T statements:

$\underline{wp}(\underline{abort}, Q)$	$\equiv \underline{false}$	aborting statement
$\underline{wp}(\underline{stop}, Q)$	$\equiv \underline{true}$	blocking statement
$\underline{wp}(\underline{skip}, Q)$	$\equiv Q$	identity statement
$\underline{wp}(\underline{x} := \underline{E}, Q)$	$\equiv \Delta\underline{E} \wedge Q[\underline{x} \backslash \underline{E}]$	multiple assignment
$\underline{wp}(\underline{x} :\in \underline{E}, Q)$	$\equiv \Delta\underline{E} \wedge (\forall \underline{x'} \in \underline{E} \bullet Q[\underline{x} \backslash \underline{x'}])$	nondeterministic ass.
$\underline{wp}(S ; T, Q)$	$\equiv \underline{wp}(S, \underline{wp}(T, Q))$	sequential composition
$\underline{wp}(S \sqcap T, Q)$	$\equiv \underline{wp}(S, Q) \wedge \underline{wp}(T, Q)$	binary choice

Weakest Preconditions of Conditional and Iteration

Let B be boolean expression:

$$\underline{wp}(\underline{if}\ B\ \underline{then}\ S\ \underline{else}\ T, Q) \equiv \Delta B \wedge (B \Rightarrow \underline{wp}(S, Q)) \wedge (\neg B \Rightarrow \underline{wp}(T, Q))$$

Let V be an integer term and v an auxiliary variable. If

$$B \wedge P \wedge V = v \Rightarrow \underline{wp}(S, P \wedge V < v)$$
$$B \wedge P \Rightarrow V > 0$$
$$P \Rightarrow B$$

P is invariant
V is variant

then:

$$P \Rightarrow \underline{wp}(\underline{while}\ B\ \underline{do}\ S, \neg B \wedge P)$$

Example: Linear Search in Array

Assume a : <u>array</u> N <u>of</u> T and let:

$P \equiv N \geq 0$

$S = n := 0 ;$ <u>while</u> $n < N$ <u>and</u> $a(n) \neq key$ <u>do</u> $n := n + 1$

$Q \equiv 0 \leq n \leq N \wedge (\forall\, i \mid 0 \leq i < n \bullet a(i) \neq key) \wedge (n < N \Rightarrow a(n) = key)$

Then we can show

$P \Rightarrow$ <u>wp</u>(S, Q)

using

invariant: $0 \leq n \leq N \wedge (\forall\, i \mid 0 \leq i < n \bullet a(i) \neq key)$

variant: $N - n$

Weakest Exceptional Preconditions ...

$\underline{wp}(S, Q, R) \equiv$ weakest precondition such that S terminates and
– on normal termination Q holds finally,
– on exceptional termination R holds finally.

Let Q, R be predicates, $\underline{x}$ a list of variables, $\underline{E}$ a list of expressions, and S, T statements:

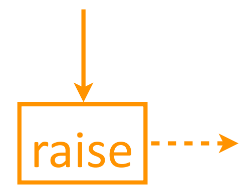
$$\underline{wp}(\underline{abort}, Q, R) \equiv \underline{false}$$

