Debugging (2/2)

Martin Kellogg

Reading Quiz: debugging 2

Q1: What is the inspiration for the name of the “wynot” tool?

A. The “wynot” tool helps answer the question “why not?”
B. It is named after the Pokémon “Wynaut”
C. “wynot” is an abbreviation for “**W**orked **Y**esterday, **NO**t **T**oday”
D. None of these are the inspiration for the tool’s name

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B. Chromium/Google Chrome
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Debugging strategies

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  - and its larger-scale cousin: **logging**

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- “printf” debugging: using print statements to find a bug
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- delta debugging
  - a **formalization** of the scientific approach to debugging
- debuggers: **inspecting program state** while it is running
  - we’ll talk a little about how they work

Debugging (Part 2/2)

Today's agenda:

- Debugging
  - **printf debugging and logging**
  - delta debugging
  - debuggers

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    something else
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This is a **misconception**: professional engineers commonly use printf debugging. But printf debugging should be just one tool in your toolbox of debugging strategies!

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- logging is a key technology for **monitoring** modern systems
  - e.g., via tools like Log4j, slf4j, etc.
- logs also play a major role in debugging **large-scale failures** of important distributed systems
  - we'll discuss this more when we talk about **post-mortems** in our DevOps lectures, near the end of the semester

Logging: levels

Typical example of a (Java) logging statement:

```
log.debug("myVariable=%s", myVariable);
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the log itself is usually a static field; the logging framework instantiates it, etc.

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levels:
error ⊆ warning ⊆ info ⊆ debug

developer chooses one level, all lower level messages are also logged

Logging: levels

Typical example of a (Java) logging statement:

```
log.debug("myVariable=%s", myVariable);
```

printf-like syntax isn't just for show: goal here is lazy evaluation, so that if debug logging isn't enabled, this string is never constructed

Logging: levels

Typical example of a (Java) logging statement:

```
log.debug("myVariable=%s", myVariable);
```

arguments to printf passed by reference, so if debug-level logging is off, this argument's toString() method is never called

Logging: advice

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- **Do** log lots of information at debug or info level, so that if something is wrong with your service you can quickly get lots of information that you can use to debug it.

Logging: advice

- **Do** log lots of information at debug or info level, so that if something is wrong with your service you can quickly get lots of information that you can use to debug it.
- **Don't** log sensitive data (e.g., credit card numbers in plaintext!)
  - this is a surprisingly common and important problem - developers have a tendency to log anything that might be useful when debugging a failure later!

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Delta debugging: summary

- ***Delta debugging*** is an automated debugging approach that finds a minimal “interesting” subset of a given set.
- Delta debugging is based on **divide-and-conquer** and relies heavily on critical assumptions (**monotonicity**, **unambiguity**, and **consistency**).
- It can be used to find which code changes cause a bug, to minimize failure-inducing inputs, and even to find harmful thread schedules.

Delta debugging: motivation

- Three Problems: One Common Approach
  - Simplifying Failure-Inducing Input
  - Isolating Failure-Inducing Thread Schedules
  - Identifying Failure-Inducing Code Changes

Delta debugging: motivation: inputs

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- Having a **test input** may not be enough
  - Even if you know the suspicious code, the input may be **too large** to step through
- This HTML input makes a version of Mozilla crash. Which portion is relevant?

