ETH Zürich

Chair of Software Engineering

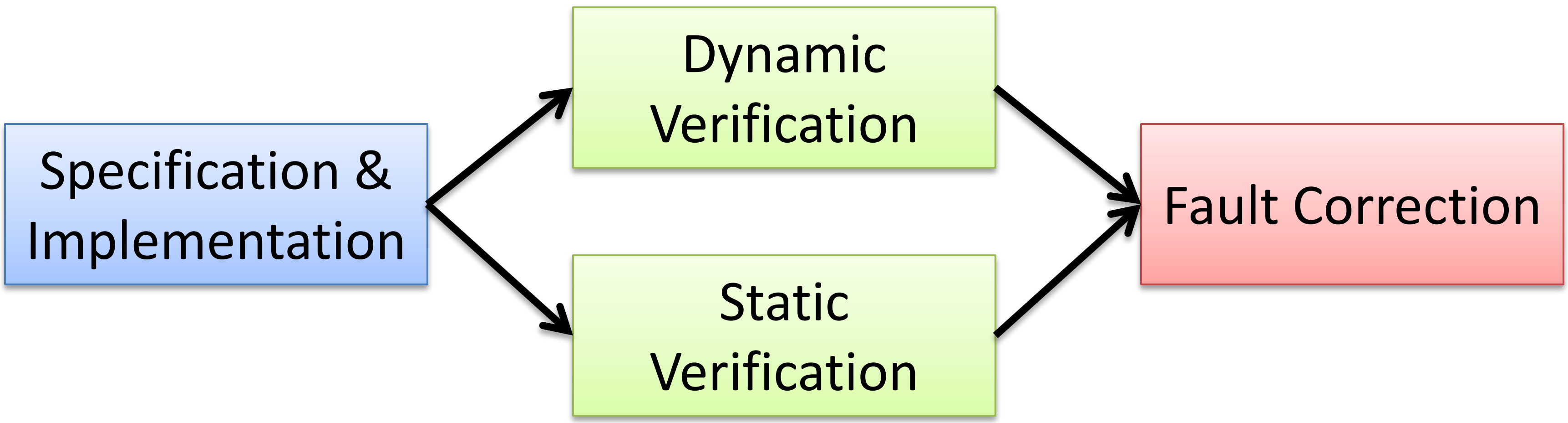
Automatic Verification of Computer Programs

these slides contain advanced material and are optional

What is verification

- Check correctness of the implementation given the specification
- Static verification
  - Check correctness without executing the program
  - E.g. static type systems, theorem provers
- Dynamic verification
  - Check correctness by executing the program
  - E.g. unit tests, automatic testing
- Automatic verification
  - Push-button verification

Overview



- Verification is just one part of the process
- All parts can (in theory) be automated

How to get the specification

- Need machine-readable specification for automatic verification (not just comments)
- Different variants:
  - Eiffel‘s „Design by Contract“
    - Built-in contracts
  - .Net 4.0 „Code Contracts“
    - Contracts implemented as a library
  - JML „Java Modeling Language“
    - Dialect of Java featuring contracts as special comments
  - D „Contracts”
    - Evolved from C++, built-in contracts

Contracts in different languages

Eiffel

```
deposit (amount: INTEGER)
  require
    amount >= 0
  do
    balance := balance + amount
  ensure
    balance = old balance + amount
  end
```

CodeContracts

```
public void deposit(int amount)
{
  Contract.Requires(amount >= 0);
  Contract.Ensures(balance ==
    Contract.OldValue<int>(balance)
    + amount);
  balance += amount;
}
```

JML

```
/*@
  requires amount >= 0;
  ensures
    balance == \old(balance)+amount
@*/
public void deposit(int amount) {
  balance += amount
}
```

D

```
function deposit(int amount)
__in {  assert(amount >= 0);
        int oldb = balance;  }
__out {
  assert(bal == oldb + amount);  }
__body {
  balance += amount
}
```

Specification – Verification – Correction

Writing full specifications

- Writing expressive specification is difficult
- Specifying full effect of routines

```
put (v: G; i: INTEGER)
  require   lower <= i and i <= upper
  ensure
    item (i) = v
    across lower |..| upper as j all
      j /= i implies item (j) = old item (j)
    end
  modifies  area
```

old not allowed in across expression

modifies not expressible in Eiffel

  - Describing what changes
  - Describing what does not change (frame condition)

