BERT: BEhavioral Regression Testing

Alessandro (Alex) Orso
School of CS -- College of Computing
Georgia Institute of Technology
http://www.cc.gatech.edu/~orso/

Tao Xie
Department of Computer Science
North Carolina State University
http://people.engr.ncsu.edu/txie/

Partially supported by: NSF, DHS, and US Air Force

2nd UPDATE: Amazon.com Web Site Down For Technical Reasons

June 06, 2008: 04:02 PM EST

DOWJONES

(Updated to add information from a company customer-service representative.)

NEW YORK -(Dow Jones)- Amazon.com Inc.'s (AMZN) Web site was down for more than an hour Friday afternoon and remained malfunctional at the time of this report.

An Amazon.com customer-service representative said the site wouldn't be fully functional for another one or two hours. She said the outage was due to an upgrade of the company's Web site, but didn't provide further details.

The company's Web site was completely down between at least 1:40 p.m. EDT to 3 p.m. before reappearing with partial functionality. Dow Jones Newswires employees were still unable to complete a full transaction on the site before getting an error message at the time of this report.

2nd UPDATE: Amazon.com Web Site Down For Technical Reasons

June 06, 2008: 04:02 PM EST

DOWJONES

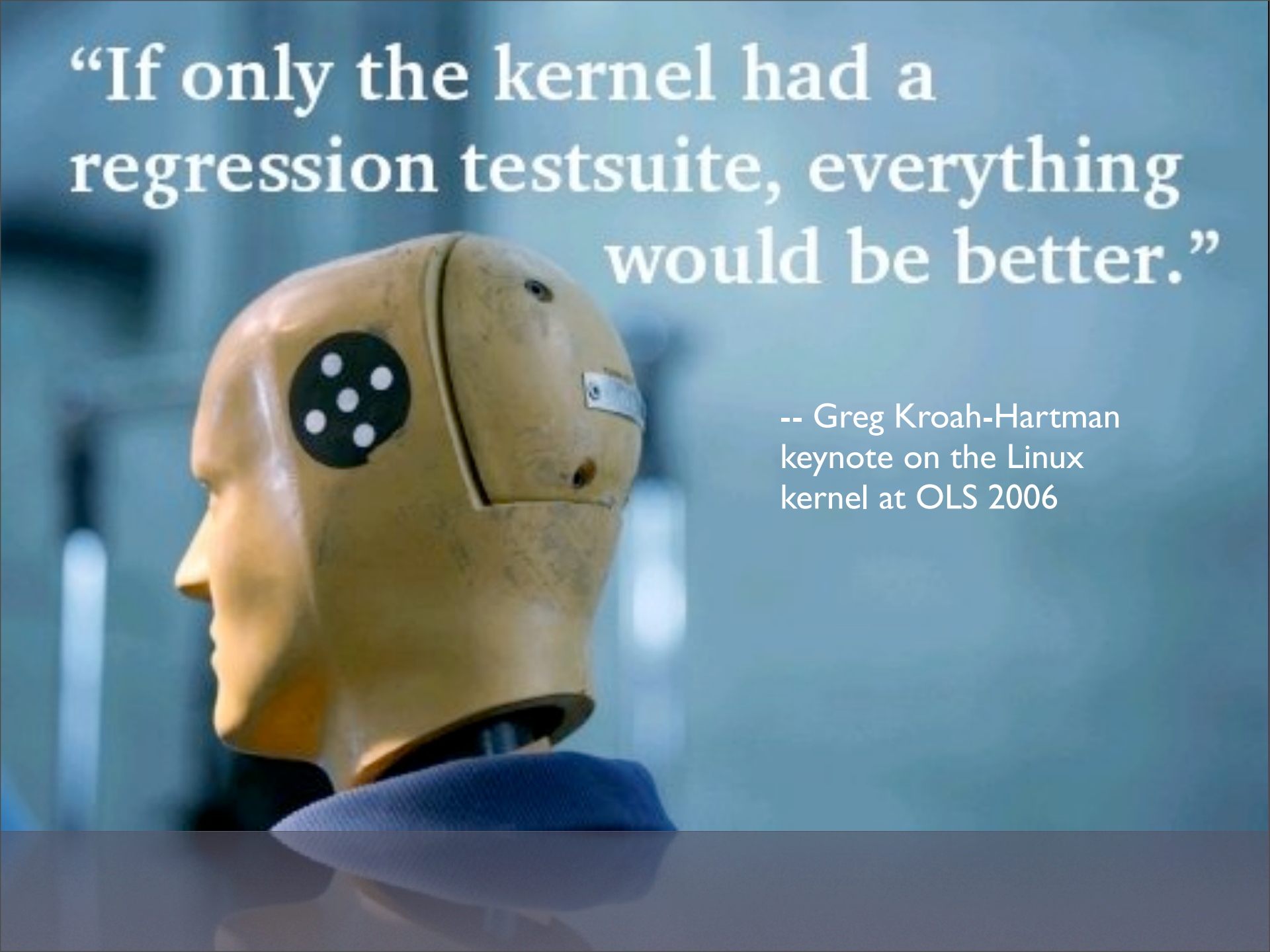
(Updated to add information from a company customer-service representative.)

NEW YORK -(Dow Jones)- Amazon.com Inc.'s (AMZN) Web site was down for more than an hour Friday afternoon and remained malfunctional at the time of this report.

An Amazon.com customer-service representative said the site wouldn't be fully functional for another one or two hours. She said the outage was due to an upgrade of the company's Web site, but didn't provide further details.

The company's Web site was completely down between at least 1:40 p.m. EDT to 3 p.m. before reappearing with partial functionality. Dow Jones Newswires employees were still unable to complete a full transaction on the site before getting an error message at the time of this report.


CNNMoney.com
A Service of CNN, Fortune & Money
Symbol
Get Quote
Keyword
Home
Business News
Markets
Personal Finance
Real Estate
Technology
Small Business
Luxury
2nd UPDATE: Amazon.com Web Site Down For Technical Reasons
June 06, 2008: 04:02 PM EST
DOWJONES
(Updated to add information from a company customer-service representative.)
NEW YORK -(Dow Jones)- Amazon.com Inc.'s (AMZN) Web site was down for more than an hour Friday afternoon and remained malf
[...] the outage was due to an upgrade of the company's Web site [...]
Dow Jones Newswires employees were still unable to complete a full transaction on the site before getting an error message at the time of this report.
Sponsored Links
Options Investing Streamlined
$9.95/Option + $0 per Contract, Any Size. Get Flat Rate Commissions!
An investor's best friend?
In a tough market, lean on Options. The investment with many advantages.
Refinance Now at 5.2% FIXED!
$200,000 mortgage under $599/mo. No


"If only the kernel had a regression testsuite, everything would be better."
-- Greg Kroah-Hartman keynote on the Linux kernel at OLS 2006

Regression Testing Process and Issues

Test suite T

Program P

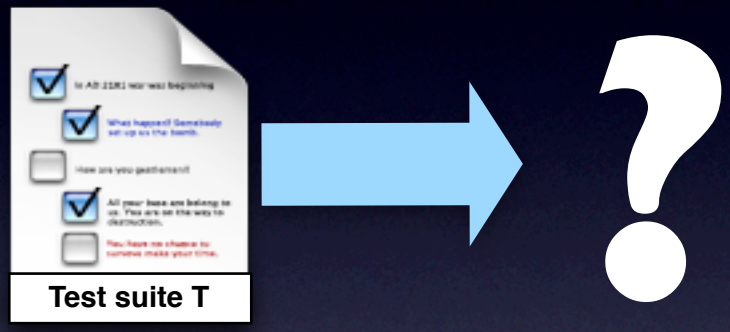
Regression Testing Process and Issues

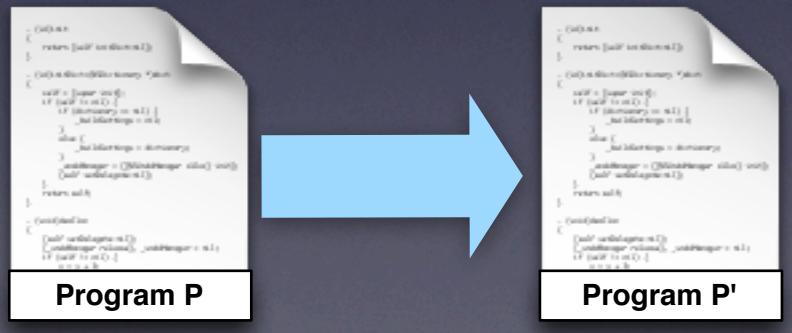
Test suite T

Program P

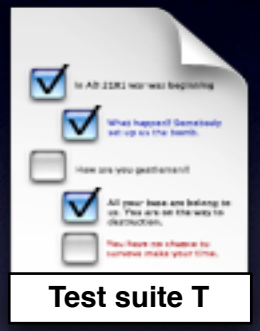
Program P'