```
<td align=left valign=top>
<SELECT NAME="op_sys" MULTIPLE SIZE=7>
<OPTION VALUE="All">All<OPTION VALUE="Windows 3.1">Windows 3.1<OPTION VALUE="Windows 95">Windows 95<OPTION VALUE="Windows
98">Windows 98<OPTION VALUE="Windows ME">Windows ME<OPTION VALUE="Windows 2000">Windows 2000<OPTION VALUE="Windows
NT">Windows NT<OPTION VALUE="Mac System 7">Mac System 7<OPTION VALUE="Mac System 7.5">Mac System 7.5<OPTION VALUE="Mac
System 7.6.1">Mac System 7.6.1<OPTION VALUE="Mac System 8.0">Mac System 8.0<OPTION VALUE="Mac System 8.5">Mac System
8.5<OPTION VALUE="Mac System 8.6">Mac System 8.6<OPTION VALUE="Mac System 9.x">Mac System 9.x<OPTION VALUE="MacOS X">MacOS
X<OPTION VALUE="Linux">Linux<OPTION VALUE="BSDI">BSDI<OPTION VALUE="FreeBSD">FreeBSD<OPTION VALUE="NetBSD">NetBSD<OPTION
VALUE="OpenBSD">OpenBSD<OPTION VALUE="AIX">AIX<OPTION VALUE="BeOS">BeOS<OPTION VALUE="HP-UX">HP-UX<OPTION
VALUE="IRIX">IRIX<OPTION VALUE="Neutrino">Neutrino<OPTION VALUE="OpenVMS">OpenVMS<OPTION VALUE="OS/2">OS/2<OPTION
VALUE="OSF/1">OSF/1<OPTION VALUE="Solaris">Solaris<OPTION VALUE="SunOS">SunOS<OPTION VALUE="other">other</SELECT>
</td>
<td align=left valign=top>
<SELECT NAME="priority" MULTIPLE SIZE=7>
<OPTION VALUE="--">--<OPTION VALUE="P1">P1<OPTION VALUE="P2">P2<OPTION VALUE="P3">P3<OPTION VALUE="P4">P4<OPTION
VALUE="P5">P5</SELECT>
</td>
<td align=left valign=top>
<SELECT NAME="bug_severity" MULTIPLE SIZE=7>
<OPTION VALUE="blocker">blocker<OPTION VALUE="critical">critical<OPTION VALUE="major">major<OPTION
VALUE="normal">normal<OPTION VALUE="minor">minor<OPTION VALUE="trivial">trivial<OPTION VALUE="enhancement">enhancement</SELECT>
</tr>
</table>
```

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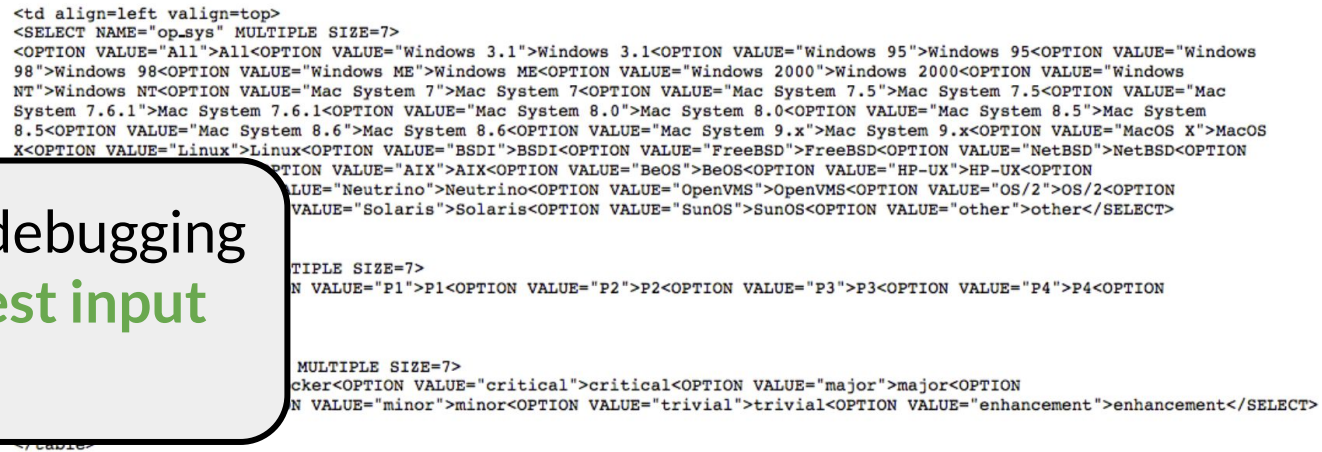
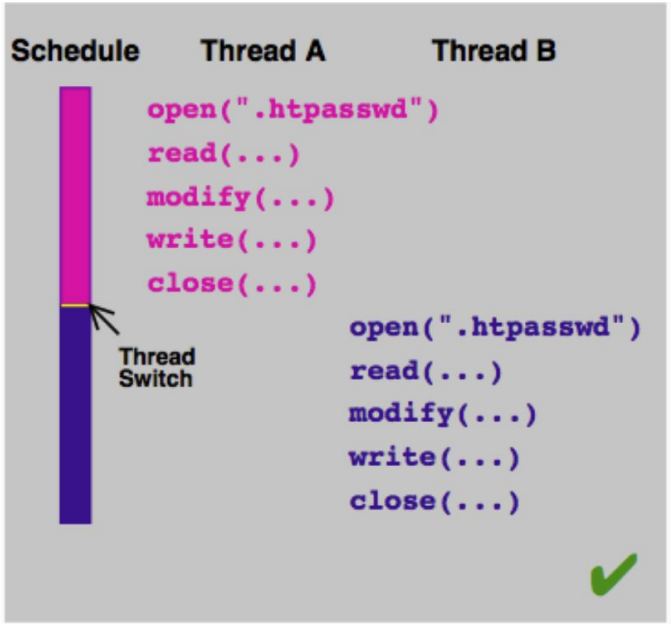
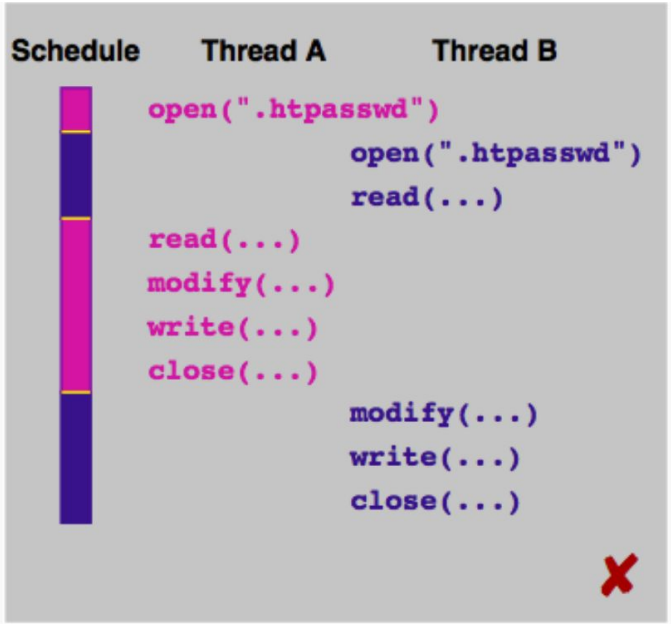


Implication: delta debugging will be useful for **test input minimization**

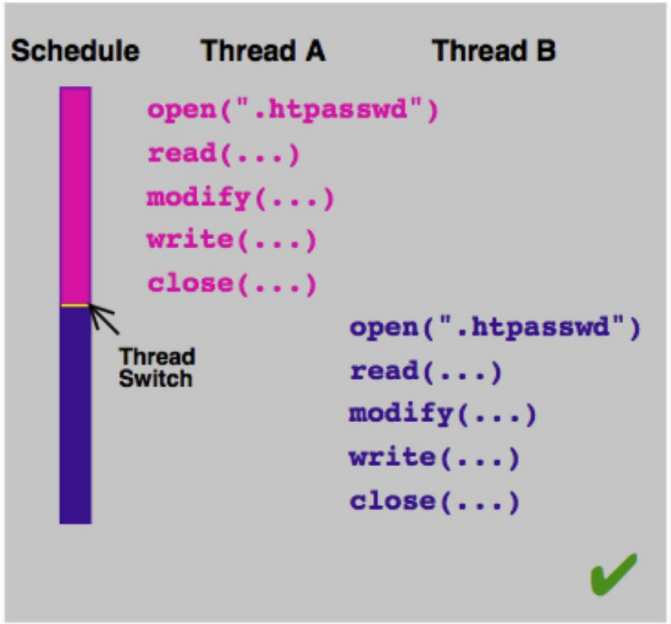
Delta debugging: motivation: thread schedules

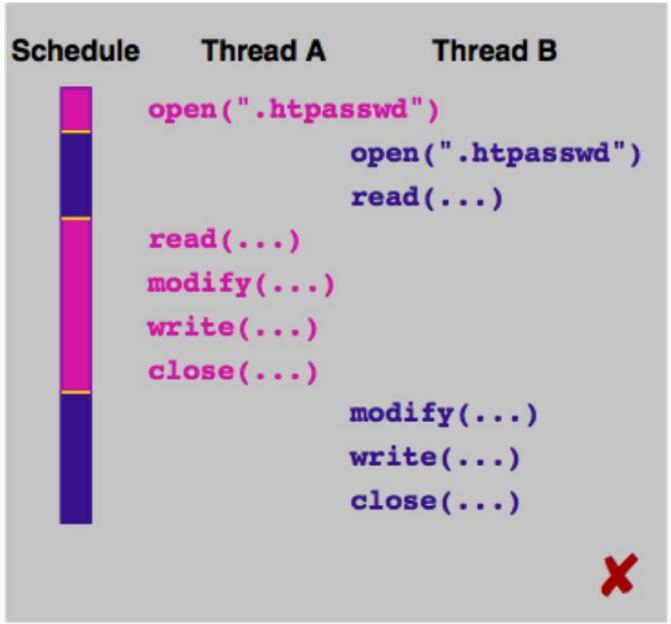




Delta debugging: motivation: thread schedules

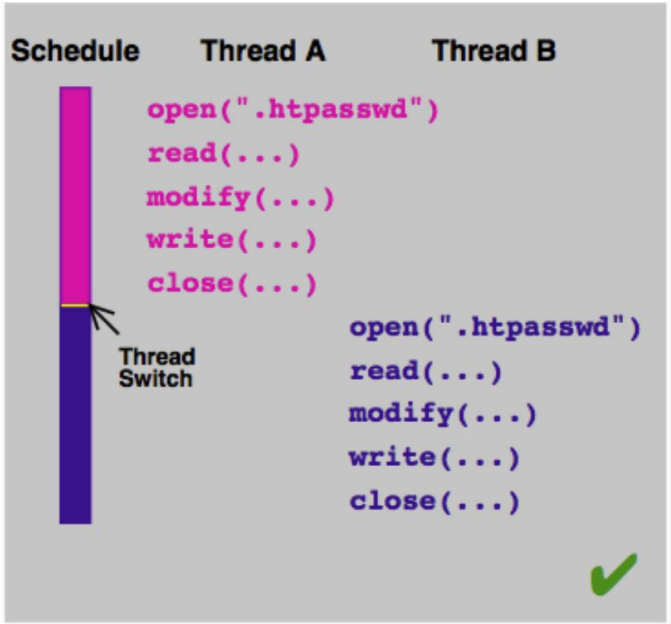
- Multithreaded programs can be **nondeterministic**

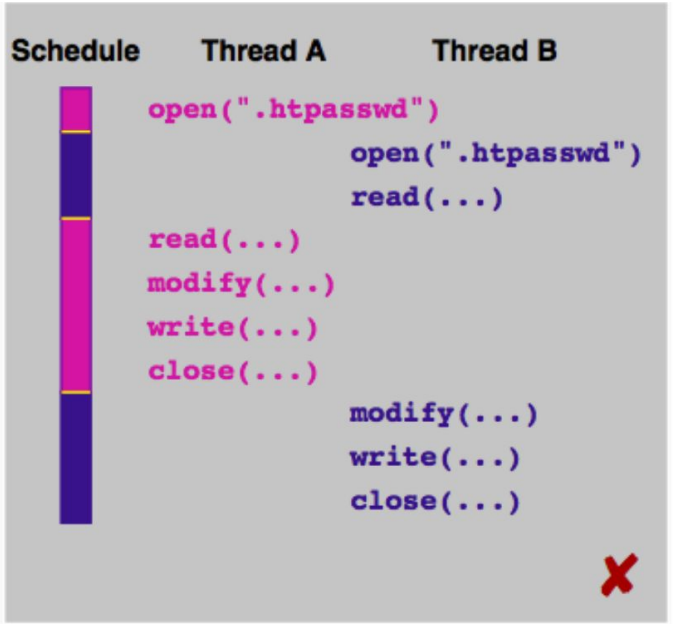