MML and EiffelBase2

- Model-based contracts use mathematical notions for expressing full specifications

```
note
  model: map
class
  V_ARRAY [G]
...
end
```

```
map: MML_MAP [INTEGER, G]
    -- Map of keys to values.
  note
    status: specification
  do
    create Result
    across Current as it loop
      Result :=
  Result.updated (it.key, it.item)
    end
  end
```

```
put (v: G; i: INTEGER)
    -- Replace value at `i'.
  note
    modify: map
  require
    has_index (i)
  do
    at (i).put (v)
  ensure
    map |=| old map.updated (i, v)
  end
```

Contract inference

- Generate contracts based on implementation
- Dynamic contract inference
  - Infer contracts based on program runs
- Static contract inference
  - Infer contracts without running the program

Dynamic contract inference

- Location invariant – a property that always holds at a given point in the program

```
...
x := 0
...
```

$x = 0$

- Dynamic invariant inference – detecting location invariants from values observed during *execution*
- For pre- and postcondition inference, select routine entry and exit as program points

DAIKON example

- Uses templates for inferred contracts, e.g.

  `x = const`   `x >= const`   `x = y`

- Program point: `ACCOUNT.deposit::ENTER`
- Variables of interest: `balance`, `amount`
- Invariants:

  ~~`balance = 0`~~

  `balance >= 0`

  ~~`amount = 10`~~

  `amount >= 1`

  ~~`balance = amount`~~

- Samples

  `balance 0`   `amount 10`

  `balance 10`   `amount 20`

  `balance 30`   `amount 1`

Static contract inference

- Infer precondition from postcondition/body
  - Weakest precondition calculus
- Infer loop invariants from postcondition
  - Generate mutations from postcondition

```
bubble_sort (a: ARRAY [T])
  require
    a.count > 0
  ensure
    sorted (a)
    permutation (a, old a)
```

```
from i := n until i = 1
invariant
  1 <= i <= n
  sorted (a[i+1..n])
  permutation (a, old a)
loop
  -- move the largest eleme
  -- in 1..i to position i
end
```

Static analysis of program

Mutation from postcondition

Directly from postcondition

Dynamic verification

- Check that program satisfies its specification by executing the program
- Manual
  - Write unit tests (xUnit framework)
  - Execute program and click around
- Automatic
  - Random testing

Automatic testing with contracts

- Select routine under test
- Precondition used for input validation
  - Test is valid if it passes precondition
- Postcondition used as test oracle
  - Test is successful if it passes postcondition

Automatic testing with contracts

Test Input

↓

Test Execution

↓

Test Oracle

```
deposit (v: INTEGER)
    require
        v > 0
    do
        balance := balance + v
    ensure
        balance = old balance + v
    end
```

	Successful	Failed
Precondition	**Test valid**	Test invalid
Body	(see postcondition)	**Error in program**
Postcondition	**Test succesful**	**Error in program**

Random testing

- Create random objects
  - Call random creation procedure
  - Call random commands
  - For arguments, generate random input
- Basic types
  - Random numbers
  - Interesting values: max_value, 1, 0, -1, …