Regression Testing Process and Issues

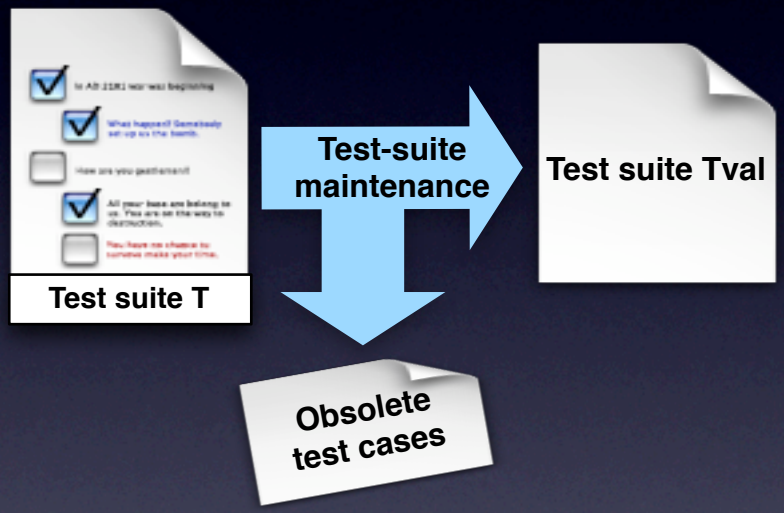




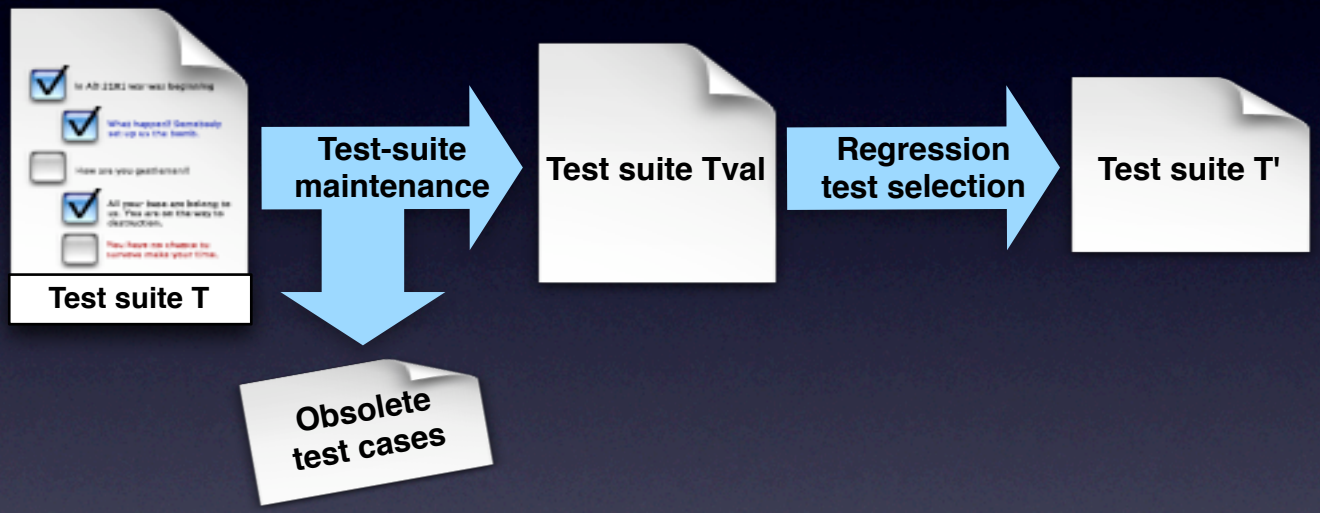
Regression Testing Process and Issues



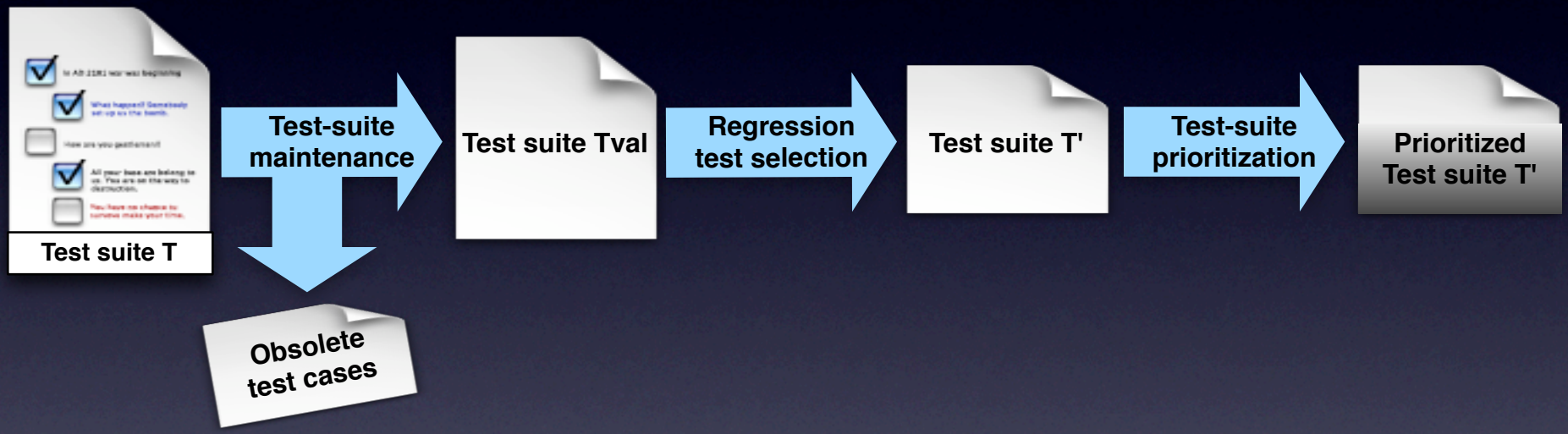
Regression Testing Process and Issues



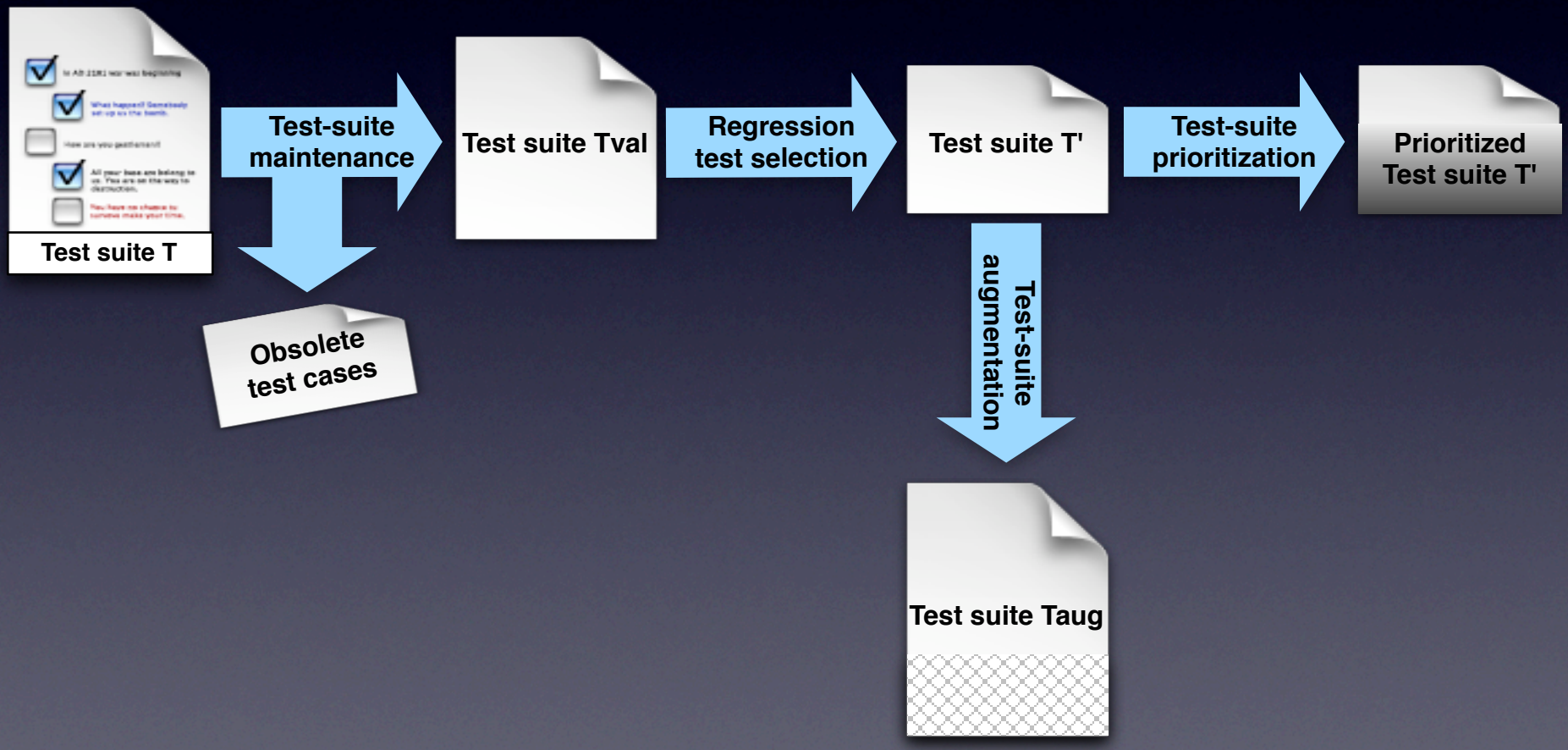
Regression Testing Process and Issues



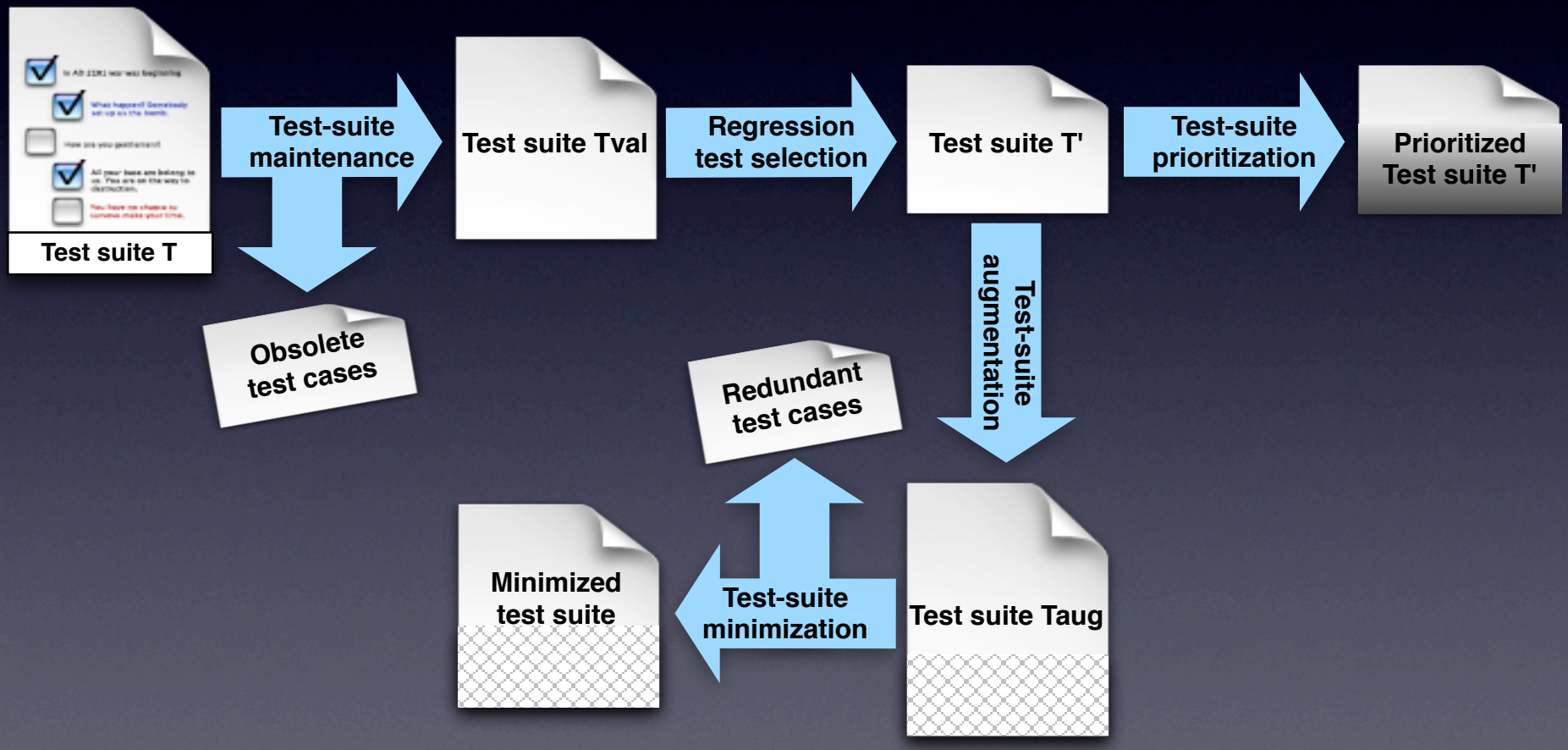
Regression Testing Process and Issues



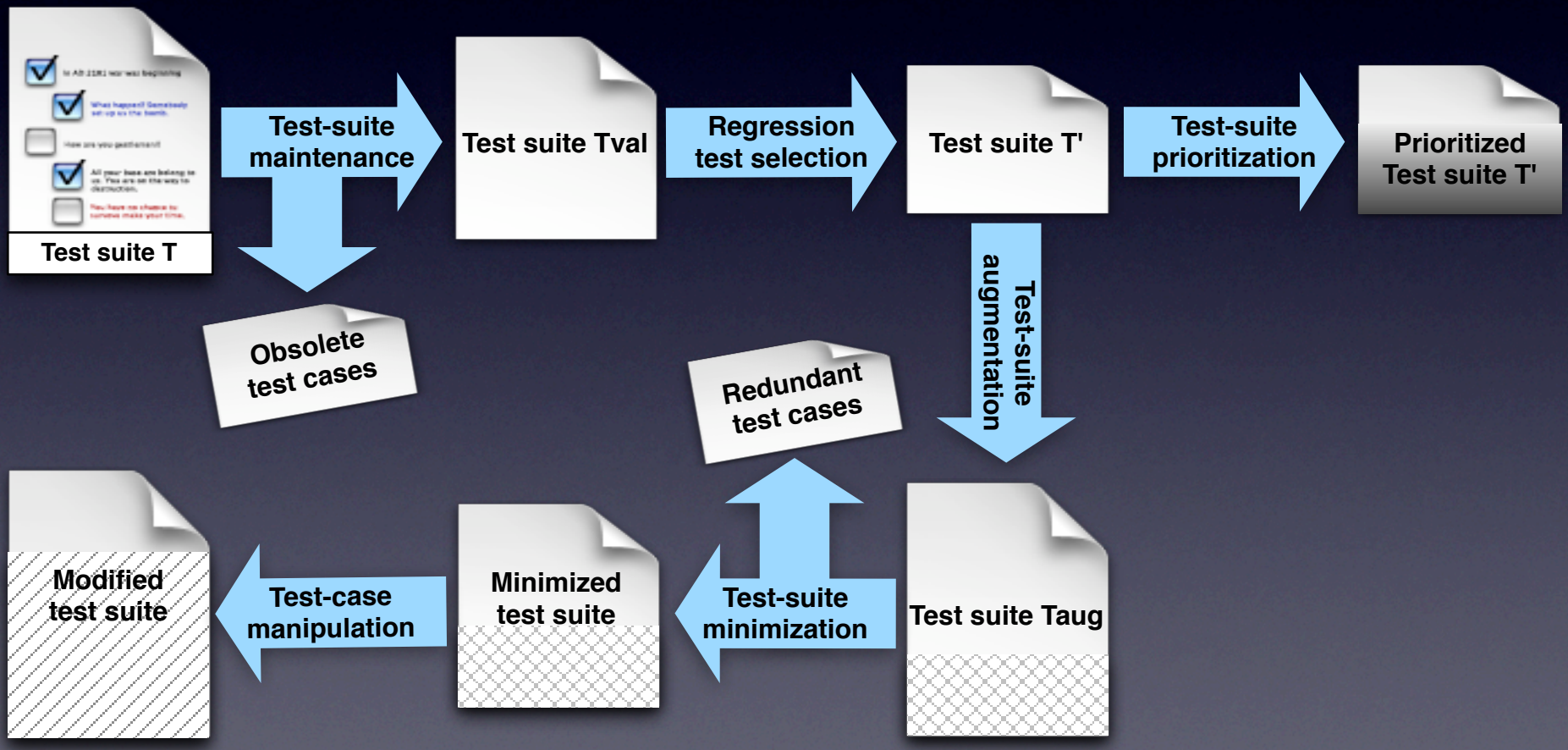
Regression Testing Process and Issues



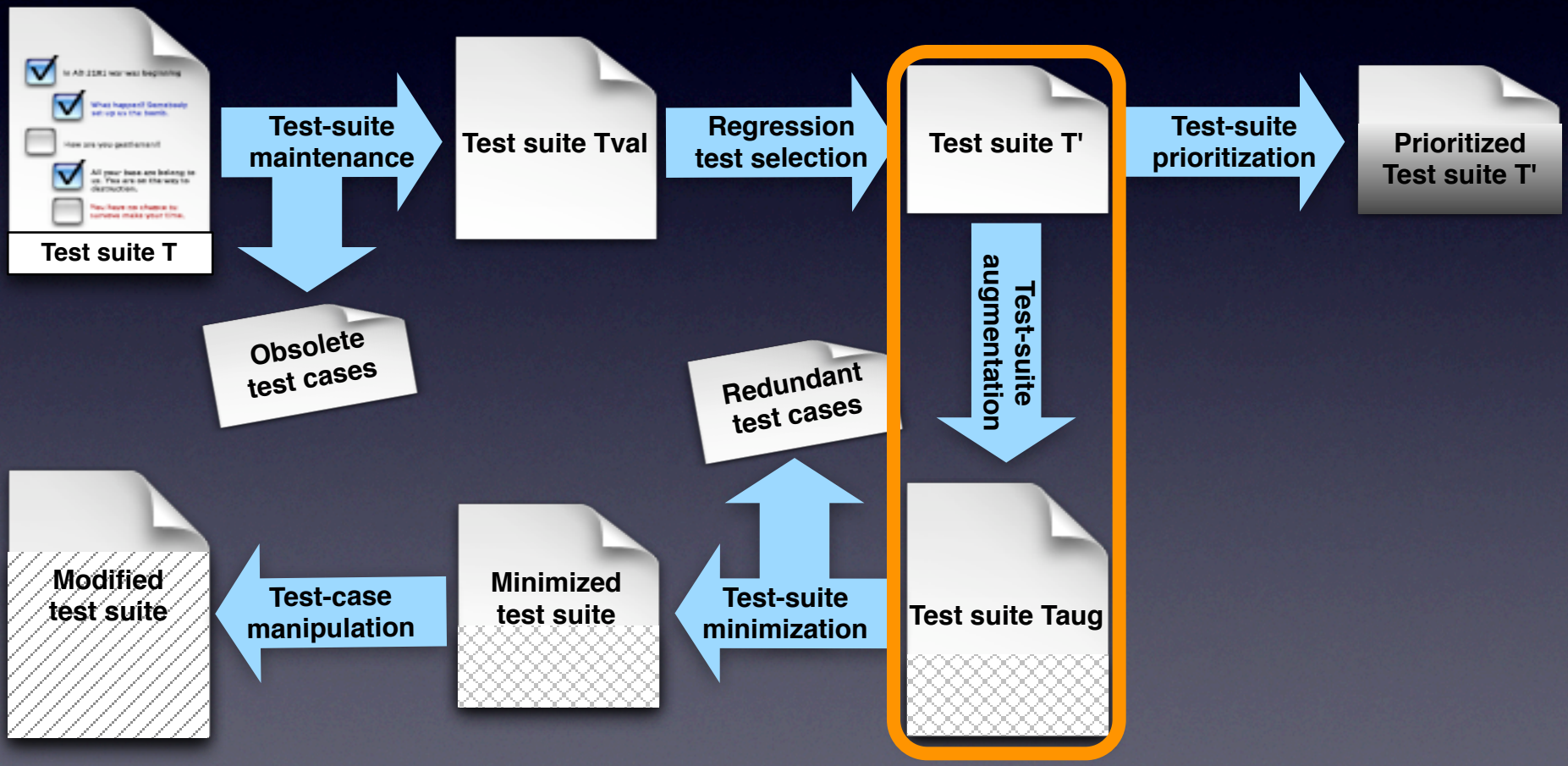
Regression Testing Process and Issues



Regression Testing Process and Issues



Regression Testing Process and Issues



Outline

- Introduction
- Our technique
- Experience
- Conclusion and future work

Outline

- Introduction
- Our technique
- Experience
- Conclusion and future work

Outline

- Introduction
- Our technique
- Experience
- Conclusion and future work

Traditional regression testing

Program P

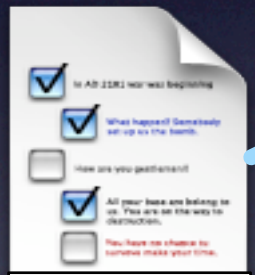
Program P'