Delta debugging: motivation: thread schedules

- Multithreaded programs can be **nondeterministic**
  - Can we find simple, bug-inducing thread schedules?





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Delta debugging: motivation: code changes

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- 178,000 lines of code have been modified between the two versions
  - Where is the bug?
    - … and **which commit** is responsible for introducing it?
  - These days: **continuous integration testing** helps
    - … but does not totally solve this. Why?

Delta debugging: differences

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- Difference in **code**: different statements or expressions in two versions of a program
- Difference in **program state**: different values of internal variables

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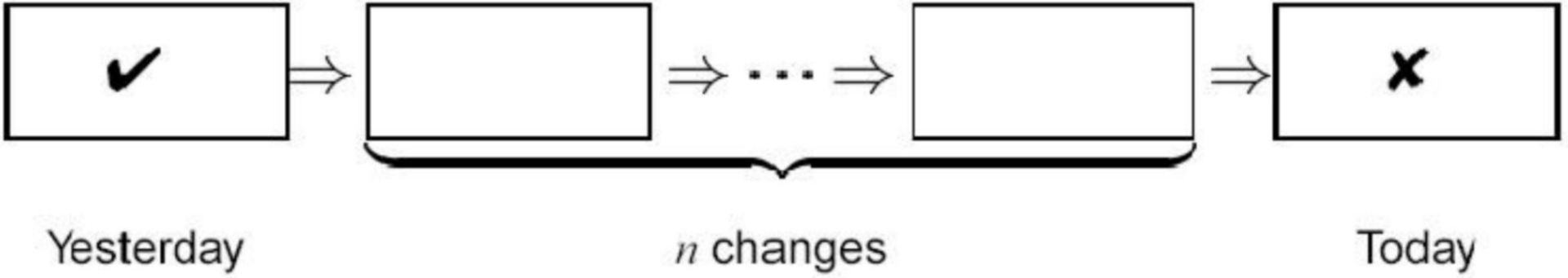
- Abstract solution: **divide-and-conquer**
  - **key idea**: split up the set into two subsets, check which of the two is still “**interesting**”
  - can be applied to working and failing inputs, code versions, thread schedules, program states, etc.

Delta debugging: unified solution

“Yesterday, my program worked. Today, it does not.”



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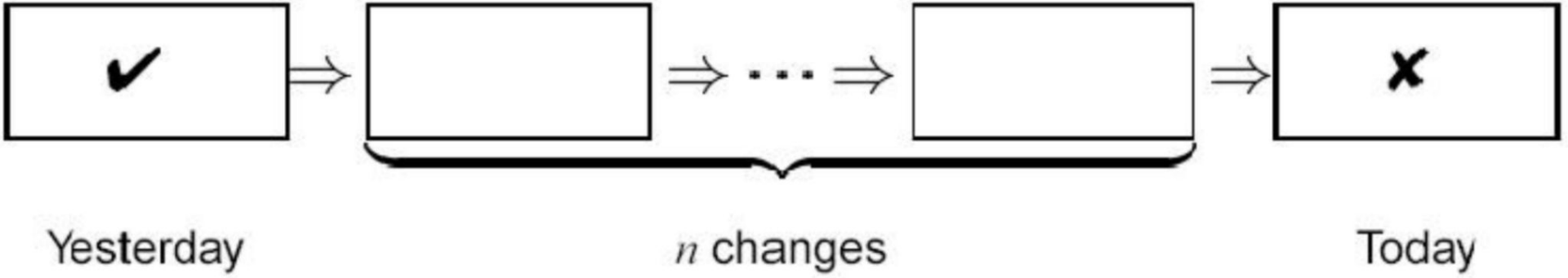

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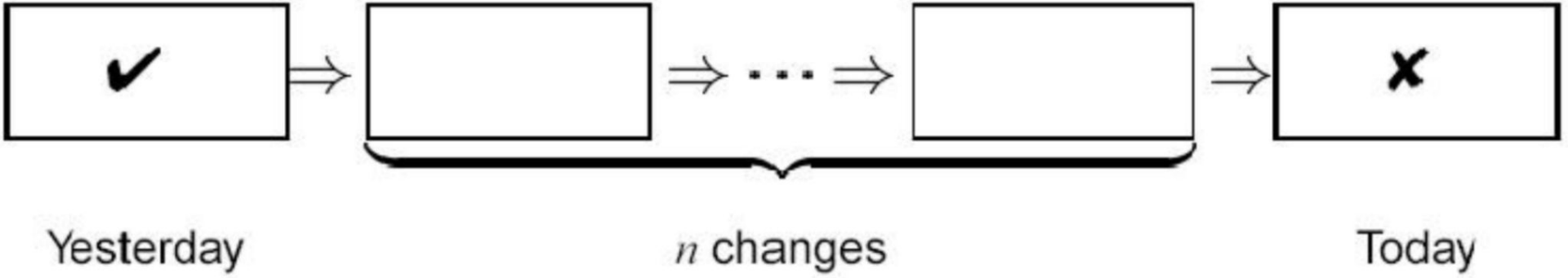

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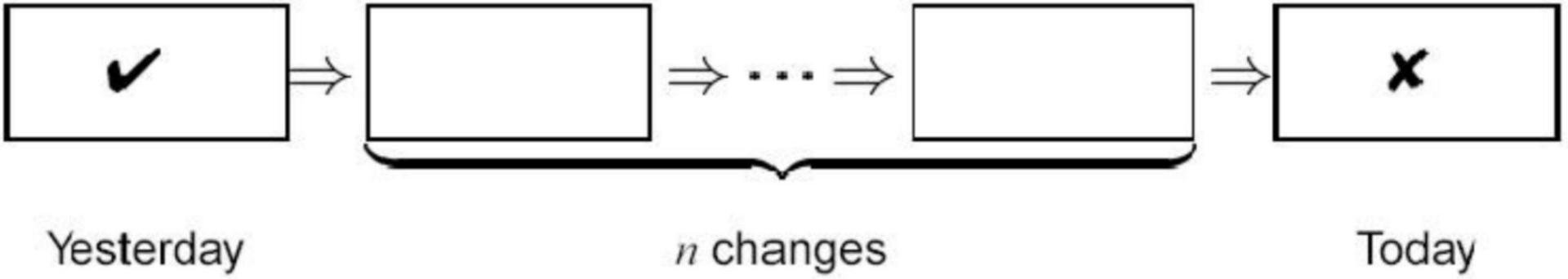

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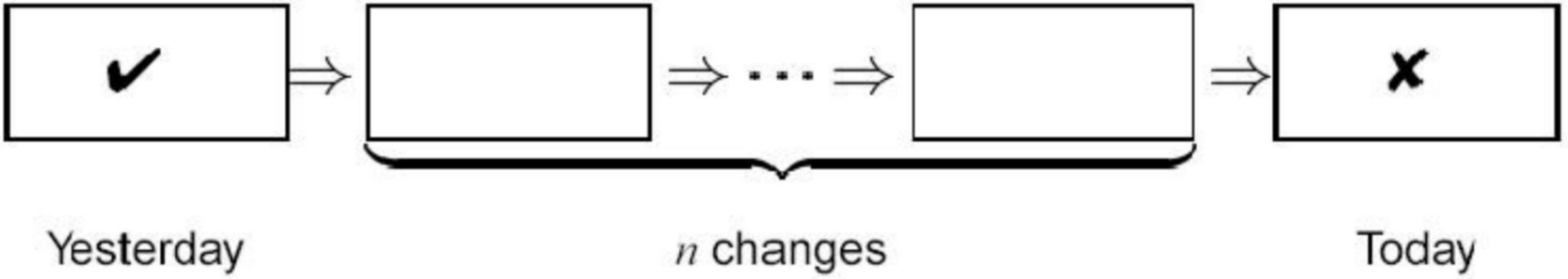

- We will iteratively:
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  - run tests to **falsify** our hypothesis

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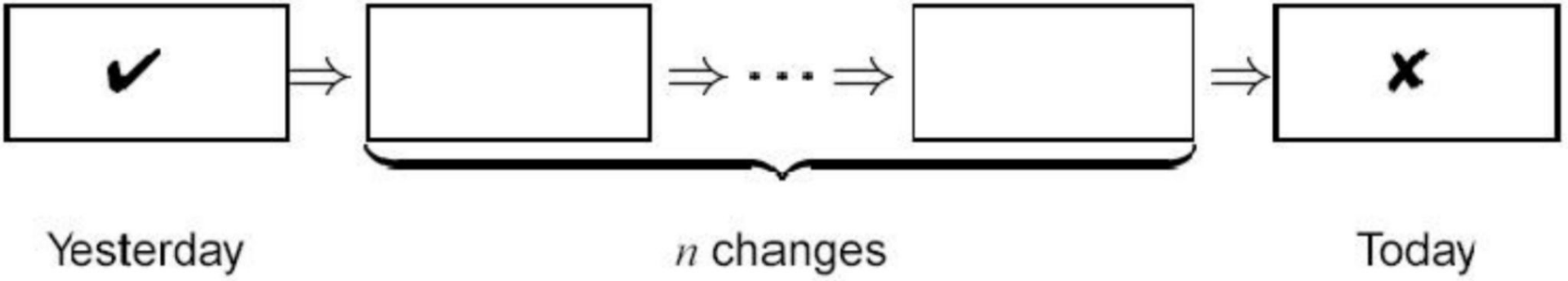
  - Forall m ⊂ M, Interesting(M - m) = No

Delta debugging: example



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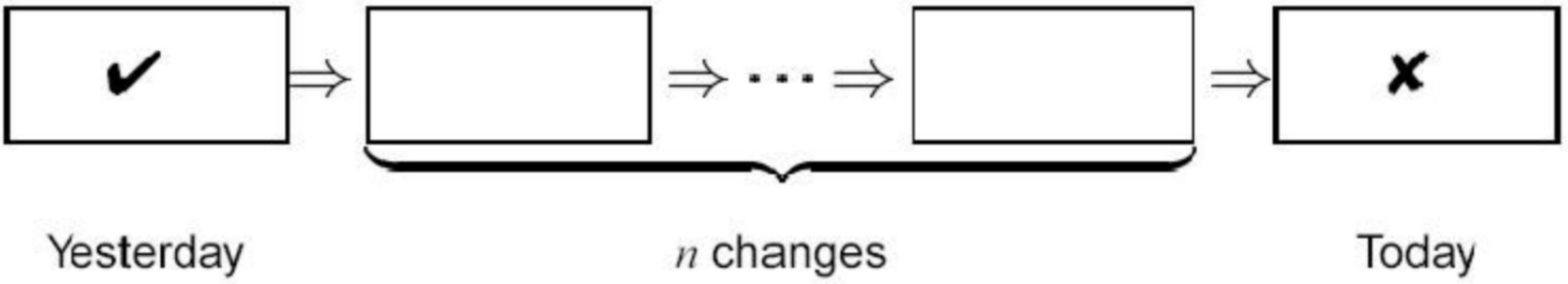

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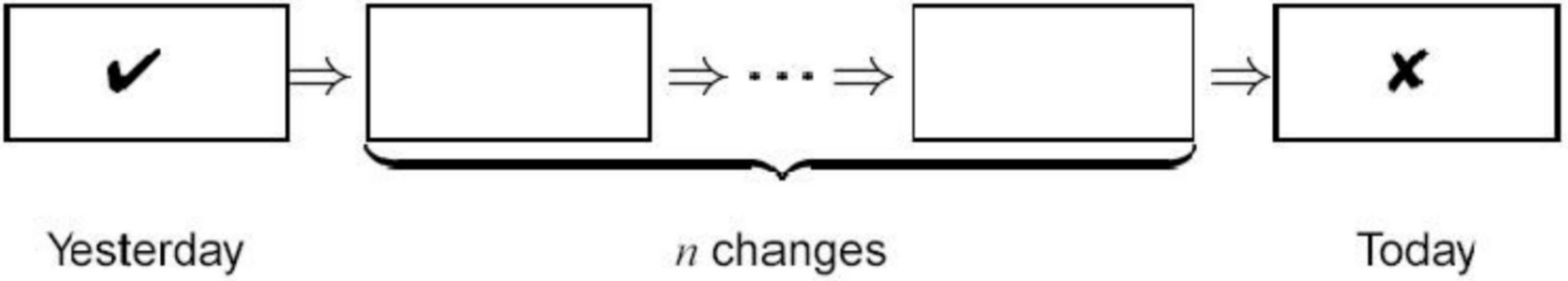

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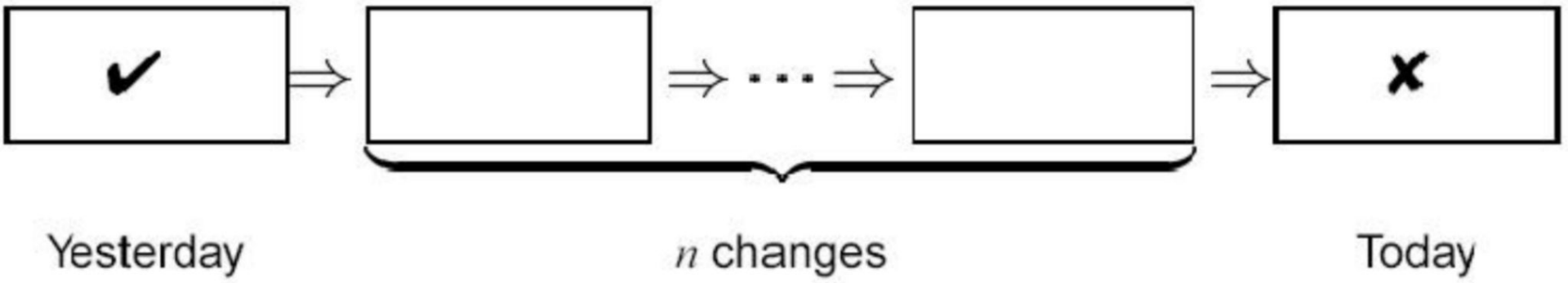

