Debugging (1/2)

Martin Kellogg

Reading quiz: debugging (1)

Q1: The student email in the first article is problematic because…

- **A.** it has too little detail
- **B.** it is ambiguous about the source of the problem
- **C.** it contains guesses about what’s wrong, but no evidence

Q2: The author of the second article argues that a debugger should be called a …

- **A.** “bug-finder”
- **B.** “inspector”
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Debugging

Two-lecture agenda:

- What is a bug, anyway?
- Bug reports, triage, and the de
- Debugging
  - printf debugging and loggi
  - delta debugging
  - debuggers

Announcements:

- revised proposal due today
- there is a midterm in this class one week from today
- if you want me to hold a review session, answer the poll I posted this morning on Discord

Debugging

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- Quality assurance is critical to software engineering
- We've discussed **static** (code review, dataflow analysis) and **dynamic** (testing) approaches to finding bugs
- Key question for today: what happens to all of the **bugs** those find?

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- cf. "design defect". I'll use "***bug***" to mean "a defect in source code"

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Definition: A ***feature request*** is a potential change to the intended purpose (requirements) of software

- An ***issue*** is either a bug report or a feature request (cf. "issue tracking system")

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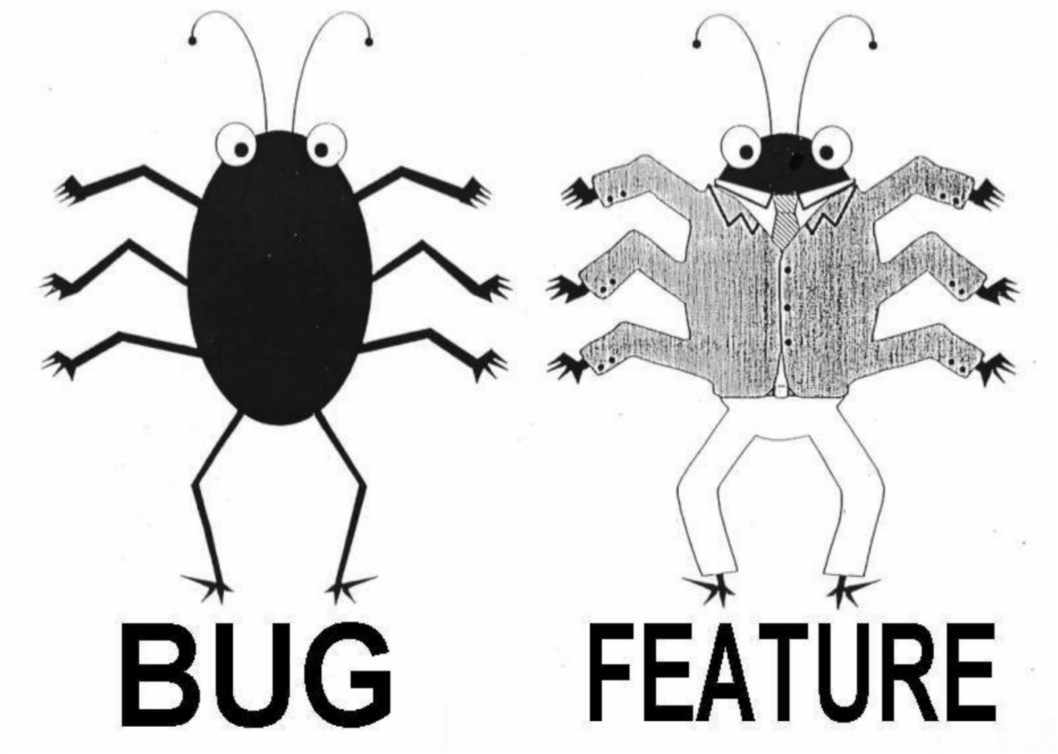
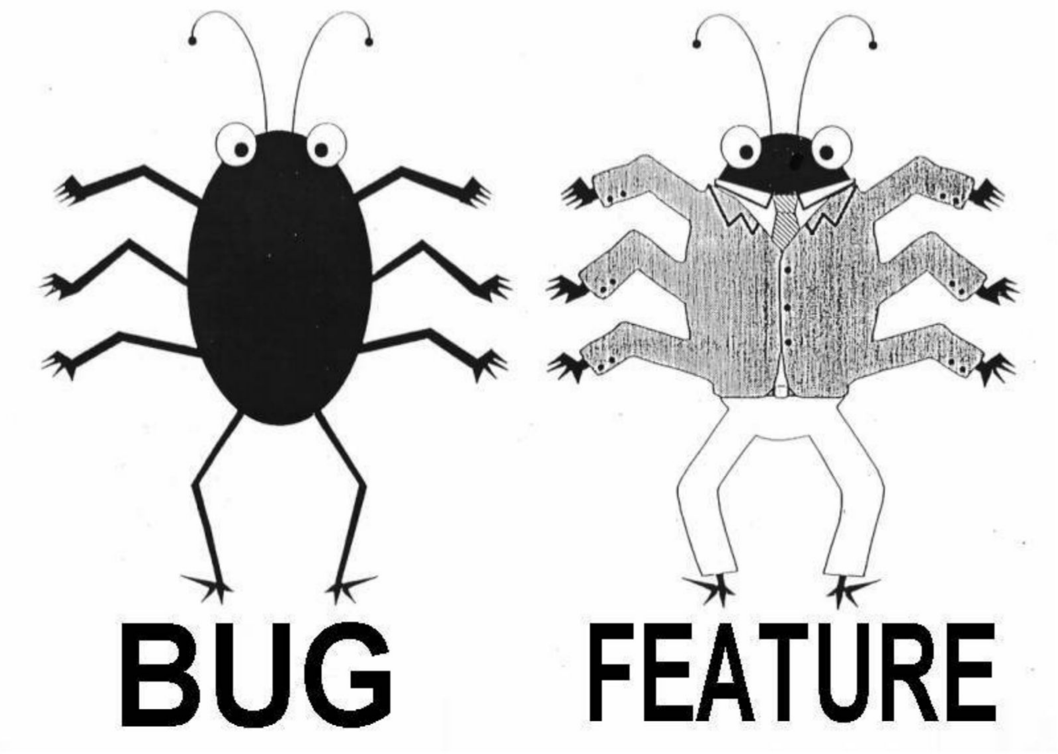