Test suite T

Traditional regression testing

Program P

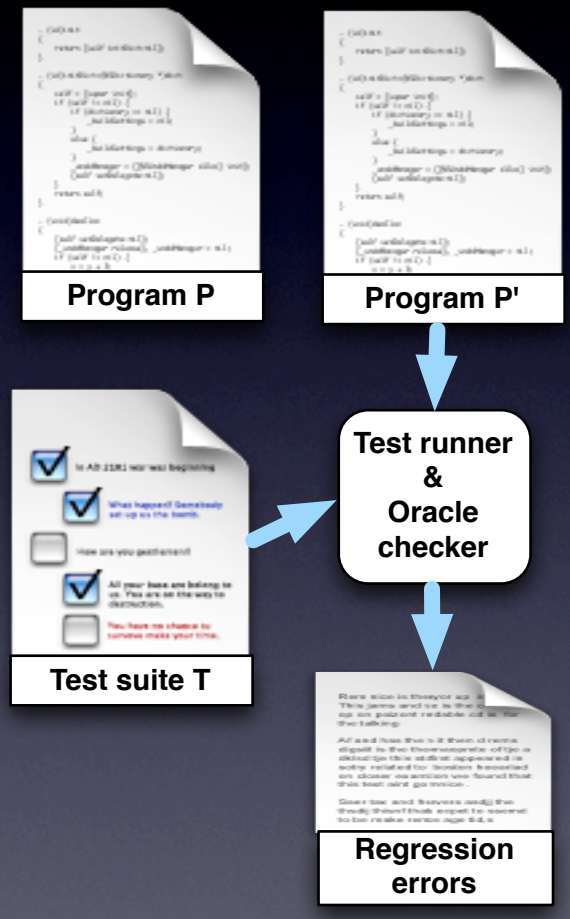
Program P'



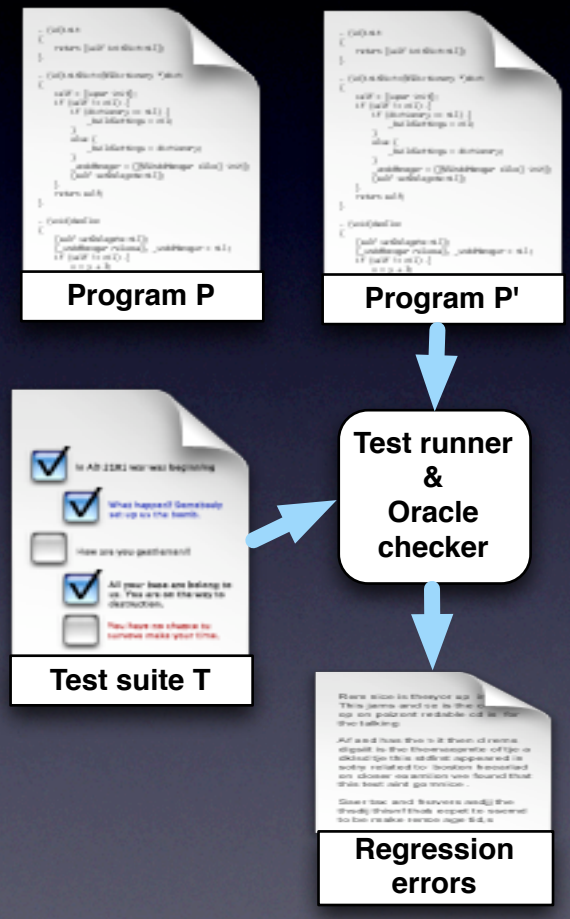
Test suite T

Test runner & Oracle checker

Traditional regression testing



Traditional regression testing




```
class BankAccount {
 double balance;

 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
   return true;
  } else {
   print("negative amount");
   return false;
  }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (balance < 0)
   print("account overdraft");
   return false;
  }
  balance = balance - amount;


  return true;
 }
}
```

```
class BankAccount {
 double balance;


 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
   return true;
  } else {
   print("negative amount");
   return false;
  }
 }
 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (balance < 0)
   print("account overdraft");
   return false;
  }
  balance = balance - amount;


  return true;
 }
}
```

```
class BankAccount {
 double balance;


 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
   return true;
  } else {
   print("negative amount");
   return false;
  }
 }
 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (balance < 0)
   print("account overdraft");
   return false;
  }
  balance = balance - amount;


  return true;
 }
}
```

```
class BankAccount {

 double balance;


 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
   return true;
  } else {
   print("negative amount");
   return false;
  }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (balance < 0)
   print("account overdraft");
   return false;
  }
  balance = balance - amount;


  return true;
 }
}
```

```
class BankAccount {

 double balance;
 bool isOverdraft;

 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
    return true;
   } else {
    print("negative amount");
    return false;
   }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (isOverdraft) {
   print("account overdraft");
   return false;
  }
  balance = balance - amount;
  if (balance < 0)
   isOverdraft = true;
  return true;
 }
}
```

```
class BankAccount {

 double balance;


 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
   return true;
  } else {
   print("negative amount");
   return false;
  }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (balance < 0)
   print("account overdraft");
   return false;
  }
  balance = balance - amount;


  return true;
 }
}
```

```
class BankAccount {

 double balance;
 bool isOverdraft;

 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
    return true;
   } else {
    print("negative amount");
    return false;
   }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (isOverdraft) {
   print("account overdraft");
   return false;
  }
  balance = balance - amount;
  if (balance < 0)
   isOverdraft = true;
  return true;
 }
}
```

```
class BankAccount {

 double balance;


 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
   return true;
  } else {
   print("negative amount");
   return false;
  }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (balance < 0)
   print("account overdraft");
   return false;
  }
  balance = balance - amount;


  return true;
 }
}
```

```
class BankAccount {

 double balance;
 bool isOverdraft;

 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
    return true;
   } else {
    print("negative amount");
    return false;
   }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (isOverdraft) {
   print("account overdraft");
   return false;
  }
  balance = balance - amount;
  if (balance < 0)
   isOverdraft = true;
  return true;
 }
}
```

```
class BankAccount {

 double balance;


 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
   return true;
  } else {
   print("negative amount");
   return false;
  }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (balance < 0)
   print("account overdraft");
   return false;
  }
  balance = balance - amount;


  return true;
 }
}
```

```
class BankAccount {

 double balance;
 bool isOverdraft;

 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
    return true;
   } else {
    print("negative amount");
    return false;
   }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (isOverdraft) {
   print("account overdraft");
   return false;
  }
  balance = balance - amount;
  if (balance < 0)
   isOverdraft = true;
  return true;
 }
}
```

Where is the fault?

```
class BankAccount {
 double balance;
 bool isOverdraft;
 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
    return true;
   } else {
    print("negative amount");
    return false;
   }
 }
 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (isOverdraft) {
   print("account overdraft");
   return false;
  }
  balance = balance - amount;
  if (balance < 0)
   isOverdraft = true;
  return true;
 }
}
```

```
class BankAccount {
 double balance;
 bool isOverdraft;
 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
    return true;
   } else {
    print("negative amount");
    return false;
   }
 }
 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (isOverdraft) {
   print("account overdraft");
   return false;
  }
  balance = balance - amount;
  if (balance < 0)
   isOverdraft = true;
  return true;
 }
}
```

```
...
void testBehavioralDifference() {
 BankAccount a =
             new BankAccount();
 a.deposit(10.00);
 a.withdraw(20.00);
 a.deposit(50.00);
 bool result = a.withdraw(20.00);
 assertEquals(result, true);
}
...
```

```
class BankAccount {
 double balance;
 bool isOverdraft;

 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
    return true;
   } else {
    print("negative amount");
    return false;
   }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (isOverdraft) {
   print("account overdraft");
   return false;
  }
  balance = balance - amount;
  if (balance < 0)
   isOverdraft = true;
  return true;
 }
}
```

```
...
void testBehavioralDifference() {
 BankAccount a =
              new BankAccount();
 a.deposit(10.00);
 a.withdraw(20.00);
 a.deposit(50.00);
 bool result = a.withdraw(20.00);
 assertEquals(result, true);
}
...
```

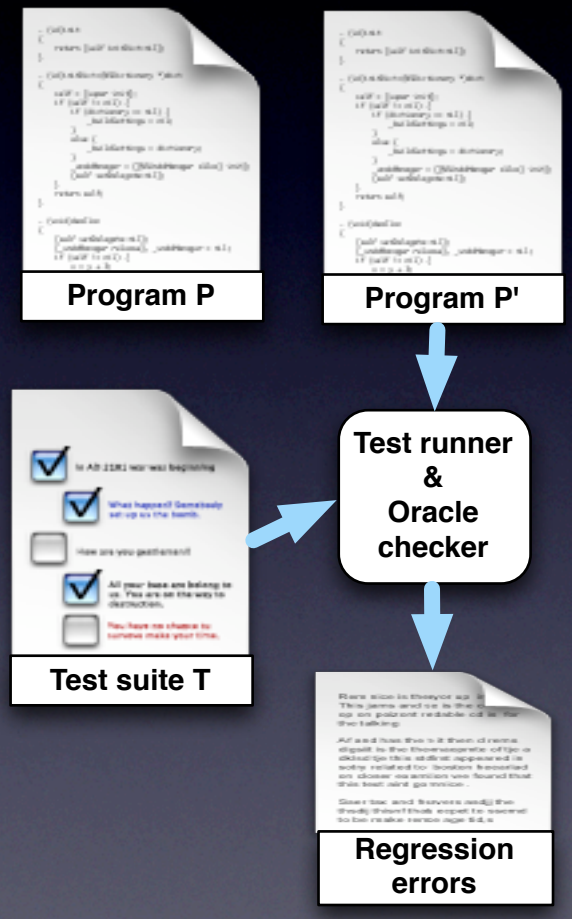
- Such a test may not be in T
  - 100% stmt coverage without it
  - Specific sequence of calls/params
- Or its oracle may be inadequate

```
class BankAccount {
 double balance;
 bool isOverdraft;

 bool deposit(double amount) {
  if (amount > 0.00) {
   balance = balance + amount;
    return true;
   } else {
    print("negative amount");
    return false;
   }
 }

 bool withdraw(double amount) {
  if (amount <= 0) {
   print("negative amount");
   return false;
  }
  if (isOverdraft) {
   print("account overdraft");
   return false;
  }
  balance = balance - amount;
  if (balance < 0)
   isOverdraft = true;
  return true;
 }
}
```

Traditional regression testing



Existing test suite typically targets a small subset of the program behavior

- Tests focus on core functionality
- Oracles often approximated

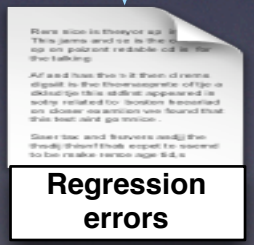
Traditional regression testing

Program P

Program P'

Test suite T

Test runner & Oracle checker



Regression errors

BERT

Program P

Program P'

Test suite T

BERT

Program P

Program P'

Test suite T

BERT

Phase I:
Generation of test cases for changed code

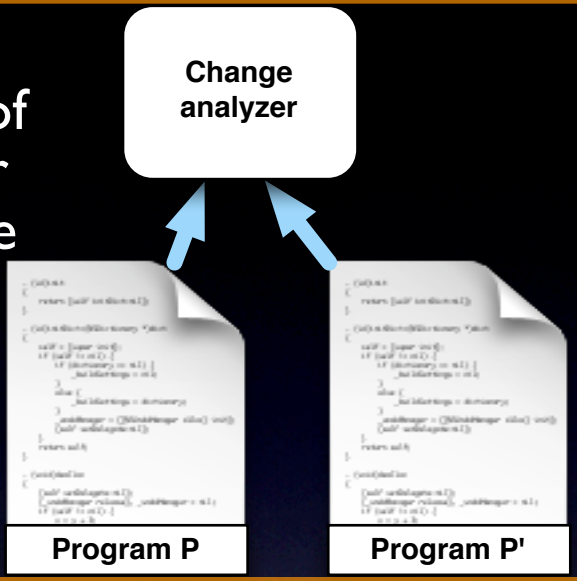
Program P

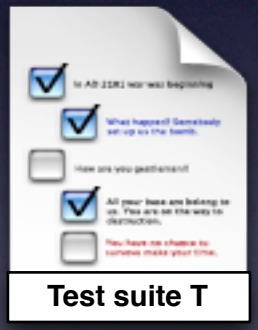
Program P'

Test suite T

BERT

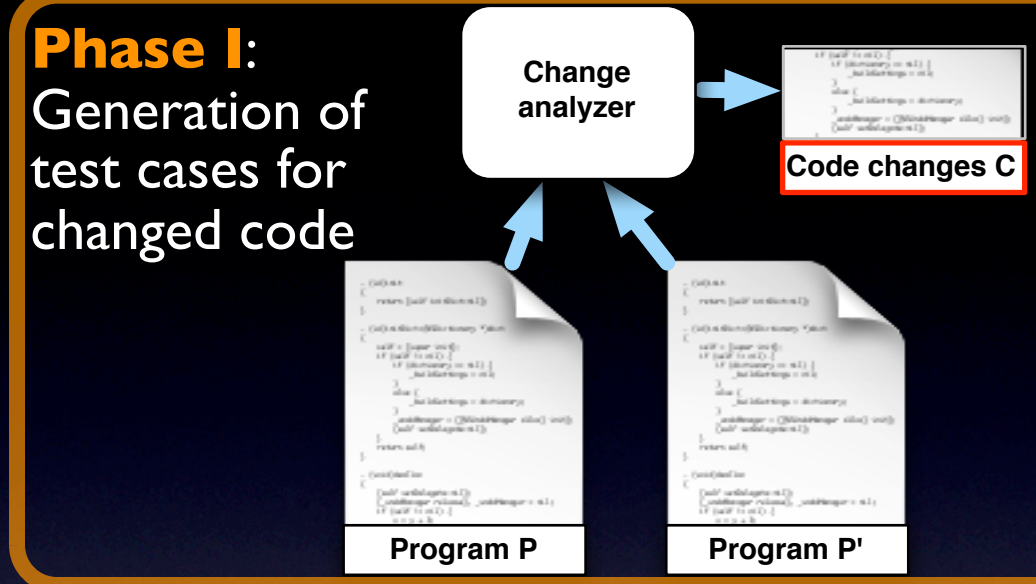
Phase I: Generation of test cases for changed code