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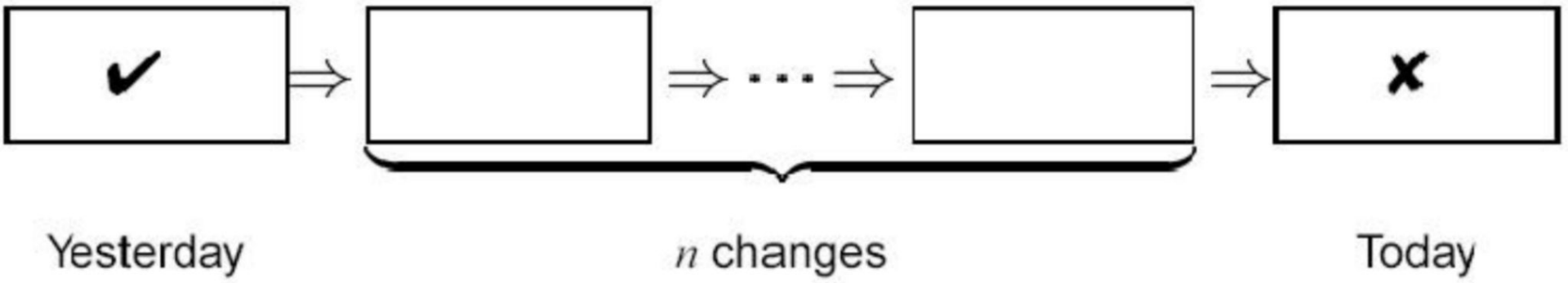

- C = set of *n* changes
- Interesting(X) = apply the changes in in X to Yesterday's version and compile. Run the tests on the result.
  - If the tests **fail**, Interesting(X) = **True**.
  - If the tests **pass**, Interesting(X) = **False**.

Delta debugging: algorithm: naive

- We could just **try all subsets** of C to find the smallest one that is Interesting

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Delta debugging: algorithm: naive

- We could just **try all subsets** of C to find the smallest one that is Interesting
  - **Problem**: if |C| = N, this takes 2^N time
  - Recall: real-world software is **unimaginably huge**
- We want a **polynomial-time** solution
  - Ideally one that is more like log(N)
  - Or we'll loop for what feels like forever

Delta debugging: algorithm candidate

Precondition: Interesting({c_1 … c_n }) = True

DD({c, , …, c_n }) =

if n = 1 then return {c_1 }

let P_1 = {c_1 , … $c_{n/2}$}

let P_2 = {$c_{n/2+1}$, …, c_n }

if **Interesting**(P_1) is True:

then return DD(P_1)

else return DD(P_2)

Delta debugging: algorithm candidate

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DD($\{c, , \ldots, c_n\}$) =

if n = 1 then return $\{c_1\}$

let $P_1 = \{c_1, \ldots c_{n/2}\}$

let $P_2 = \{c_{n/2+1}, \ldots, c_n\}$

if **Interesting**(P_1) is True:

then return DD(P_1)

else return DD(P_2)

This is just **binary search**! It won't work if you need a big subset to be Interesting

Delta debugging: algorithm: assumptions

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- **Any subset** of changes may be Interesting
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  - What happens in such a case?

Delta debugging: algorithm: interference

- By **Monotonicity**
  - If Interesting(P_1) = False and Interesting(P_2) = False

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  - If Interesting(P_1) = False and Interesting(P_2) = False
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- In Delta Debugging, this is called ***interference***

Delta debugging: algorithm: interference

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  - Consider P_1