Terminology: bug vs. features

- what is a bug and what is a feature is **subjective**
- good rule of thumb: in any system with a large number of users, **someone** relies on every behavior of the system (intended or not) as if it were a feature



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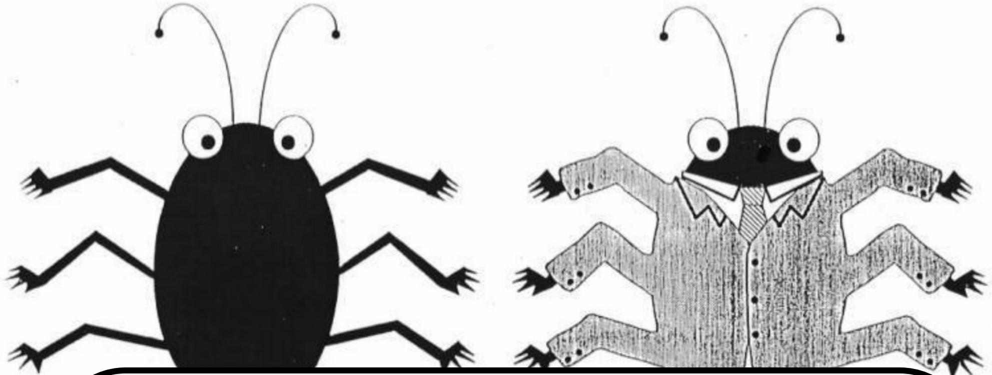

This is often why "**old**" systems (e.g., Linux, Windows, etc.) have behaviors that are **unintuitive** or difficult to learn: **someone relies on them**, so changing them would be considered a bug!

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- The overall process is **not linear**
  - There are multiple entry points, some cycles, and multiple exit points (and some never leave ...)

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Definition: the ***status*** of a defect report tracks its position in the lifecycle ("new", "resolved", etc.)