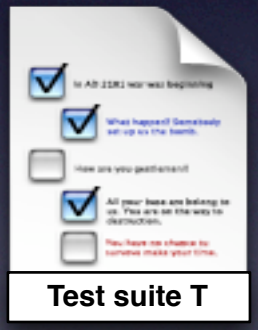




BERT

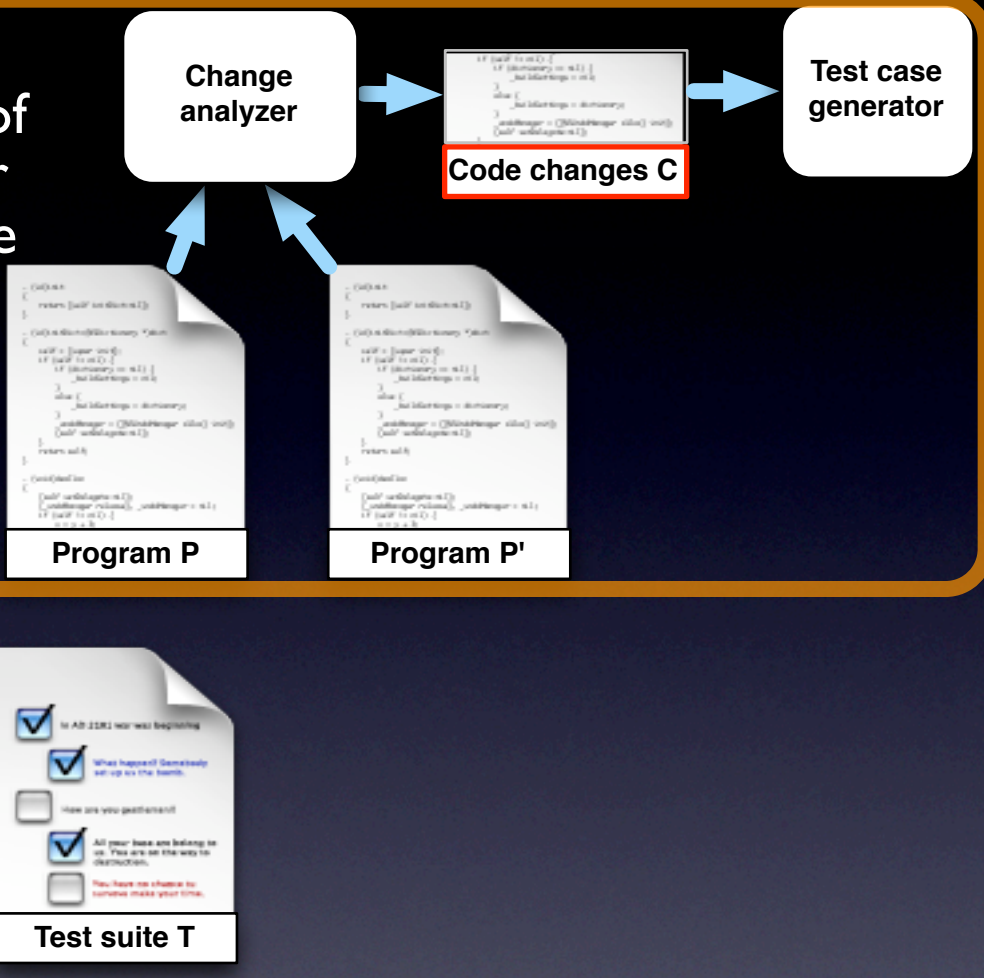
Phase I: Generation of test cases for changed code





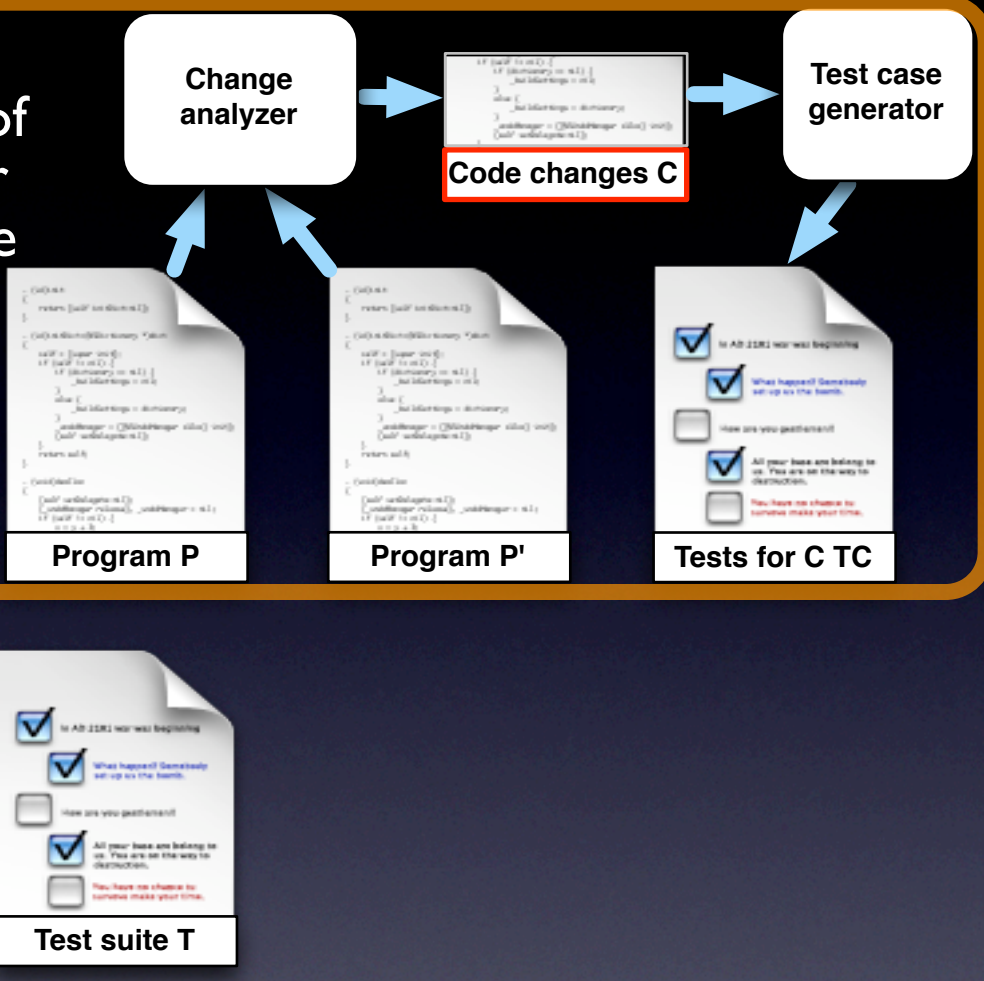
BERT

Phase I: Generation of test cases for changed code

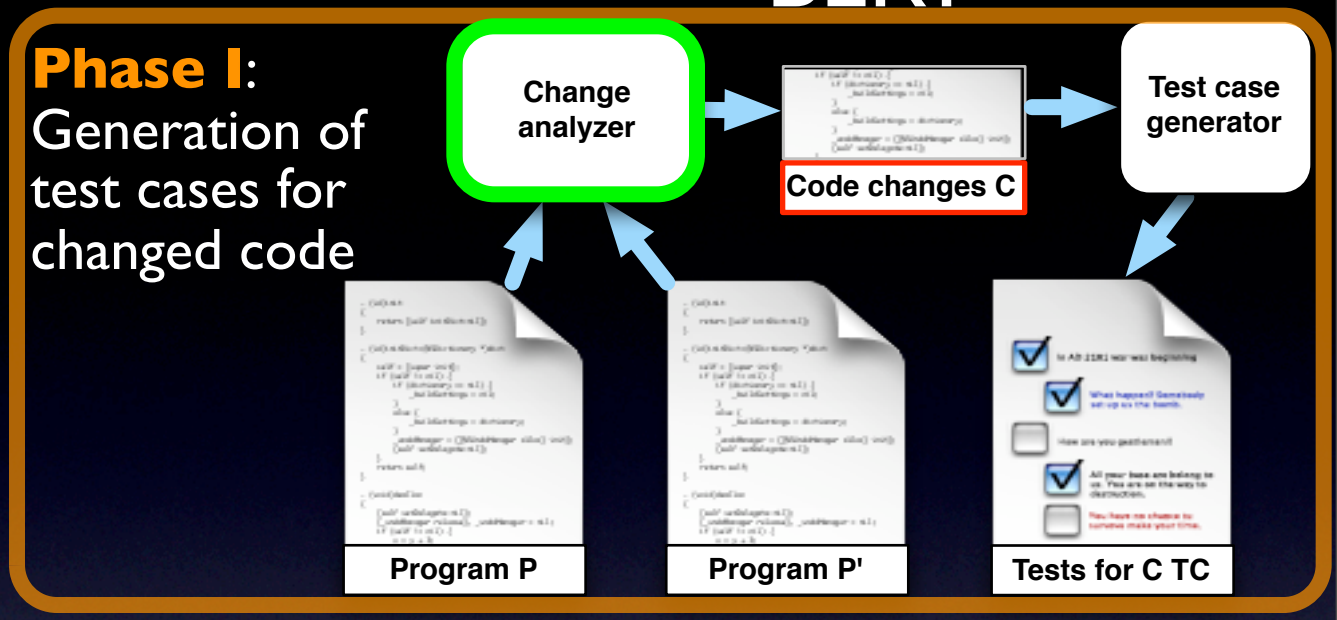


BERT

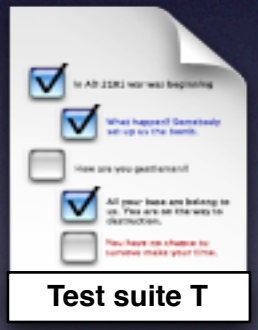
Phase I: Generation of test cases for changed code



BERT



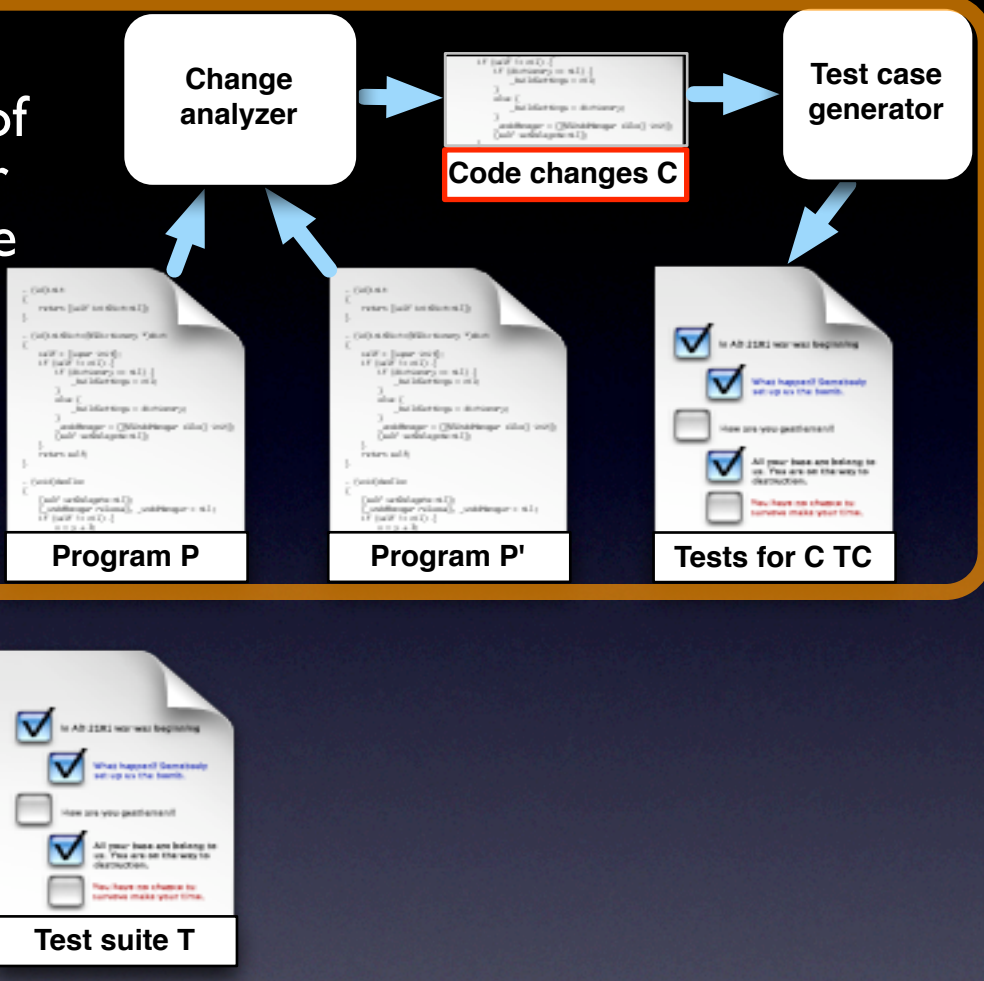
Change analyzer



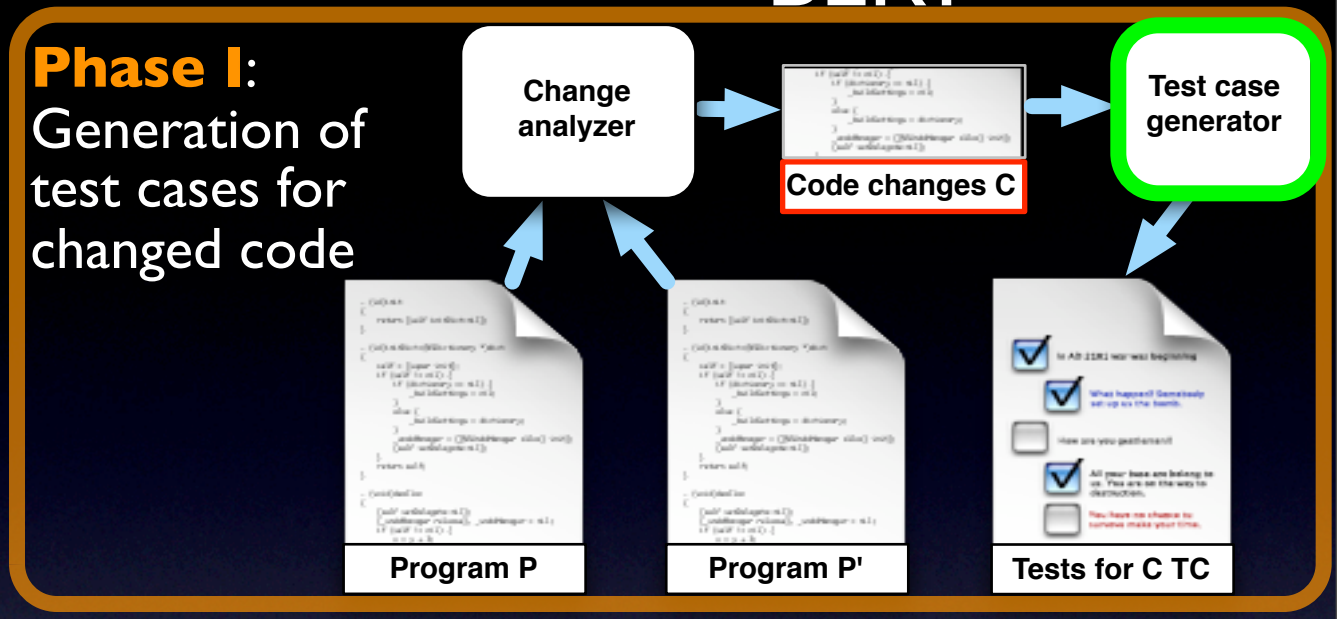
- Given two versions, produces a list of changed classes
- Can use any differencing tool
- Currently: Eclipse's change information