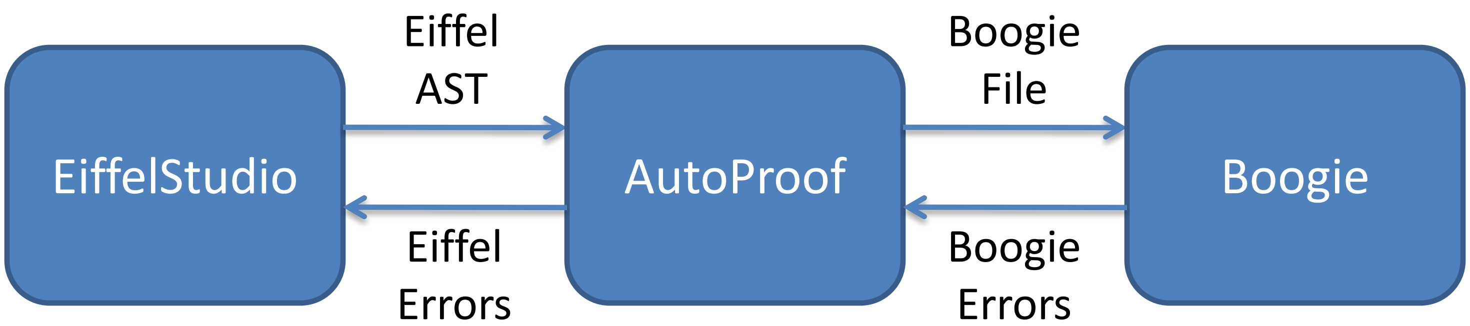
AutoTest

- Basic operation:
  - Record sequence of calls made to create objects
  - Call routine under test with different objects
  - If execution is ok, this is a successful test case
  - If a postcondition is violated, this is a failing test case
- Improve test case generation
  - Smarter input selection
    (e.g. use static analysis to select objects)
  - Test case minimization (removing unnecessary calls)
  - Build object pool
  - …

Static verification

- Need a model of the programming language
  - What is the effect of an instruction
- Translate program to a mathematical representation
- Use an automatic or interactive theorem prover to check that specification is satisfied in every possible execution

AutoProof process



- Translates AST from EiffelStudio to Boogie
- Uses Boogie verifier to check Boogie files
- Traces verification errors back to Eiffel source

AutoProof translation

```
make
  local
    a: ACCOUNT
  do
    create a.make
    check a.balance = 0 end
  end
```

```
implementation APPLICATION.make {
  var a;
entry:
  havoc a;
  assume (a!= Void) && (!Heap[a, $allocated]);
  Heap[a, $allocated] := true;
  Heap[a, $type] := ACCOUNT;
  call create.ACCOUNT.make(a);
  assert Heap[a, ACCOUNT.balance] = 0;
}
```

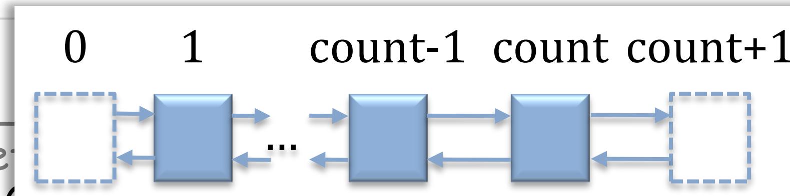
Automatic Fault Correction

- Build a test suite
  - Manual or automatic
- Find and localize faults
  - Failing test cases
  - Static analysis
- Try fixes
  - Apply fix templates with random code changes
- Validate fixes
  - Run test suite again, now all tests have to pass

AutoFix: model-based localization

- Abstract state as boolean queries
- Find differences between passing and failing tests

```
move_item (v: G)
        -- from TWO_WAY_
        -- Move `v' to the le
    require v /= Void ; has (v)
    local idx: INTEGER ; found: BOOLEAN
    do
        idx := index
        from start until found or after loop
            found := (v = item)
            if not found then forth end
        end
        remove
        go_i_th (idx)
        put_left (v)
    end
```



Invar. from passing

not is_empty
not before
not after
…

Invar. from failing

not is_empty
before
not after
…

AutoFix: instantiating fixes

- Fix schema for common fixes

```
if fail_condition then
   fixing_action
else
   original_instruction
end
```

```
if fail_condition then
   fixing_action
end
original_instruction
```

Instantiate

```
move_item (v: G)
   require v /= Void ; has (v)
   local idx: INTEGER ; found: BOOLEAN
   do
      idx := index
      from start until found or after loop
         found := (v = item)
         if not found then forth end
      end
      remove
      go_i_th (idx)
      put_left (v)
   end
```

```
if before then
   forth
end
put_left(v)
```