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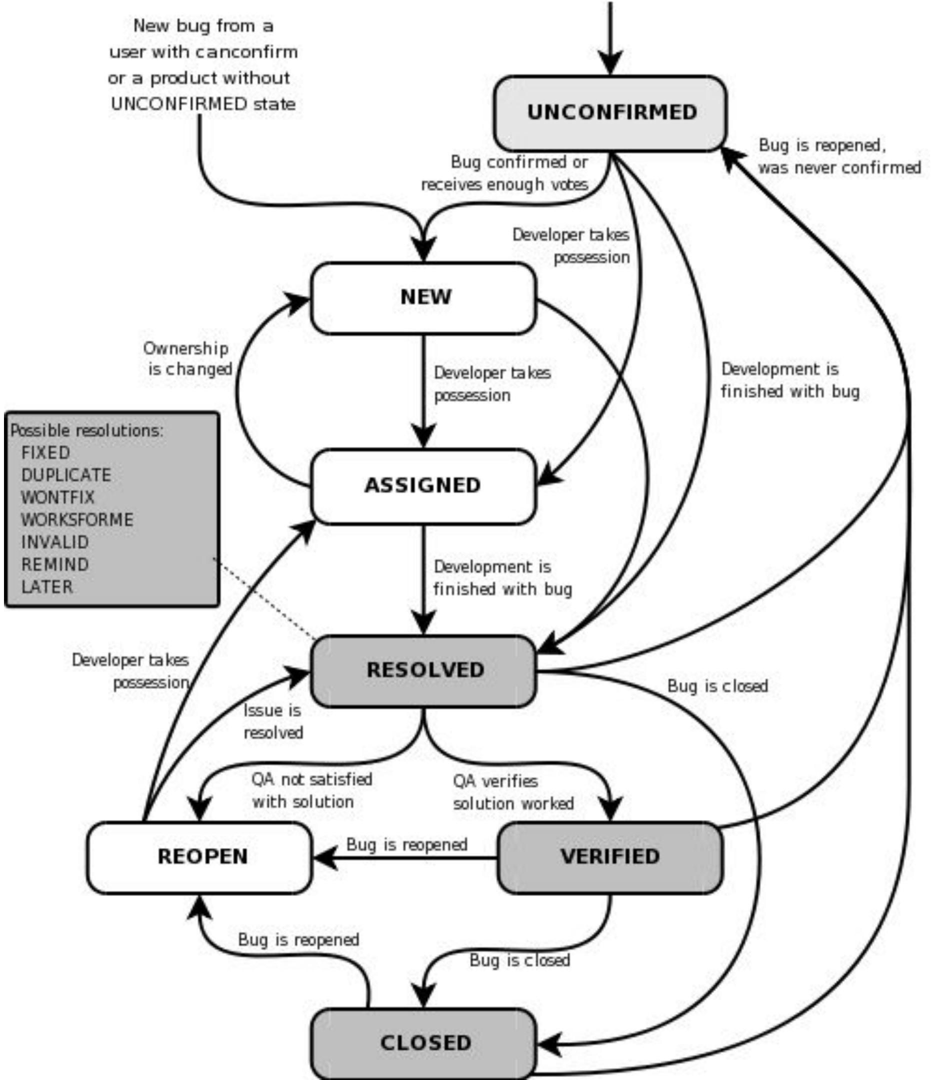
- For example, Bugzilla (a widely-used open-source issue tracker) uses **this** → flow for issues