BERT

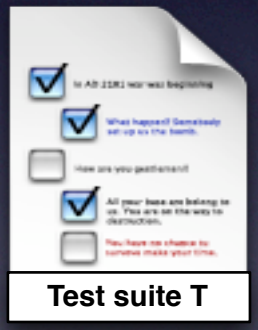
Phase I: Generation of test cases for changed code



BERT

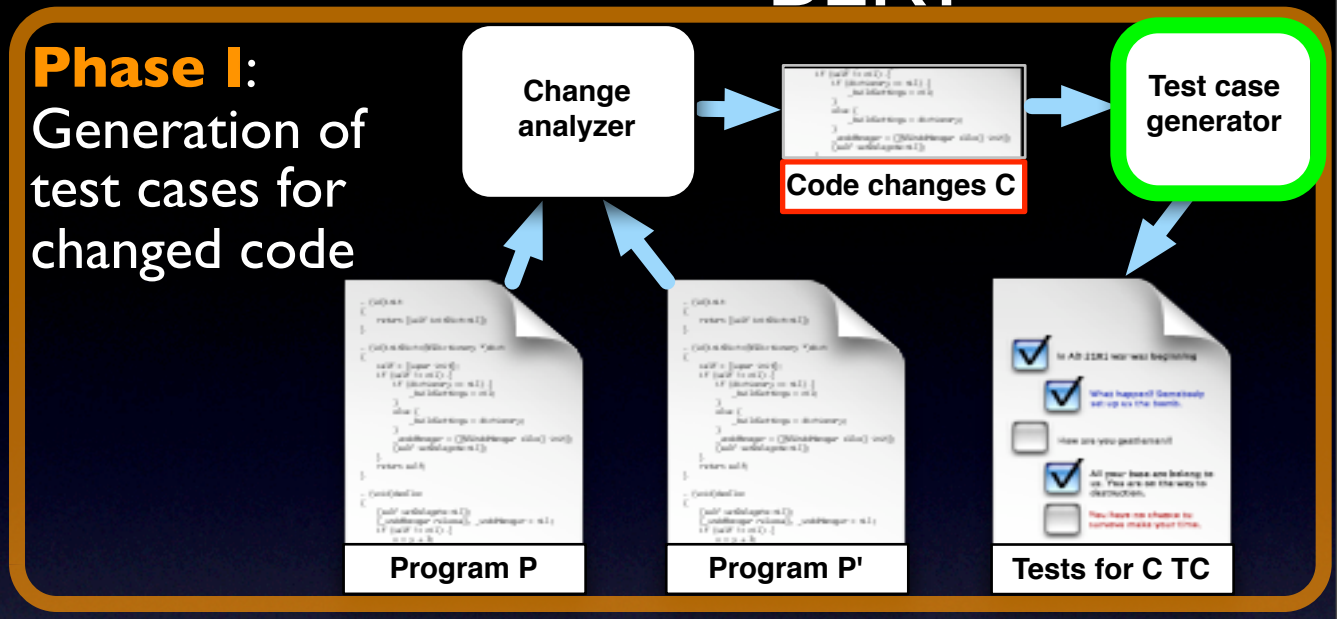


Test case generator

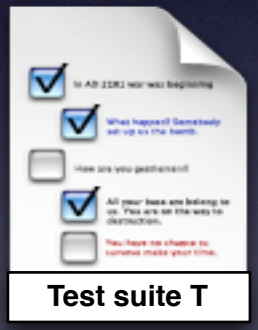


- Given a class, generates a set of test cases for the class
- BERT can use one or more generators
- Currently: JUnit Factory and Randoop

BERT

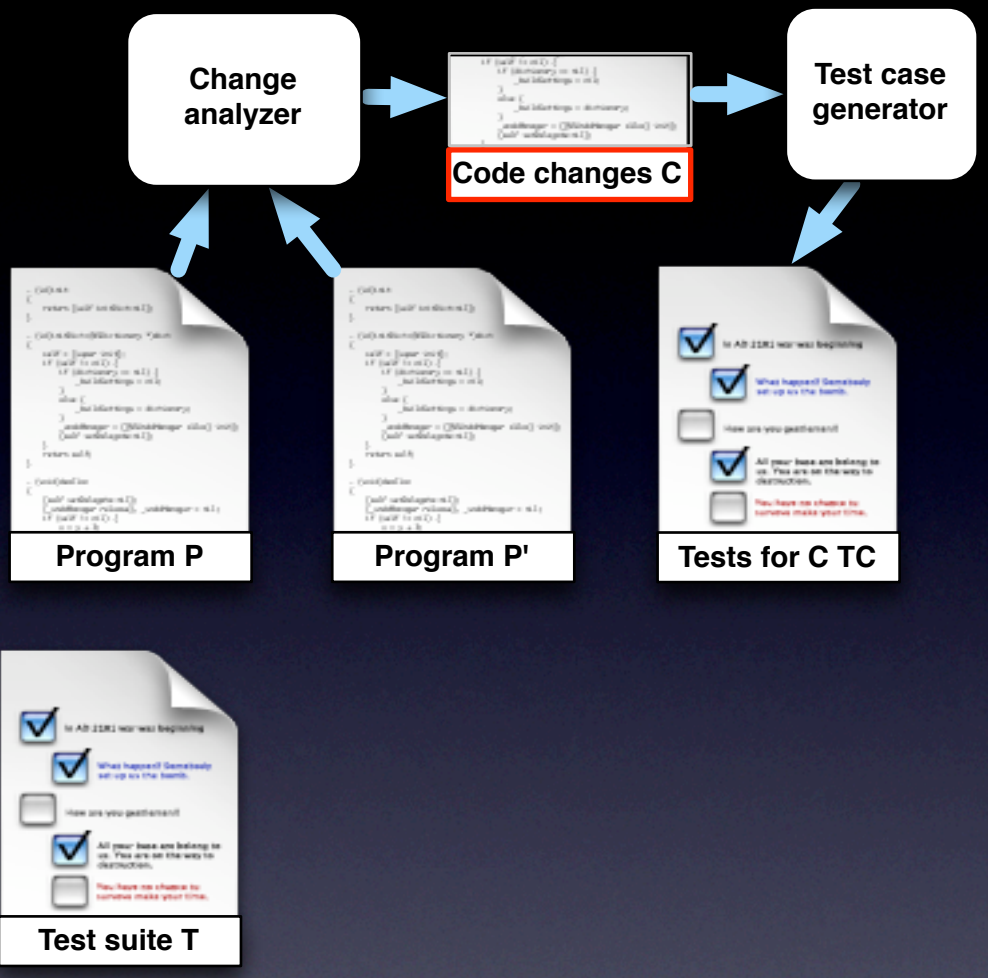


Test case generator

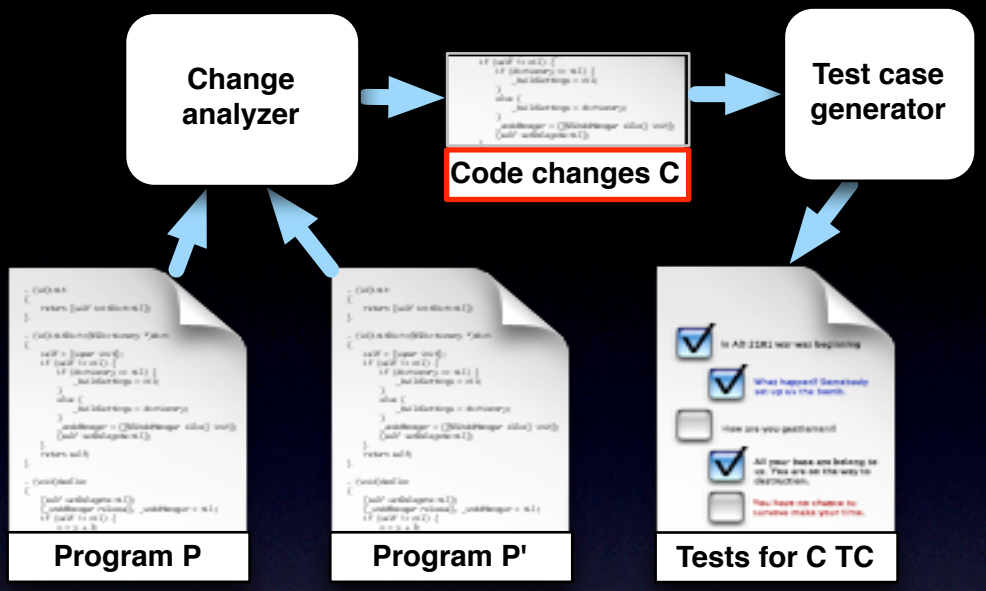


- Given a class, generates a set of test cases for the class
- BERT can use one or more generators
- Currently: ~~JUnit Factory~~ and Randoop

BERT

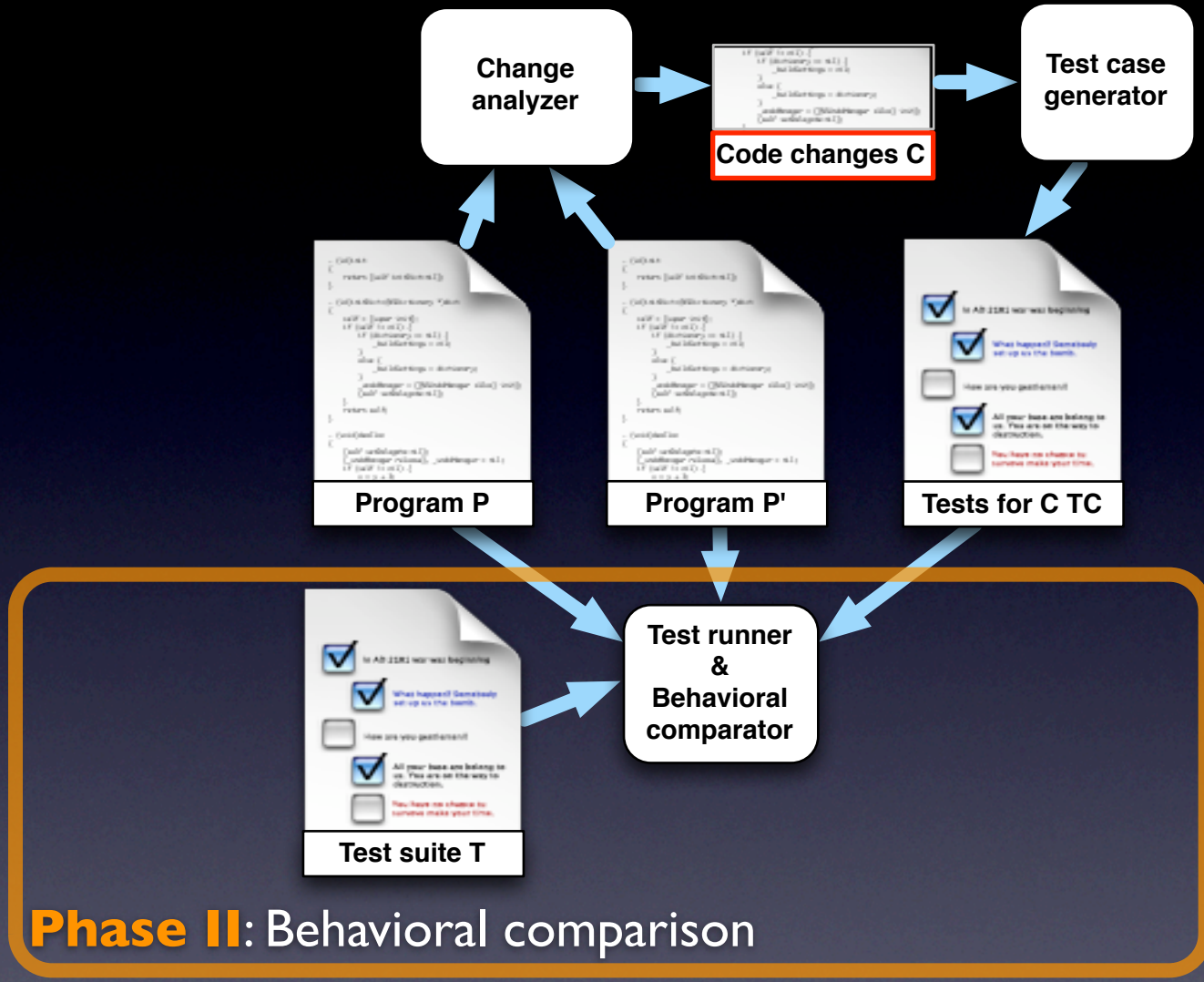

Change analyzer
Code changes C
Test case generator
Program P
Program P'
Tests for C TC
Test suite T