$$\underline{wp}(\underline{stop}, Q, R) \equiv \underline{true}$$

$$\underline{wp}(\underline{skip}, Q, R) \equiv Q$$

$$\underline{wp}(\underline{raise}, Q, R) \equiv R$$

raising exception

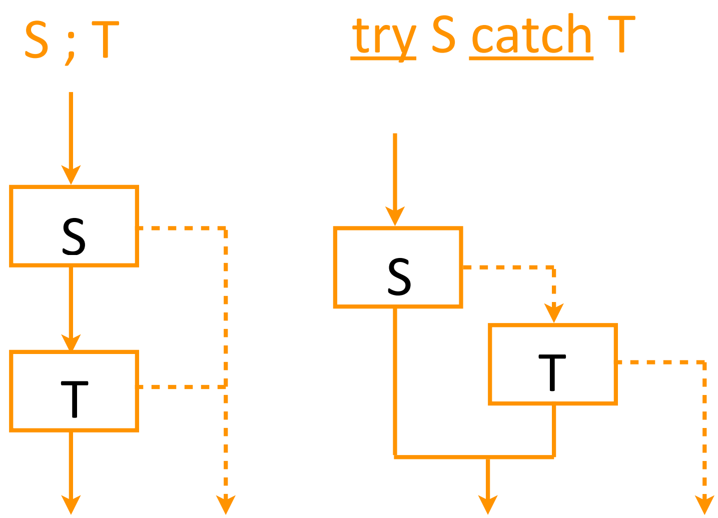


$$\underline{wp}(\underline{x} := \underline{E}, Q, R) \equiv (\Delta\underline{E} \Rightarrow Q[\underline{x} \backslash \underline{E}]) \wedge (\neg\Delta\underline{E} \Rightarrow R)$$

$$\underline{wp}(\underline{x} :\in \underline{E}, Q, R) \equiv \Delta\underline{E} \wedge (\forall\, \underline{x'} \in \underline{E} \bullet Q[\underline{x} \backslash \underline{x'}]) \wedge (\neg\Delta\underline{E} \Rightarrow R)$$

$$\underline{wp}(S \sqcap T, Q, R) \equiv \underline{wp}(S, Q, R) \wedge \underline{wp}(T, Q, R)$$

Weakest Exceptional Precondition of Sequential and Exceptional Composition



<u>wp</u>(S ; T, Q, R) ≡ <u>wp</u>(S, <u>wp</u>(T, Q, R), R)

<u>wp</u>(<u>try</u> S <u>catch</u> T, Q, R) ≡ <u>wp</u>(S, Q, <u>wp</u>(T, Q, R))

exceptional composition

Weakest Exceptional Precondition of Conditional and Iteration

$$\underline{wp}(\underline{if}\ B\ \underline{then}\ S\ \underline{else}\ T, Q, R) \equiv \begin{array}{l} (\Delta B \wedge B \Rightarrow \underline{wp}(S, Q, R)) \wedge \\ (\Delta B \wedge \neg B \Rightarrow \underline{wp}(T, Q, R)) \wedge \\ (\neg\Delta B \Rightarrow R) \end{array}$$

If

$$\begin{array}{lll} \Delta B \wedge B \wedge P \wedge V = v & \Rightarrow & wp(S, P \wedge V < v, R) \\ \Delta B \wedge B \wedge P & \Rightarrow & V > 0 \\ \neg\Delta B \wedge P & \Rightarrow & R \end{array}$$

P is invariant

V is variant

then:

$$P \Rightarrow wp(\underline{while}\ B\ \underline{do}\ S, \neg B \wedge P, R)$$

Properties of Weakest Exceptional Preconditions

Reduction: If S contains neither raise nor try-catch statements, then:

$$\underline{wp}(S, Q) \equiv \underline{wp}(S, Q, \underline{false})$$

Conjunctivity:

$$\underline{wp}(S, Q, R) \wedge \underline{wp}(S, Q', R') \equiv \underline{wp}(S, Q \wedge Q', R \wedge R')$$

Monotonicity:

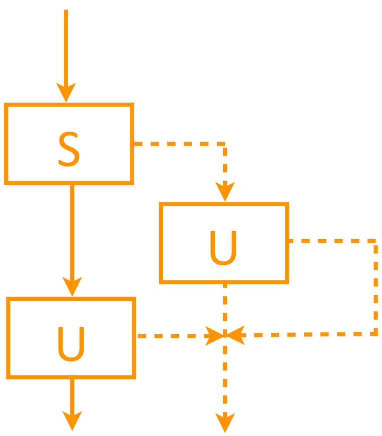
if $Q \Rightarrow Q'$ and $R \Rightarrow R'$ then $\underline{wp}(S, Q, R) \Rightarrow \underline{wp}(S, Q', R')$

Separation:

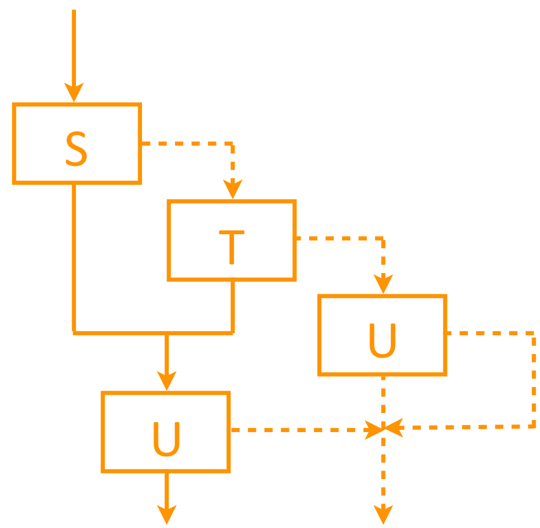
$$\underline{wp}(S, \underline{true}, R) \wedge \underline{wp}(S, Q, \underline{true}) \equiv \underline{wp}(S, Q, R)$$

Derived Statements

try S finally U



try S catch T finally U



a(E) := F = a := a(E ← F)

if B then S = if B then S else skip

assert B = if ¬B then raise

try S finally U = try S catch (U ; raise) ; U

try S catch T finally U = try S catch try T catch (U ; raise) ; U

= try (try S catch T) finally U

Domains

$\underline{tr}\ S = \underline{wp}(S, \underline{true}, \underline{true})$	termination
$\underline{nr}\ S = \underline{wp}(S, \underline{true}, \underline{false})$	normal termination
$\underline{ex}\ S = \underline{wp}(S, \underline{false}, \underline{true})$	exceptional termination
$\underline{en}\ S = \neg\underline{wp}(S, \underline{false}, \underline{false})$	enabledness

Properties:

$\underline{tr}\ \underline{abort} \equiv \underline{false}$	$\underline{tr}\ \underline{stop} \equiv \underline{true}$	$\underline{tr}\ \underline{skip} \equiv \underline{true}$	$\underline{tr}\ \underline{raise} \equiv \underline{true}$
$\underline{nr}\ \underline{abort} \equiv \underline{false}$	$\underline{nr}\ \underline{stop} \equiv \underline{true}$	$\underline{nr}\ \underline{skip} \equiv \underline{true}$	$\underline{nr}\ \underline{raise} \equiv \underline{false}$
$\underline{ex}\ \underline{abort} \equiv \underline{false}$	$\underline{ex}\ \underline{stop} \equiv \underline{true}$	$\underline{ex}\ \underline{skip} \equiv \underline{false}$	$\underline{ex}\ \underline{raise} \equiv \underline{true}$
$\underline{en}\ \underline{abort} \equiv \underline{true}$	$\underline{en}\ \underline{stop} \equiv \underline{false}$	$\underline{en}\ \underline{skip} \equiv \underline{true}$	$\underline{en}\ \underline{raise} \equiv \underline{true}$

$\underline{tr}(x := E) \equiv \underline{true}$	$\underline{tr}(S\ ;\ T) \Rightarrow \underline{tr}\ S$	$\underline{tr}(S \sqcap T) \equiv \underline{tr}\ S \wedge \underline{tr}\ T$
$\underline{nr}(x := E) \equiv \Delta E$	$\underline{nr}(S\ ;\ T) \Rightarrow \underline{nr}\ S$	$\underline{nr}(S \sqcap T) \equiv \underline{nr}\ S \wedge \underline{nr}\ T$
$\underline{ex}(x := E) \equiv \neg\Delta E$	$\underline{ex}(S\ ;\ T) \Leftarrow \underline{ex}\ S$	$\underline{ex}(S \sqcap T) \equiv \underline{ex}\ S \wedge \underline{ex}\ T$
$\underline{en}(x := E) \equiv \underline{true}$	$\underline{en}(S\ ;\ T) \Rightarrow \underline{en}\ S$	$\underline{en}(S \sqcap T) \equiv \underline{en}\ S \vee \underline{en}\ T$

...