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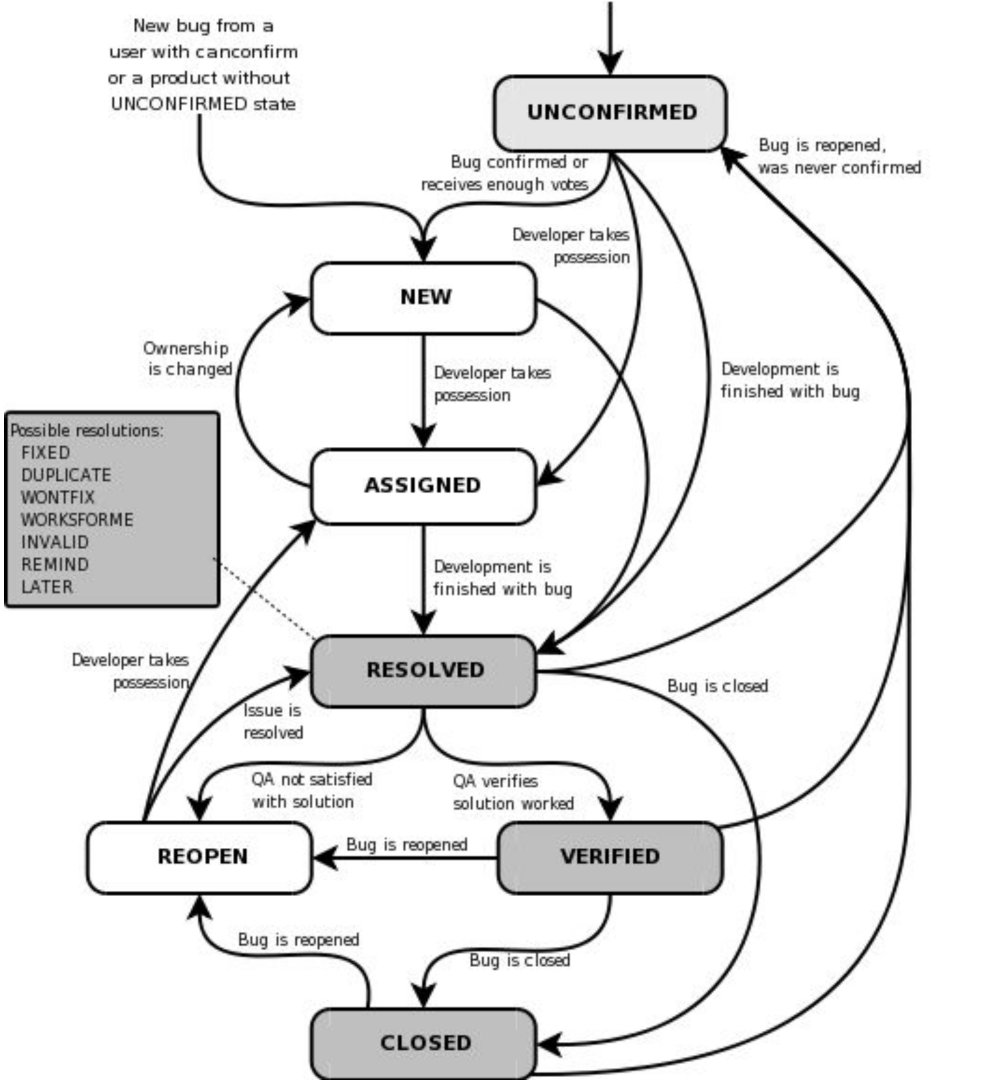

Defect report lifecycle

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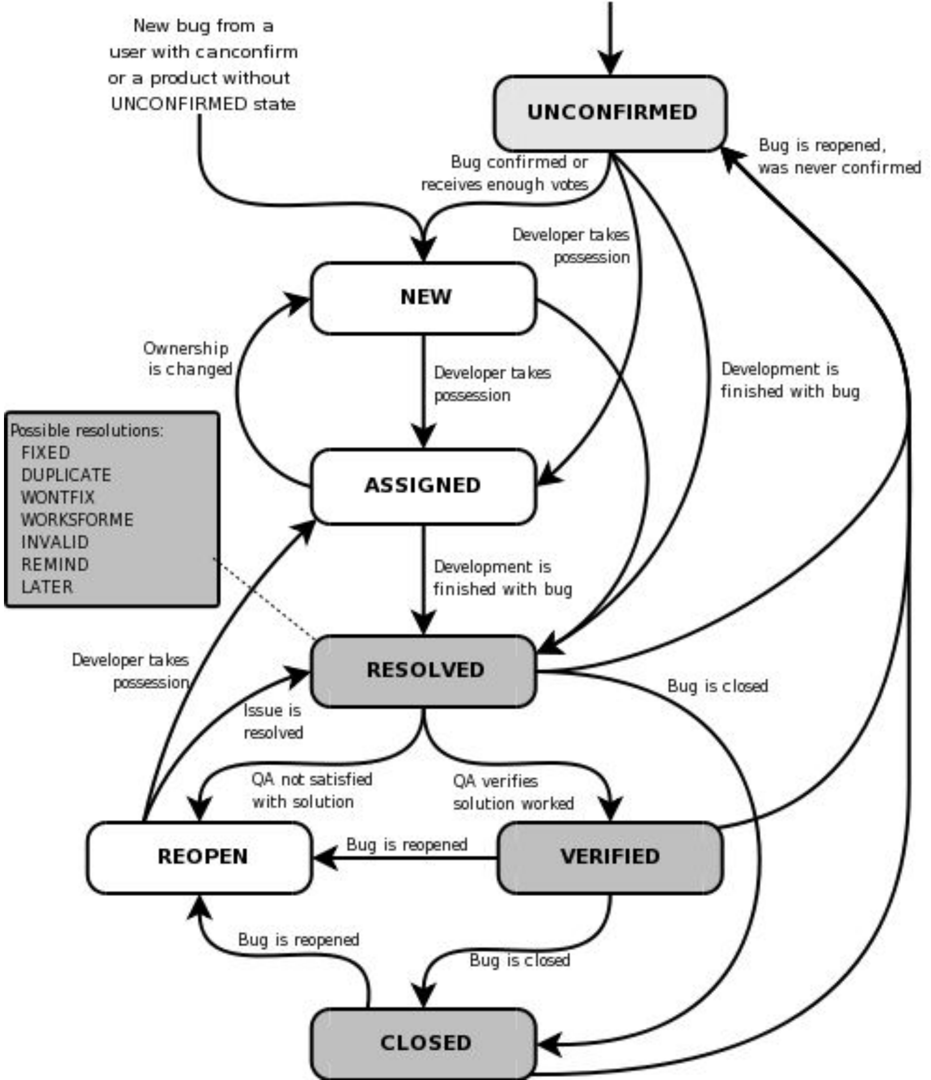
  - you should use an issue tracker for the group project (GitHub is okay)