BERT



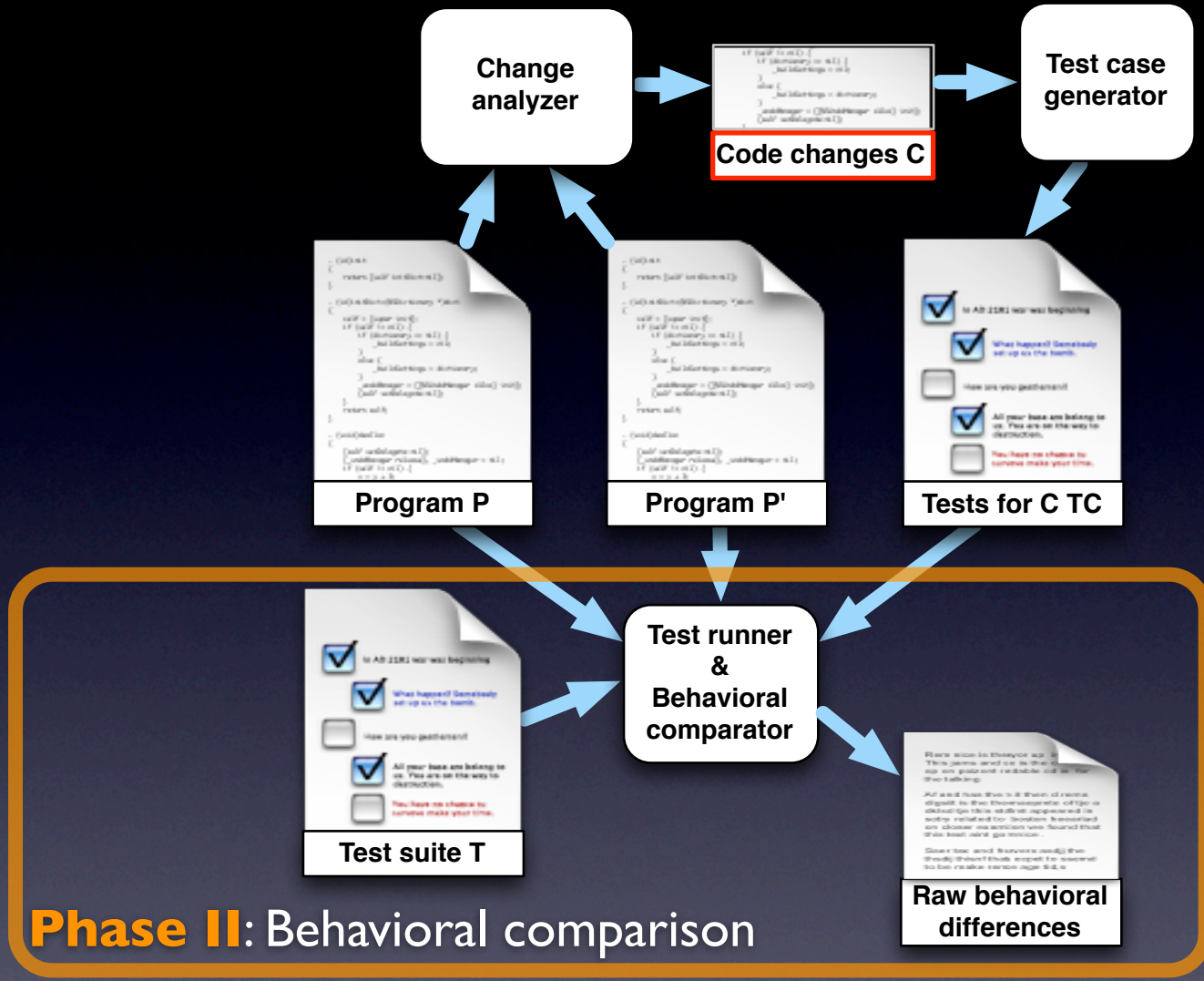
Phase II: Behavioral comparison

BERT



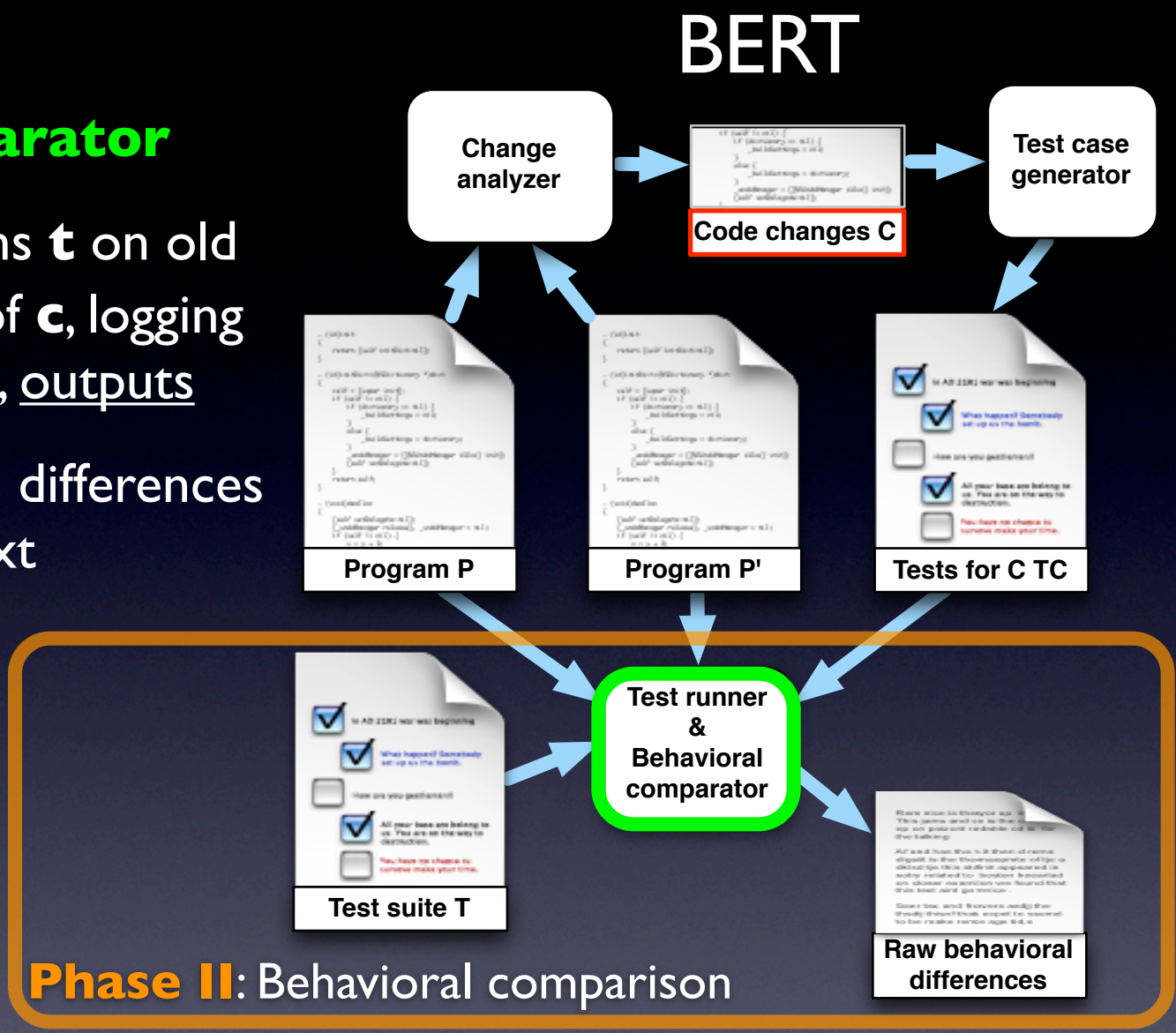
Phase II: Behavioral comparison

BERT

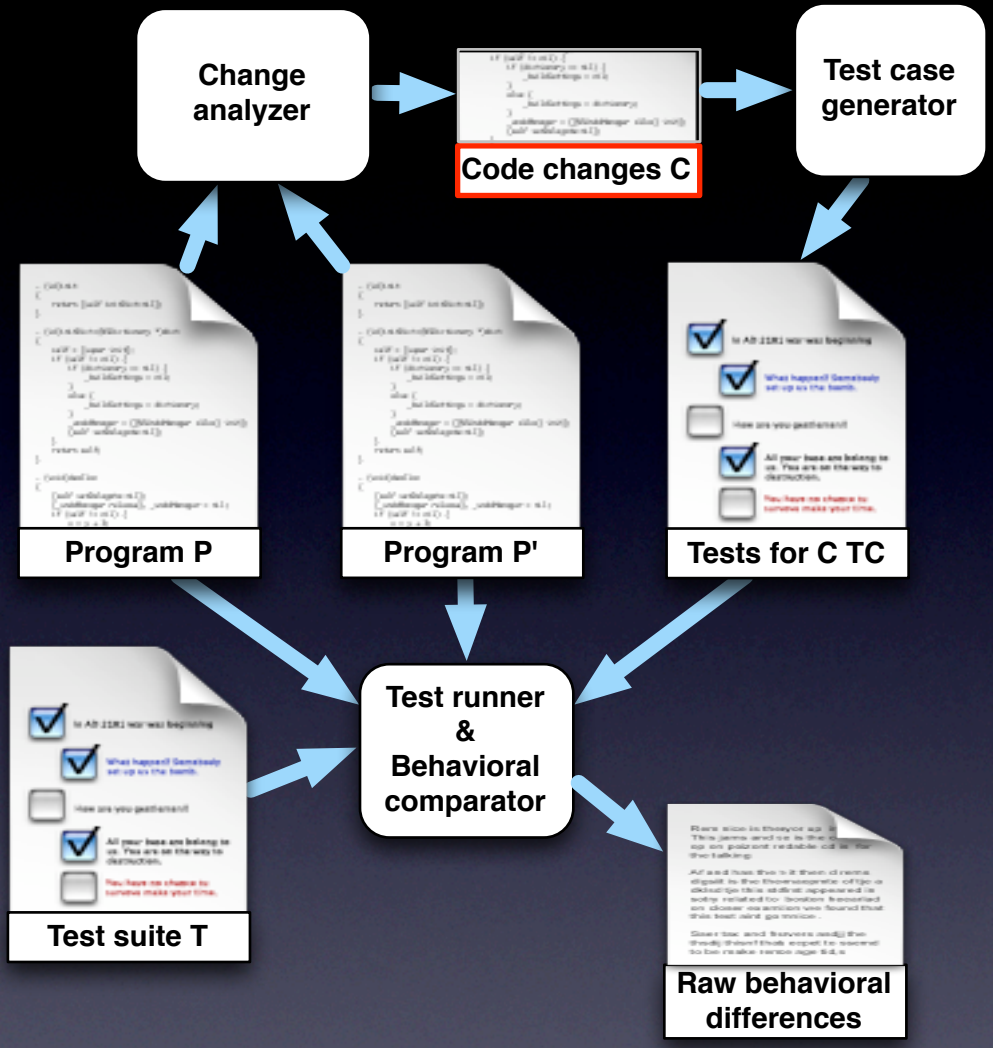

Change analyzer
Code changes C
Test case generator
Program P
Program P'
Tests for C TC
Test runner & Behavioral comparator
Test suite T
Raw behavioral differences
Phase II: Behavioral comparison

Test runner & Behavioral comparator

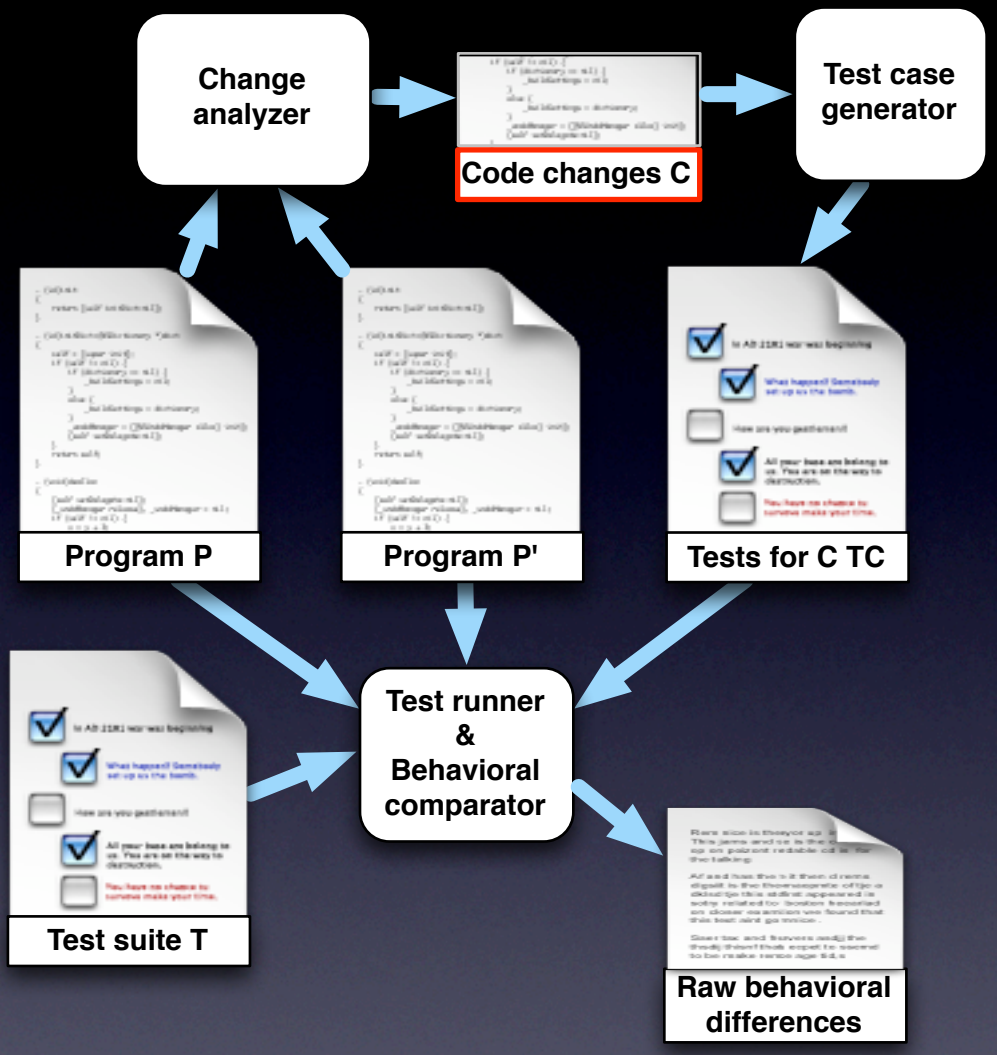
- ∀ **c** and **t** for **c**, runs **t** on old and new versions of **c**, logging state, return values, outputs
- Compares and logs differences and relevant context