    - Find a minimal subset D_2 of P_2
    - Such that Interesting($P_1 \cup D_2$) = True

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Key point: combination of elements from both

Delta debugging: algorithm: example

- Suppose {3,6} Is Smallest Interesting Subset of {1, …, 8}

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- Let’s use DD to find it

1 2 3 4 5 6 7 8 = Interesting

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1 2 3 4

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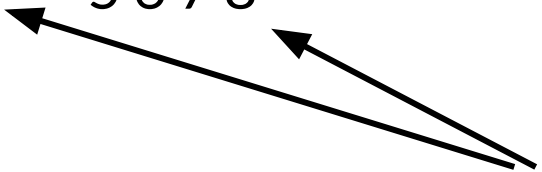

First step: partition C = {1, …, 8}
into P_1 = {1, …, 4} and P_2 = {5, …, 8}

Delta debugging: algorithm: example

- Suppose {3,6} Is Smallest Interesting Subset of {1, …, 8}
- Let's use DD to find it

1 2 3 4 5 6 7 8 = Interesting
1 2 3 4 = ???
5 6 7 8 = ???

Next step: test P_1 and P_2

Delta debugging: algorithm: example

- Suppose {3,6} Is Smallest Interesting Subset of {1, …, 8}
- Let's use DD to find it

1 2 3 4 5 6 7 8 = Interesting
1 2 3 4 = False
5 6 7 8 = False

Interference! Sub-step: find minimal subset D_1 of P_1 such that Interesting(D_1 + P_2)

Delta debugging: algorithm: example

- Suppose {3,6} Is Smallest Interesting Subset of {1, …, 8}
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1 2	5 6 7 8	= False	
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Delta debugging: algorithm: example

- Suppose {3,6} Is Smallest Interesting Subset of {1, …, 8}
- Let's use DD to find it

1 2 3 4 5 6 7 8	= Interesting
1 2 3 4	= False
5 6 7 8	= False
1 2 5 6 7 8	= False
3 4 5 6 7 8	= True
3 5 6 7 8	= True

$D_1 = \{ 3 \}$

Now we need to find D_2

Delta debugging: algorithm: example

- Suppose {3,6} Is Smallest Interesting Subset of {1, …, 8}
- Let's use DD to find it

1 2 3 4	5 6 7 8	= Interesting	$D_1 = \{ 3 \}$
1 2 3 4		= False	
	5 6 7 8	= False	Now we need to find D_2
1 2	5 6 7 8	= False	
3 4	5 6 7 8	= True	
3	5 6 7 8	= True	
1 2 3 4	5 6	= True	

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- Suppose {3,6} Is Smallest Interesting Subset of {1, …, 8}
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1 2	5 6 7 8	= False
3 4	5 6 7 8	= True
3	5 6 7 8	= True
1 2 3 4	5	= False