Total Correctness Assertion

$$\{P\}\ S\ \{Q, R\} \equiv P \Rightarrow wp(S, Q, R)$$

$$\{P\}\ S\ \{Q\} \equiv P \Rightarrow \underline{wp}(S, Q, \underline{false})$$

Example of annotation:

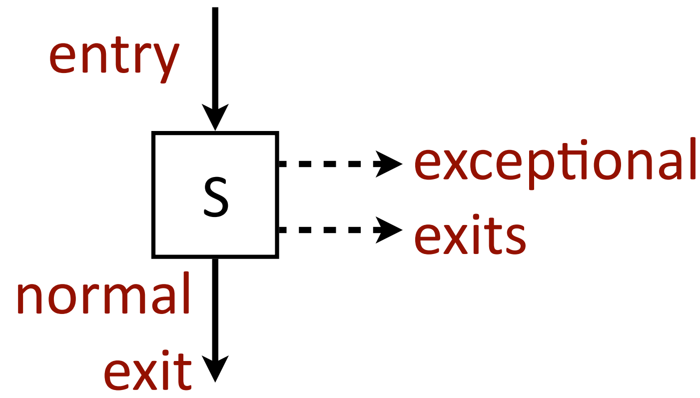
$\{P\}$	$\Leftarrow$	$\{P_1\}\ S_1\ \{Q_1, R_1\} \wedge$
<u>try</u>		$\{P_2\}\ S_2\ \{Q_2, R_2\} \wedge$
$\quad\{P_1\}$		$(P \Rightarrow P_1) \wedge$
$\quad S_1$		$(R_1 \Rightarrow P_2) \wedge$
$\quad\{Q_1, R_1\}$		$(R_2 \Rightarrow R) \wedge$
<u>catch</u>		$(Q_1 \Rightarrow Q) \wedge$
$\quad\{P_2\}$		$(Q_2 \Rightarrow Q)$
$\quad S_2$		
$\quad\{Q_2, R_2\}$		
$\{Q, R\}$		

Example: Saturating Vector Division

```
{true}
    i := 0
    {i = 0}
    ;
    {invariant I:
        i ∈ [0, n] ∧ ∀ j ∈ [0, i) • (b(j) ≠ 0 ∧ c(j) = a(j) div b(j)) ∨ (b(j) = 0 ∧ c(j) = maxint)}
    {variant V: n – i}
    while i < n do
        {i < n ∧ I ∧ V = v}
            try
                c(i) := a(i) div b(i)
                {i < n ∧ I ∧ b(j) ≠ 0 ∧ c(i) = a(i) div b(i) ∧ V = v, i < n ∧ I ∧ b(i) = 0 ∧ V = v}
            catch
                {i < n ∧ I ∧ b(i) = 0 ∧ V = v}
                c(i) := maxint
                {i < n ∧ I ∧ b(i) = 0 ∧ c(i) = maxint ∧ V = v}
            {i < n ∧ I ∧ ((b(i) ≠ 0 ∧ c(i) = a(i) div b(i)) ∨ (b(i) = 0 ∧ c(i) = maxint)) ∧ V = v}
            ;
            i := i + 1
        {I ∧ V < v}
    {i ≥ n ∧ I}
{∀ j ∈ [0, n) . (b(j) ≠ 0 ∧ c(j) = a(j) div b(j)) ∨ (b(j) = 0 ∧ c(j) = maxint)}
```

Method Specifications ...

One precondition +
one postcondition for each exit
(Cristian 1984)




```
public static void int search(int[] a, int x)
   throws NullPointerException, NotFoundException
/* requires: a is sorted
   ensures:  0 <= result < a.length && a[result] == x
   signals NullPointerException: a == null
   signals NotFoundException: x not in a
*/
[Liskov & Guttag 00, Leavens et al 06:JML, Barnet et al 05:Spec#]
```

All possible failures would need to be anticipated: impractical

- tools do not verify “unchecked” exceptions (Jacobs & Müller 2007)
- typical use as control structure for undesired or rare cases

In Eiffel methods have only one exceptional exit (Meyer 1997)

- specified with a precondition and a single postcondition
- exceptional exit taken if postcondition not established
- “valid” outcome even in presence of unanticipated failures

```
method is
   require
      pre
   do
      body
   ensure
      post
   rescue
      handler
```

We further elaborate on this view.