Defect report lifecycle: new bugs

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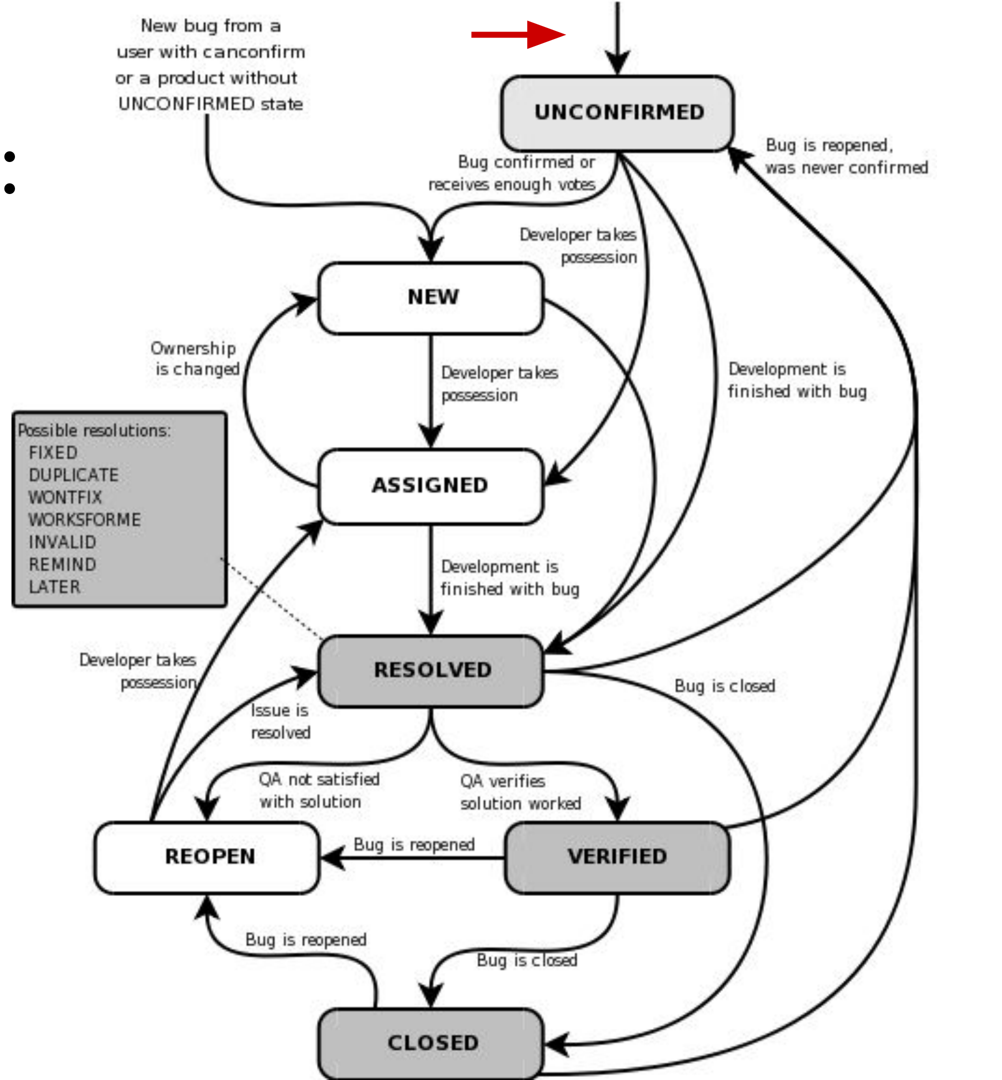