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Delta debugging: algorithm: example

- Suppose {3,6} Is Smallest Interesting Subset of {1, …, 8}
- Let's use DD to find it

1 2 3 4	5 6 7 8	= Interesting	$D_1 = \{ 3 \}$
1 2 3 4		= False	
	5 6 7 8	= False	$D_2 = \{ 6 \}$
1 2	5 6 7 8	= False	
3 4	5 6 7 8	= True	
3	5 6 7 8	= True	
1 2 3 4	6	= True	

Delta debugging: algorithm: example

- Suppose {3,6} Is Smallest Interesting Subset of {1, …, 8}
- Let's use DD to find it

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1 2 3 4		= False
	5 6 7 8	= False
1 2	5 6 7 8	= False
3 4	5 6 7 8	= True
3	5 6 7 8	= True
1 2 3 4	6	= True

$D_1 = \{ 3 \}$

$D_2 = \{ 6 \}$

So, final answer =
$D_1 \cup D_2 = \{ 3, 6 \}$

Delta debugging: final algorithm

Precondition: Interesting($\{c_1 \ldots c_n\}$) = True

DD(P, $\{c, , \ldots, c_n\}$) =

if n = 1 then return $\{c_1\}$

let $P_1 = \{c_1, \ldots c_{n/2}\}$

let $P_2 = \{c_{n/2+1}, \ldots, c_n\}$

if **Interesting**($P_1 \cup P$) is True then return DD(P, P_1)

else if **Interesting**($P_2 \cup P$) is True then return DD(P, P_2)

else return **DD**($P \cup P_2, P_1$) $\cup$ **DD**($P \cup P_1, P_2$)

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  - DD is **logarithmic**: 2 * log |C|
  - Why?

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  - Is this realistic?

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  - DD is **logarithmic**: 2 * log |C|
  - Why?
- Otherwise, DD is **linear**
  - Assuming constant time per Interesting() check
  - Is this realistic?
- If Interesting can return “Unknown”
  - DD is **quadratic**: $|C|^2 + 3|C|$
  - If all tests are Unknown except last one (unlikely)

Assumptions restated on this slide for convenience

Delta debugging: questioning assumptions

- **All three** assumptions are **questionable**
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Monotonicity is rare in the real world. But DD still finds *an* interesting subset if Interesting is not monotonic (might not be minimal)

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Ambiguity will cause DD to fail. Hint: try tracing DD on Interesting ({2, 8}) = True, but Interesting({2, 8} intersect {3, 6}) = False