Pattern: Masking

<u>try</u> request next command
<u>catch</u> command := help

desired (but possibly weakened) postcondition is always established

If

{P} S {Q, H}
{H} T {Q}

then:

{P} <u>try</u> S <u>catch</u> T {Q}

Pattern: Masking with Re-raising

<u>try</u> process file A and output file B
<u>catch</u> (delete file B ; <u>raise</u>)

in a modular design, each module restores a consistent state before passing on the exception

If

{P} S {Q, H}
{H} T {R, R}

then:

{P} <u>try</u> S <u>catch</u> (T ; <u>raise</u>) {Q, R}

Pattern: Flagging

<u>try</u> (process file A and output file B ; done := <u>true</u>)
<u>catch</u> (delete file B ; done := <u>false</u>)

occurrence of exception is recorded for further actions

If

$\{P\}\ S\ \{Q, H\}$
$\{H\}\ T\ \{R\}$

then:

$\{P\}$
<u>try</u> (S ; done := <u>true</u>) <u>catch</u> (T ; done := <u>false</u>)
$\{(done \wedge Q) \vee (\neg done \wedge R)\}$

Pattern: Rollback with Masking

u0, v0, w0 := u, v, w ;
<u>try</u> display form for entering u, v, w
<u>catch</u> u, v, w := u0, v0, w0

prevents that an inconsistent state, e.g. broken invariant, or undesirable state, e.g. that only allows termination, is left

If

$\{P\}$ backup $\{P \land B\}$
$\{B\}$ restore $\{P\}$
$\{P \land B\}$ S $\{Q, B\}$
$\{P\}$ T $\{Q\}$

B = backup available

T can "clean up"

then:

$\{P\}$ backup ; <u>try</u> S <u>catch</u> (restore ; T) $\{Q\}$

Pattern: Rollback with Propagation

like rollback with masking, but backup is allowed to fail

B = backup available

If

$\{P\}$ backup $\{P \wedge B, P\}$

$\{B\}$ restore $\{P, P\}$

$\{P \wedge B\}$ S $\{Q, B\}$

then:

$\{P\}$ backup ; <u>try</u> S <u>catch</u> (restore ; <u>raise</u>) $\{Q, P\}$

Interlude: Partial Correctness

If {P} S {Q, P}, then S is partially correct with respect to P, Q.

Several patterns ensure partial correctness.

Eiffel method specifications can be understood as partial correctness specifications.

```
method is
   require
      pre
   do
      body
   ensure
      post
   rescue
      handler
```

Pattern: Degraded Service

```
try              -- try the simplest formula, will work most of the time
        z := √(x² + y²)
catch -- overflow or underflow has occurred
        try
                m := max(abs(x), abs(y)) ;
                try              -- try the formula with scaling
                        t := √((x / m)² + (y / m)²)
                catch -- underflow has occurred
                        t := 1 ;
                z := m × t
        catch -- overflow on unscaling has occurred
                z := +∞ ;
                raise
```

(Hull et al 1994)

several statements achieve the same goal, but one some are preferred over others; if the first one fails, we fall back to a less desirable one

If

$\{P\}\ S_1\ \{Q, H_1\}$

$\{H_1\}\ S_2\ \{Q, H_2\}$

$\{H_2\}\ S_3\ \{Q, R\}$

then:

$\{P\}\ \underline{\text{try}}\ S_1\ \underline{\text{catch}}\ (\underline{\text{try}}\ S_2\ \underline{\text{catch}}\ S_3)\ \{Q, R\}$

Pattern: Recovery Block ...