tion

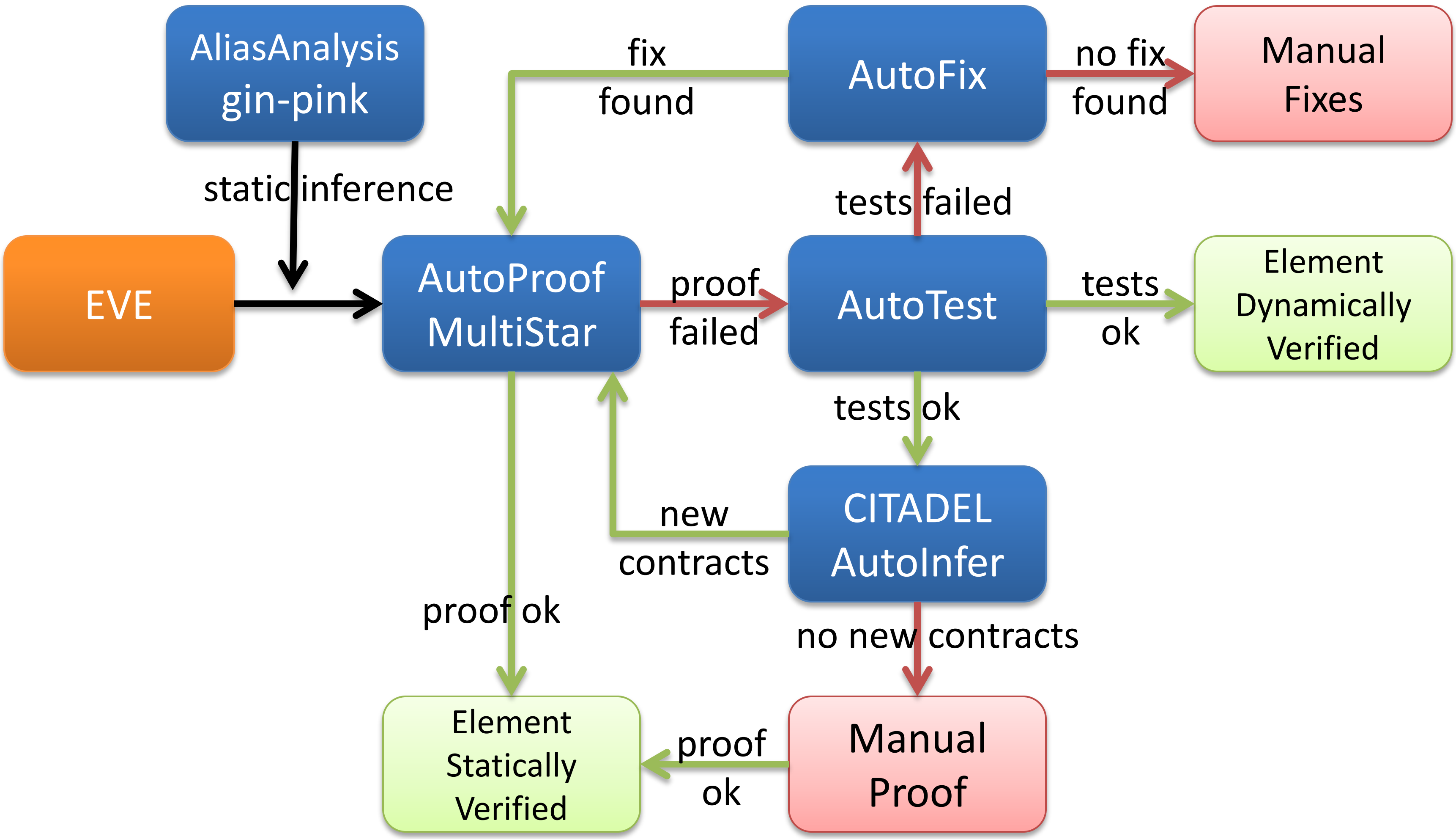
Demo

- AutoTest
- AutoProof
- AutoFix

Eiffel Verification Environment (EVE)

- Research branch of EiffelStudio
- Integrates most tools developed by us
  - AutoTest (dynamic verification)
  - AutoProof (static verification)
  - AutoFix (fault correction)
  - AutoInfer (dynamic contract inference)
  - MultiStar (static verification)
  - AliasAnalysis (static analysis)
- Other tools currently not integrated
  - CITADEL (dynamic contract inference)
  - gin-pink (static loop invariant inference)

Putting It All Together



References

- EVE: Eiffel Verification Environment
  http://se.inf.ethz.ch/research/eve/
- AutoTest, AutoProof, AutoFix, CITADEL, …
  http://se.inf.ethz.ch/research/
- CodeContracts
  http://research.microsoft.com/en-us/projects/contracts/
- Java Modeling Language (JML)
  http://www.cs.ucf.edu/~leavens/JML/
- D Programming Language
  http://dlang.org/
- Daikon
  http://groups.csail.mit.edu/pag/daikon/
- Boogie Verifier
  http://boogie.codeplex.com/