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The world is **often inconsistent**. Example: we are minimizing changes to a program to find patches that makes it crash. Some subsets may not build or run!

Delta debugging: in the real world

- `git bisect` implements a DD-like algorithm (look it up!)
- for thread schedules: DejaVu tool by IBM, CHESS by Microsoft, etc.
- Eclipse plugins for code changes (“DDinput”, “DDchange”)
- you can also do delta debugging **by hand** (I do this often for programs that cause compiler bugs!)

Debugging (Part 2/2)

Today's agenda:

- Debugging
  - printf debugging and logging
  - delta debugging
  - **debuggers**

Debuggers

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- Can operate on source code or assembly code
- **Inspect** the values of registers, memory
- **Key Features** (we’ll explain all of them): attach to process, single-stepping, breakpoints, conditional breakpoints, watchpoints

Debuggers: how do they work

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- You can install a **signal handler** – a procedure that will be executed when the signal occurs.
  - Signal handlers are vulnerable to **race conditions**. Why?

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Debuggers: how do they work: attaching

- Attaching a debugger to a process requires **operating system** support
- There is a **special system call** that allows one process to act as a debugger for a target
  - What are the **security** concerns?
- Once this is done, the debugger can basically "**catch signals**" delivered to the target
  - this isn't exactly what happens, but it's a good explanation …

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A ***breakpoint*** is a user-specified program statement on which the debugger should stop the program and begin an interactive debugging session

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  - Set up signal handler
  - Add in **exception causing instructions** at desired breakpoints
  - **Inspect** globals, do other debugger things, etc.

Debuggers: how do they work: breakpoints

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#define BREAKPOINT *(0)=0
int global = 11;
int debugger_signal_handler() {