(Horning et al 1974, Randell 1975)

ensure A
by S_1
else by S_2
else by S_3
else error

acceptance test

alternatives

backup ;
try (S_1 ; assert A)
catch
restore ;
try (S_2 ; assert A)
    catch
        restore ;
        try (S_3 ; assert A)
        catch (restore ; raise)

... Pattern: Recovery Block

If

$\{P\}$ backup $\{P \wedge B, P\}$	$\{P \wedge B\}\ S_1\ \{Q_1 \wedge B, B\}$	$Q_1 \wedge A_1 \Rightarrow Q$
$\{B\}$ restore $\{P \wedge B\}$	$\{P \wedge B\}\ S_2\ \{Q_2 \wedge B, B\}$	$Q_2 \wedge A_2 \Rightarrow Q$
	$\{P \wedge B\}\ S_3\ \{Q_3 \wedge B, B\}$	$Q_3 \wedge A_3 \Rightarrow Q$

then:

```
{P}
    backup ;
    try (S1 ; assert A1)
    catch
        restore ;
        try (S2 ; assert A2)
        catch
            restore ;
            try (S3 ; check A3)
            catch (restore ; raise)
{Q, P}
```

Repeated Attempts

ra = <u>while</u> n > 0 <u>do</u>
<u>try</u> (S ; n := –1)
<u>catch</u> (T ; n := n – 1) ;
<u>if</u> n = 0 <u>then</u> <u>raise</u>

If

$\{P\}\ S\ \{Q, R\}$
$\{R\}\ T\ \{P\}$

then:

$\{n \geq 0 \land P\}\ ra\ \{Q, P\}$

Repeated Attempts with Rollback

```
rr  =   backup ;
        while n > 0 do
            try (S ; n := –1)
            catch (restore ; n := n – 1) ;
        if n = 0 then raise
```

Assume that S, restore do not modify n. If

$\{P\}$ backup $\{P \wedge B, P\}$

$\{B\}$ restore $\{P \wedge B\}$

$\{P \wedge B\}$ S $\{Q, B\}$

then:

$\{n \geq 0 \wedge P\}$ rr $\{Q, P\}$

Conditional Retry

cr = done := false ;
<u>while</u> ¬done and B <u>do</u>
<u>try</u> (S ; done := true)
<u>catch</u> T ;
<u>if</u> ¬done <u>then</u> <u>raise</u>

Mimics Eiffel's rescue and retry statements

Assume that S preserves $V = v$. If

$\{\Delta B \wedge B \wedge P\}\ S\ \{Q, R\}$

$\{R \wedge V = v\}\ T\ \{P \wedge V < v\}$

$\Delta B \wedge B \wedge P \Rightarrow V > 0$

then:

$\{P\}\ cr\ \{Q, P\}$

Eiffel Example: Approximate Square Root

Let $p \equiv 0 \leq l < u \wedge l^2 \leq n < u^2$

```
sqrt(n, l, u : INTEGER) : INTEGER
    {p}
    local
        m : INTEGER
    {rescue invariant: p}
    {rescue variant: u – l }
    do
        {loop invariant: p}
        {loop variant: u – l}
        from until u – l = 1 loop
            m := l + (u – l) // 2
            {p ∧ m = (l + u) // 2}
            if n < m ∗ m then u := m else l := m end
            {p, p ∧ m = (l + u) // 2 ∧ n < m²}
        end
        {p ∧ u – l = 1}
        Result := l
    rescue
        {p ∧ m = (l + u) // 2 ∧ n < m²}
        u := m
        {p}
        retry
        {retry: p}
    end
    {Result² ≤ n < (Result + 1)²}
```

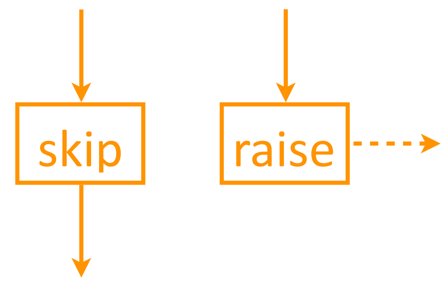
Eiffel statements have 3 exits:
- normal exit
- raising exception
- retrying method body

The retry exit leads to a loop structure, which necessitates invariant and variant

Retry (3rd) postcondition

Eiffel Statements

$$\underline{\text{wp}}(\underline{\text{skip}}, Q, R, U) \equiv Q$$
$$\underline{\text{wp}}(\underline{\text{raise}}, Q, R, U) \equiv R$$
$$\underline{\text{wp}}(\underline{\text{retry}}, Q, R, U) \equiv U$$



Most statements are unaffected by third exit, except the rescue-loop.