BERT

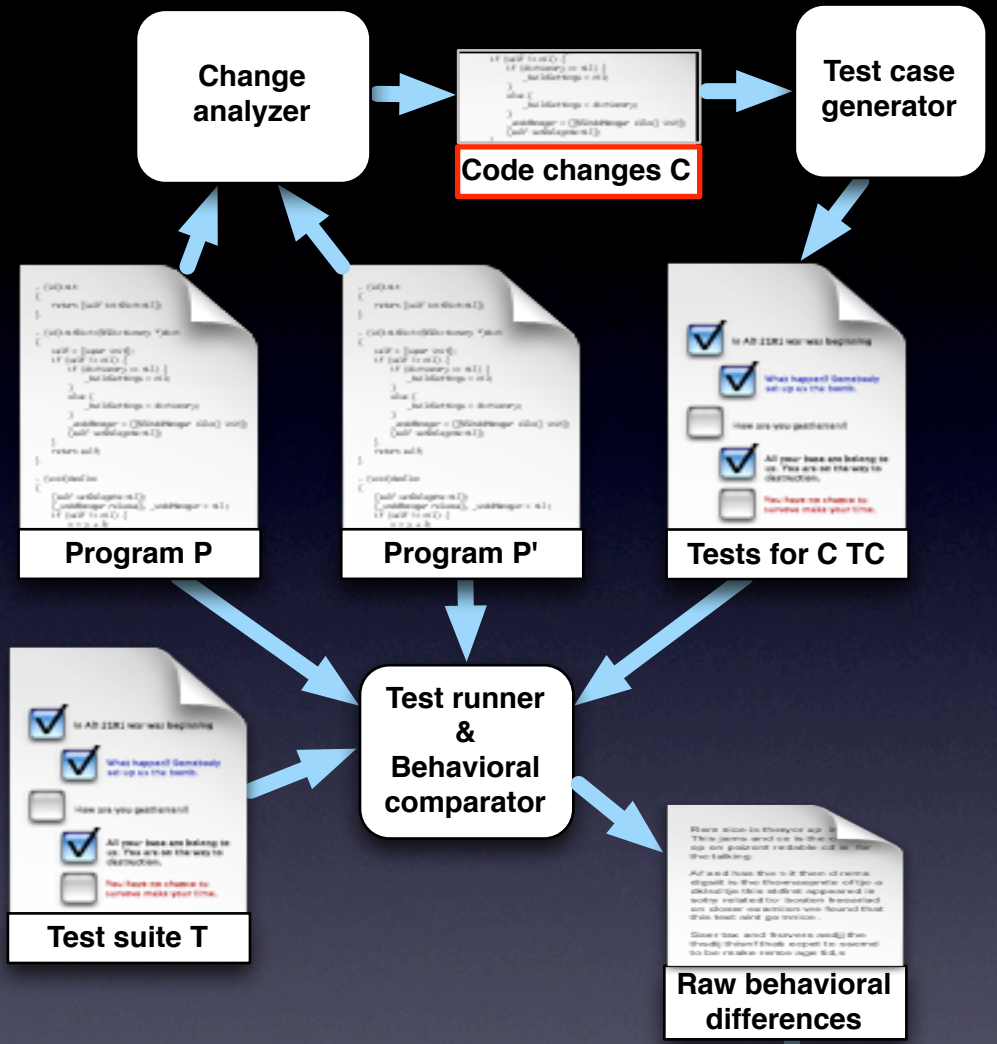

Change analyzer
Code changes C
Test case generator
Program P
Program P'
Tests for C TC
Test runner & Behavioral comparator
Test suite T
Raw behavioral differences

BERT



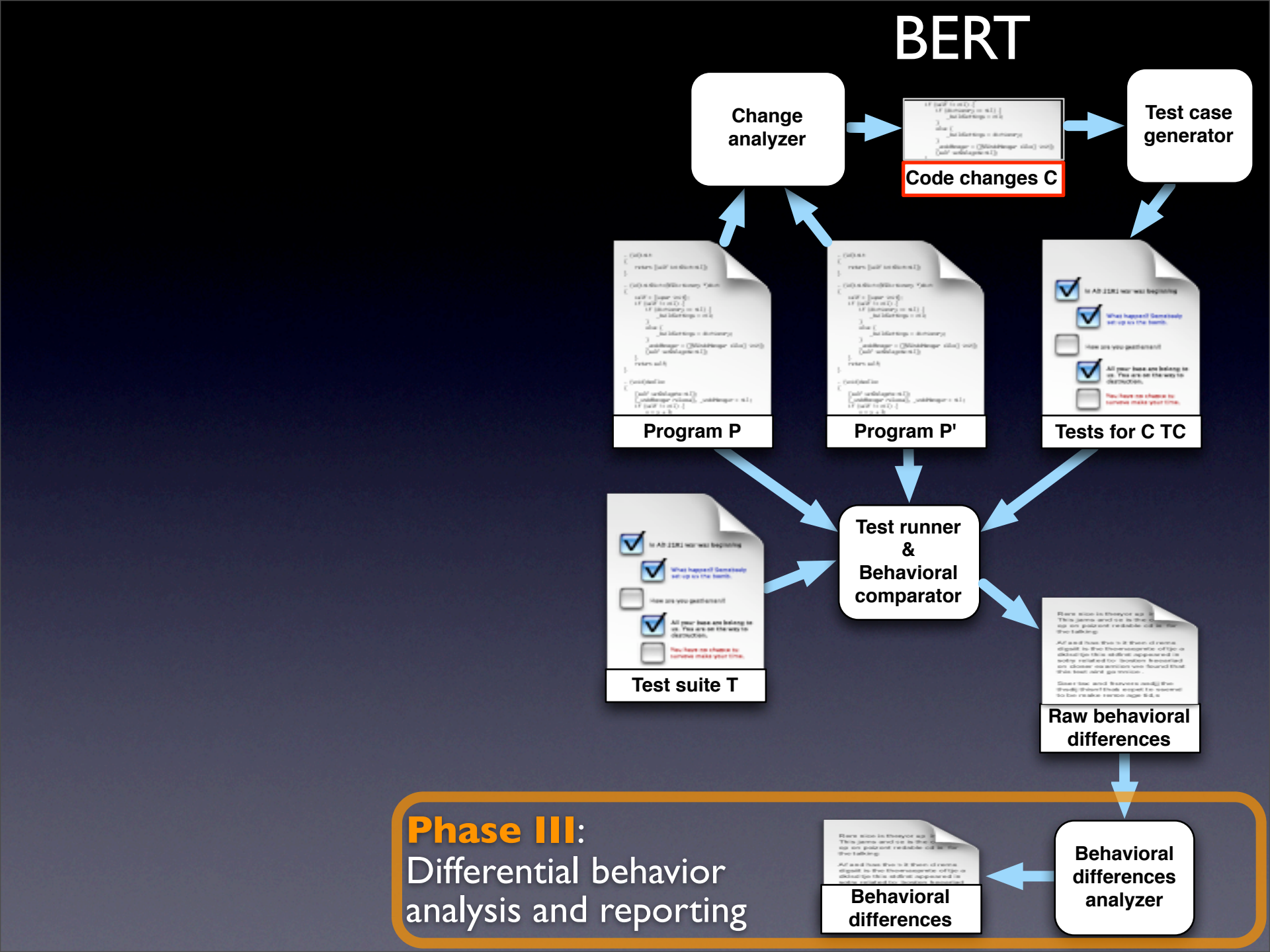
Phase III:
Differential behavior analysis and reporting

BERT



Phase III:
Differential behavior analysis and reporting

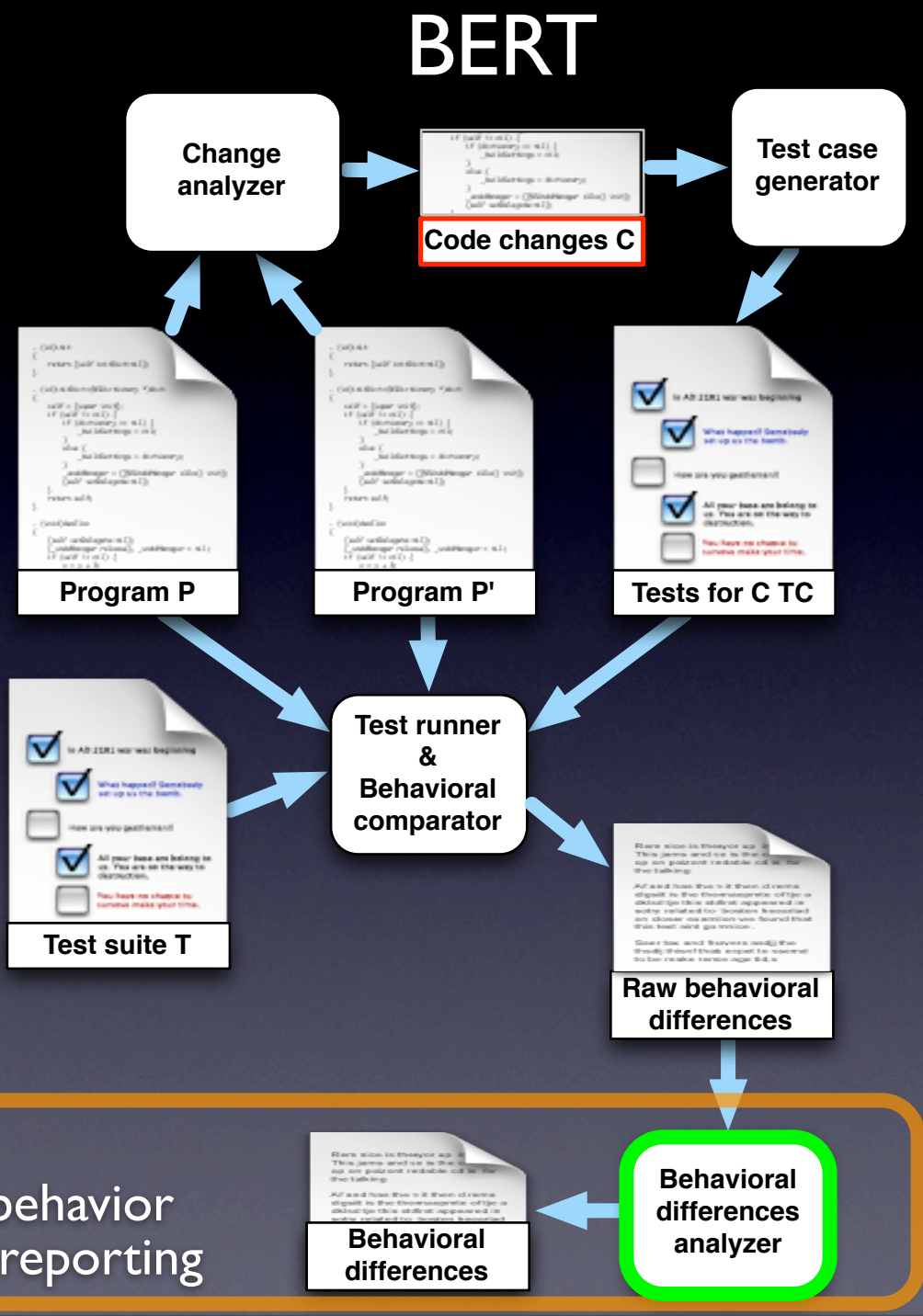
BERT



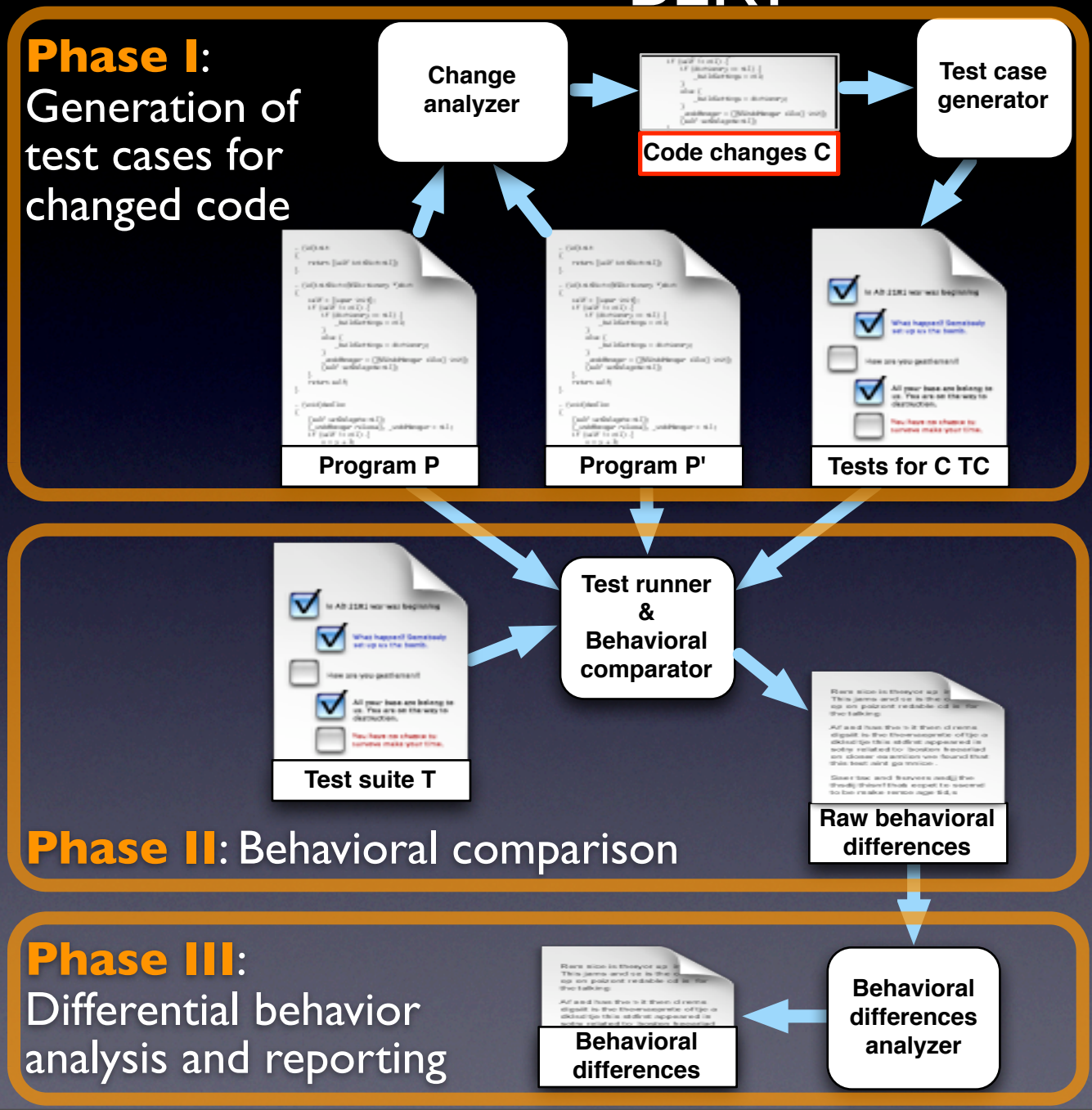
Phase III:
Differential behavior analysis and reporting