  printf("debugger prompt: \n");
  // debugger code goes here!
}
void main() {
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  global = 33;
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All code added by the debugger in **purple**

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"**BREAKPOINT**" macro is guaranteed to cause SIGSEGV

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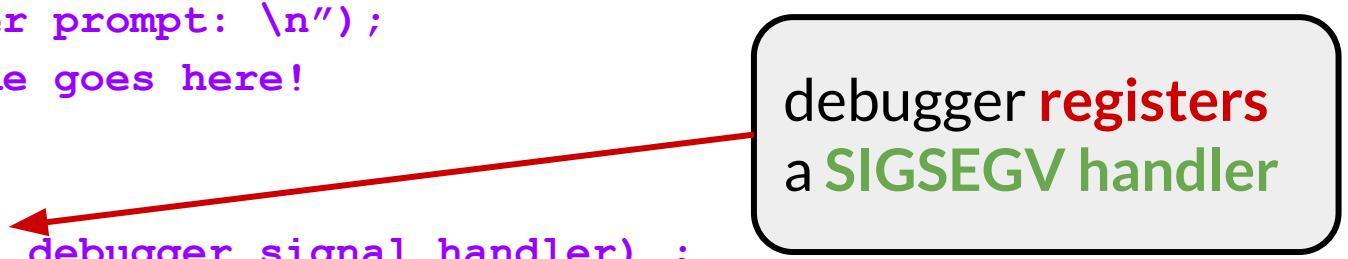

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at the user-specified breakpoint, the debugger **forces** a SIGSEGV (which its handler will intercept)

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- The “**single step**” or “**next**” interactive command is equal to:

Debuggers: single-stepping

- Debuggers also allow you to advance through code **one instruction at a time** (this is called ***single-stepping***)
- To implement this, put a breakpoint at the first instruction (= at program start)
- The "**single step**" or "**next**" interactive command is equal to:
  - Put a breakpoint at the next instruction
  - Resume execution
  - (No, really.)

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- How could we implement this?

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Hardware Watchpoints:

- Special register holds **L**: if the value at address **L** ever changes, the CPU raises an exception

Related tool: profilers

Note: from here on, this is **NOT** fair game for the midterm/final - we did not get to these slides in class!

NOT FAIR GAME FOR EXAMS

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This explanation of **sampling** leaves out some things:

- need to map PC values back to procedure names
- need to sum up map results
- sampling is cheap but can miss periodic behavior

Debugging: takeaways

- Debugging is a lot easier when you treat it as a science, rather than an art
- printf debugging and logging are good for determining what causes failures after the fact
- delta debugging is a semi-automated approach to formalizing the abstract debugging problem
  - useful way of thinking about how to debug anything
  - try `git bisect`
- debuggers are fantastic when you want to understand a program's internal state