Let V be an expression over the naturals. If

$$\{P \land V = v\}\ S\ \{Q,\ H \land V = v,\ P \land V < v\}$$
$$\{H \land V = v\}\ T\ \{R,\ R,\ P \land V < v\}$$

P is the rescue invariant
V is the rescue variant

then:

$$\{P\}\ \underline{\text{do}}\ S\ \underline{\text{rescue}}\ T\ \underline{\text{end}}\ \{Q, R, U\}$$

Conclusions

- Despite putting forth best effort in the design, possibility of faults remains and programs need to respond to faults.
- Exception handling with try-catch statements allows systematic treatment of faults (c.f. resumption).
- Notion of partial correctness is methodological guide: either desired postcondition is established or precondition re-established.
- Exception patterns: masking, flagging, propagating, rollback, degraded service, recovery block, repeated attempts, conditional retry.
- Use of exception best reserved for truly exceptional situations rather than as an extra control structure.

Outlook ...

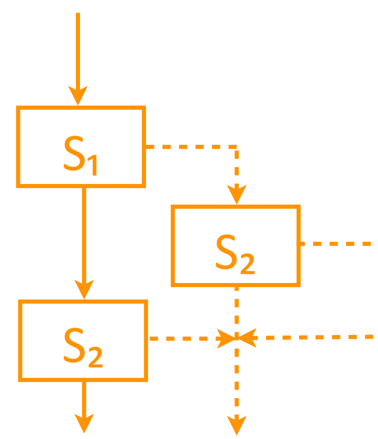
- try-catch-finally, intuitively:
  - catch statement ensures safety by establishing a consistent state,
  - finally statement ensures liveness by freeing all resources (freeing memory; closing files, windows, network connections).

$\{P\}$
try
    S_1
    $\{Q_1, R_1\}$
finally
    $\{Q_1\}$ $\{R_1\}$
    S_2
    $\{Q, R\}$ $\{R, R\}$
$\{Q, R\}$

$\Leftarrow$

$\{P\}\ S_1\ \{Q_1, R_1\} \wedge$
$\{Q_1\}\ S_2\ \{Q, R\} \wedge$
$\{R_1\}\ S_2\ \{R, R\}$

Two separate conditions needed for S_2!



... Outlook ...

- When an exception occurs, the condition in that situation is relevant, not the cause; exception types can be used to distinguish different conditions (cf causes of exceptions: supporting debugging, necessitates re-raising exceptions).

<u>try</u>
    ... $\{P\}\ x := x / y\ \{..., P\}$
    ... $\{Q\}\ a[i] := 0\ \{..., Q\}$
<u>catch</u>
    $\{P \vee Q\}$
    T

```
static int top() throws UnderflowException {
     try {return a[n-1];}
     catch (ArrayIndexOutOfBoundsException e)
        {throw new UnderflowException();}
  }
```

- Some exceptions may be more severe than others, e.g. may make repeated attempts futile: different exception types need to be distinguished.

<u>while</u> n > 0 <u>do</u>
    <u>try</u> (S ; n := –1)
    <u>catch</u> (T ; n := n – 1) ;
<u>if</u> n = 0 <u>then</u> <u>raise</u>

... Outlook

- Concurrent programs: in case of a fault in one thread/process, others may need to revert to a previous state as well. To prevent a ping-pong leading to reverting all the way to the initial state, certain checkpoints need to be established.

- Data abstraction and classes: class invariant has to be re-established, otherwise cascade of errors.

```
class BadStack
    public const C = 100
    private var a : array C of integer
    private var n := 0
    public method push(x : integer)
        a(n) := x ; n := n + 1          -- OK
    public method pop() : integer
        n := n – 1 ; result := a(n)     -- BAD, may break invariant 0 ≤ n ≤ C
    public method empty : boolean
        result := n = 0
    public method full : boolean
        result := n = C
```

OK

BAD, may break invariant $0 \leq n \leq C$

Further Reading

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