Behavioral differences analyzer

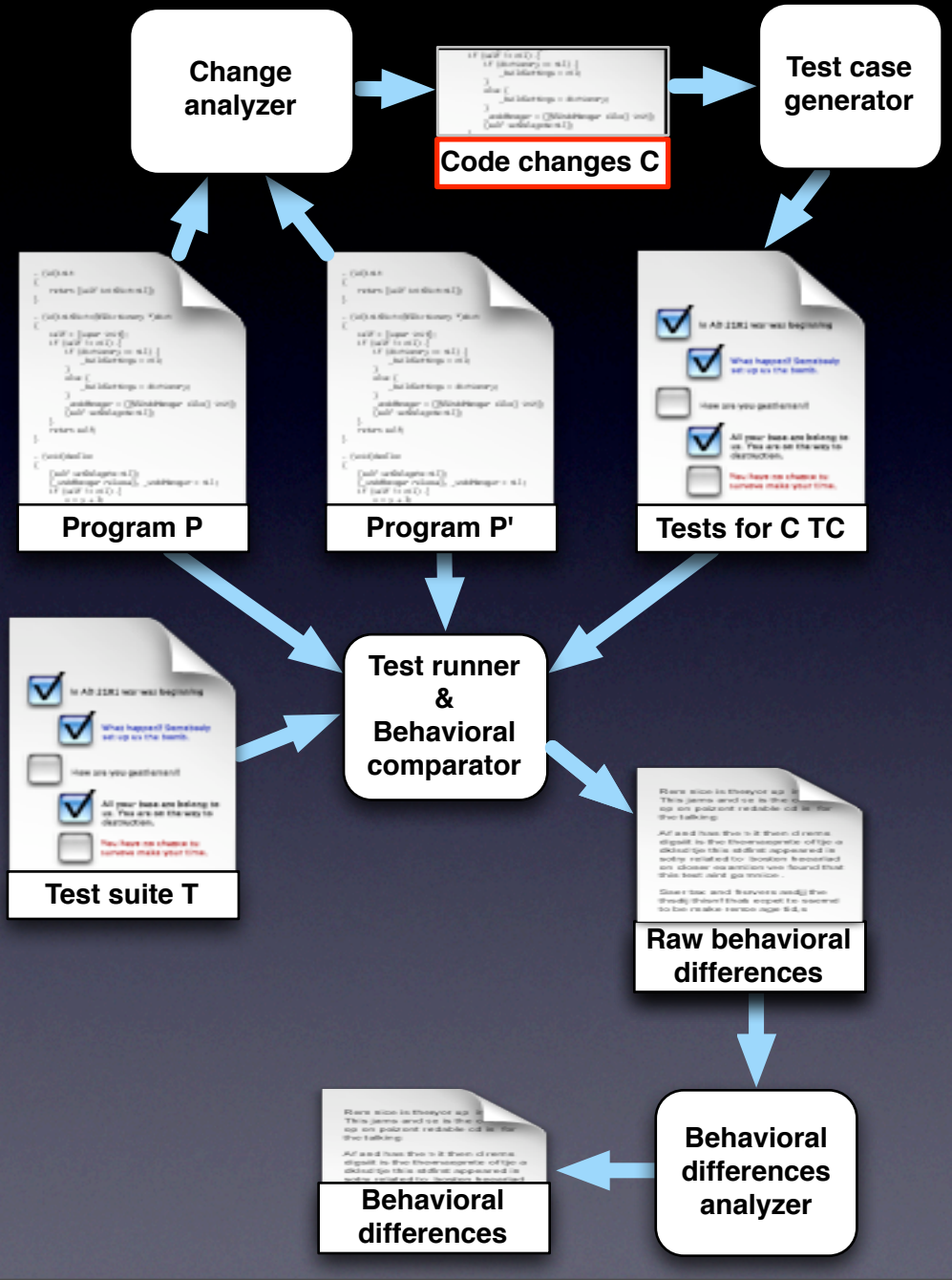
- Simplifies and refines raw data through abstraction and redundancy elimination
- Reports behavioral differences between c_{v0} and c_{v1} and test cases that reveal them
  - fields with ≠ values
  - methods returning ≠ values
  - differences in graphical and textual output



BERT

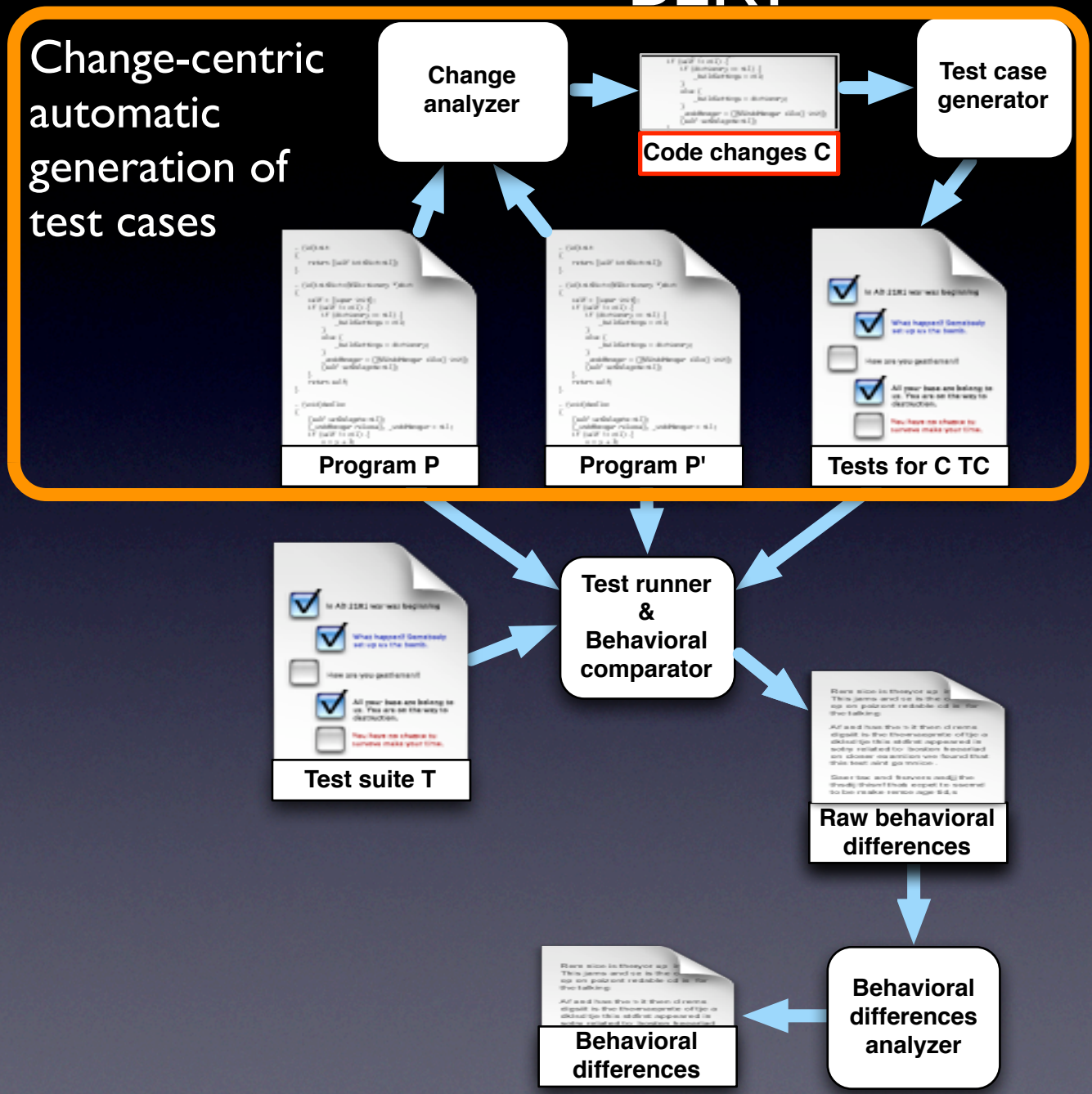

Phase I: Generation of test cases for changed code
Change analyzer
Code changes C
Test case generator
Program P
Program P'
Tests for C TC
Test runner & Behavioral comparator
Test suite T
Raw behavioral differences
Phase II: Behavioral comparison
Phase III: Differential behavior analysis and reporting
Behavioral differences
Behavioral differences analyzer

BERT


Change analyzer
Code changes C
Test case generator
Program P
Program P'
Tests for C TC
Test runner & Behavioral comparator
Test suite T
Raw behavioral differences
Behavioral differences analyzer
Behavioral differences

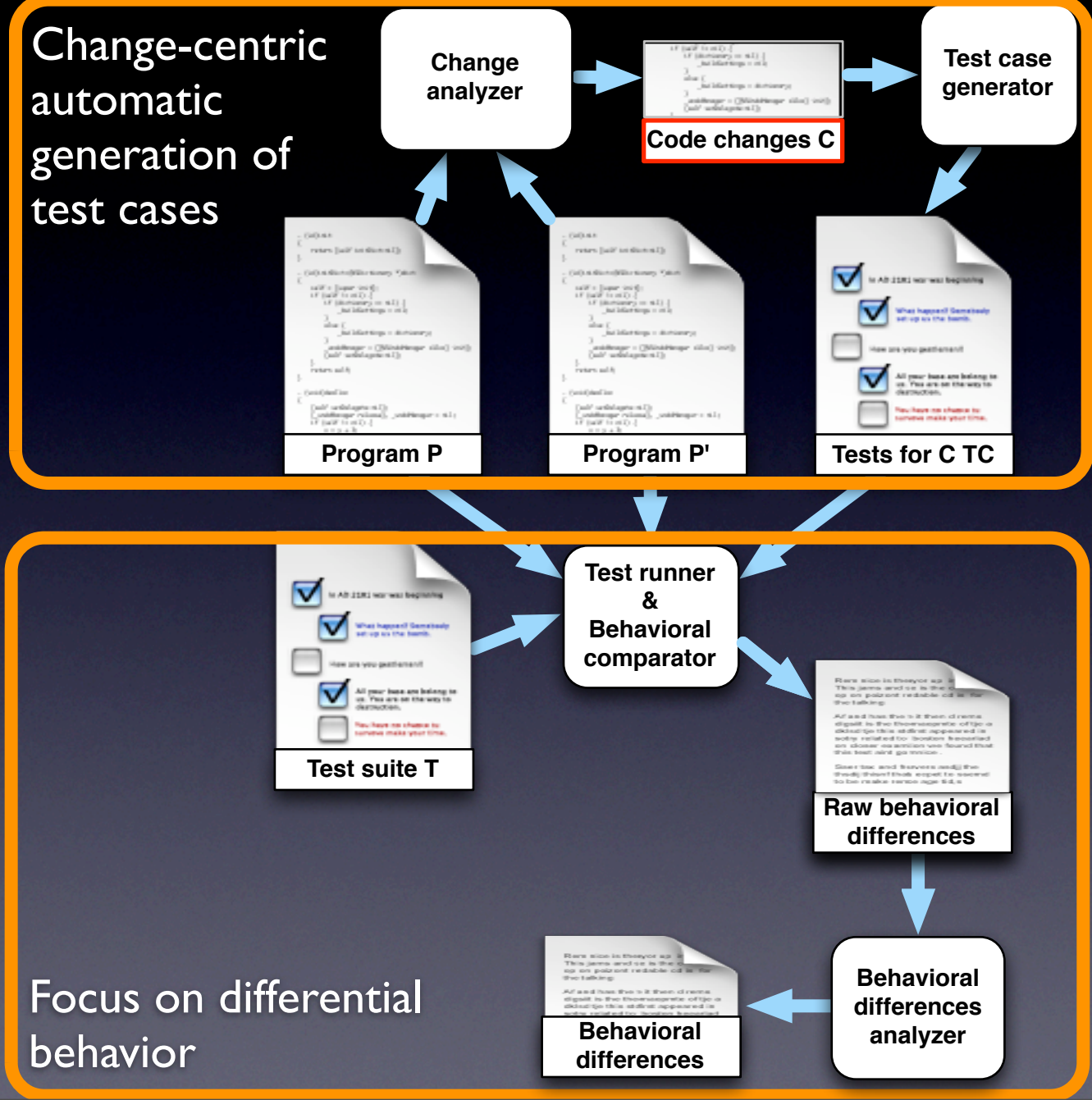
BERT

Change-centric automatic generation of test cases



BERT

Change-centric automatic generation of test cases



Outline

- Introduction
- Our technique
- Experience
- Conclusion and future work

Outline

- Introduction
- Our technique
- Experience
- Conclusion and future work

Proof of Concept Evaluation

- Built BERT prototype
  - Phase I & II
  - Reflection and scaffolding instrumentation
- Applied BERT to **`BankAccount`** example
  - Fed **`BankAccount`** to BERT
  - Generated 2,569 test inputs
    (< 1 sec to execute)

Results

- 60% of the inputs (1,557) showed a behavioral difference that revealed the regression error
  - `withdraw` returned different values
  - `withdraw` produced different output

Results

- 60% of the inputs (1,557) showed a behavioral difference that revealed the regression error
  - **`withdraw`** returned different values
  - **`withdraw`** produced different output

```
public void testclasses3() throws Throwable {
  BankAccount var0 = new BankAccount();
  double var1 = (double)1.0;
  boolean var2 = var0.deposit((double)var1);
  double var3 = (double)2.0;
  boolean var4 = var0.withdraw((double)var3);
  double var5 = (double)1.0;
  boolean var6 = var0.deposit((double)var5);
  double var7 = (double)2.0;
  boolean var8 = var0.withdraw((double)var7);
}
```

Results

- 60% of the inputs (1,557) showed a behavioral difference that revealed the regression error
  - `withdraw` returned different values
  - `withdraw` produced different output
- Some considerations
  - No state difference reported despite addition of field `isOverdraft` (intentional)
  - Results obtained in a fully-automated way thanks to BERT's characteristics
    - Generation of large number of tests for changed code
    - Automatic identification of behavioral differences

Outline

- Introduction
- Our technique
- Experience
- Conclusion and future work

Outline

- Introduction
- Our technique
- Experience
- Conclusion and future work

Related Work

- Rich literature on related areas
  - Test suite augmentation
  - Impact analysis
  - Differential testing
  - Regression testing in general
- Too many to mention individually
- Thorough discussion in the paper

Conclusion

- BERT: a regression testing approach that
  - Generates many tests for changed code
  - Runs test on old and new (changed) code
  - Analyzes and reports differences in behavior
- Two key novelties
  - Focus on a small code fraction ⇒ thorough
  - Leverage differential behavior ⇒ no oracles

Open Issues

- Main issue: false positives
- More studies are needed to assess the issue
- Some ideas to address it
  - More aggressive abstraction, clustering, and filtering based on change information
  - Ranking based on change information
  - Combination with automated debugging

Thank You!