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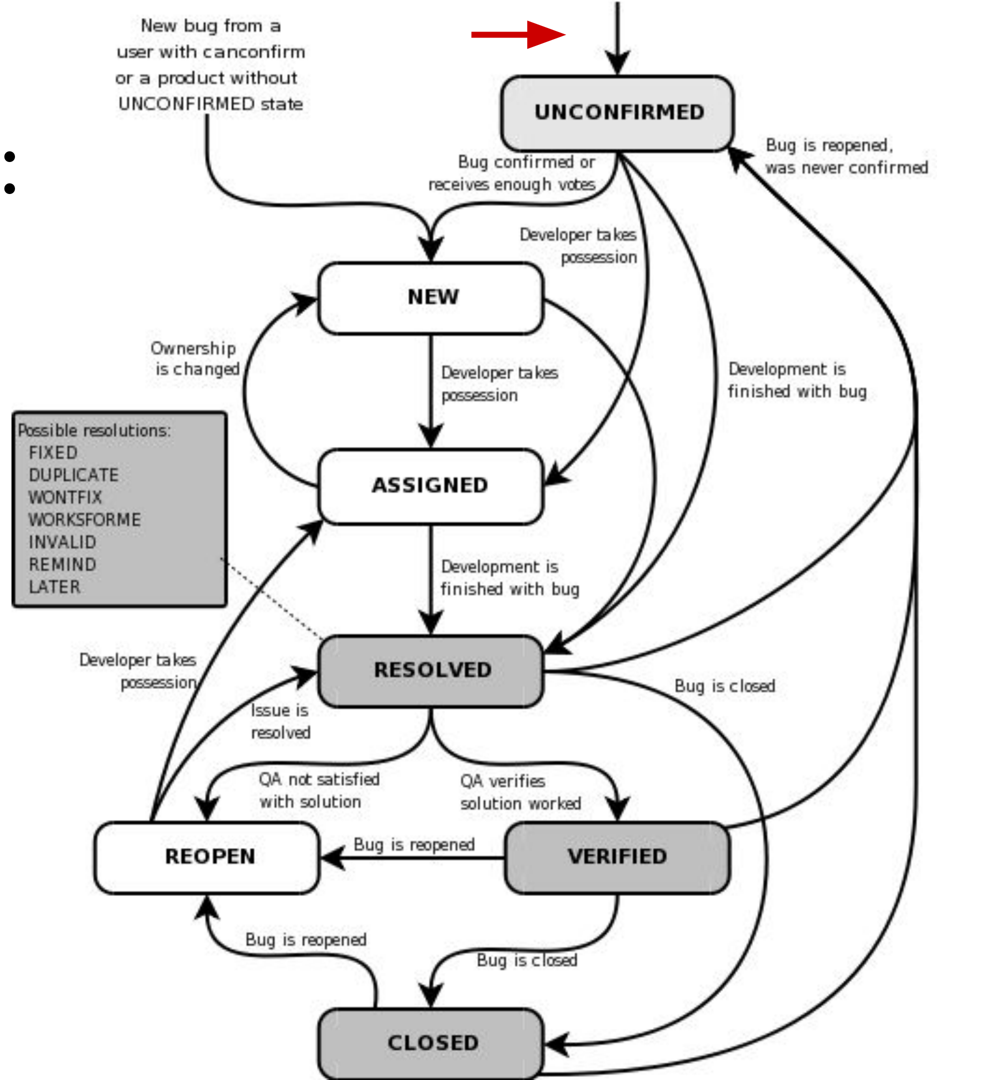

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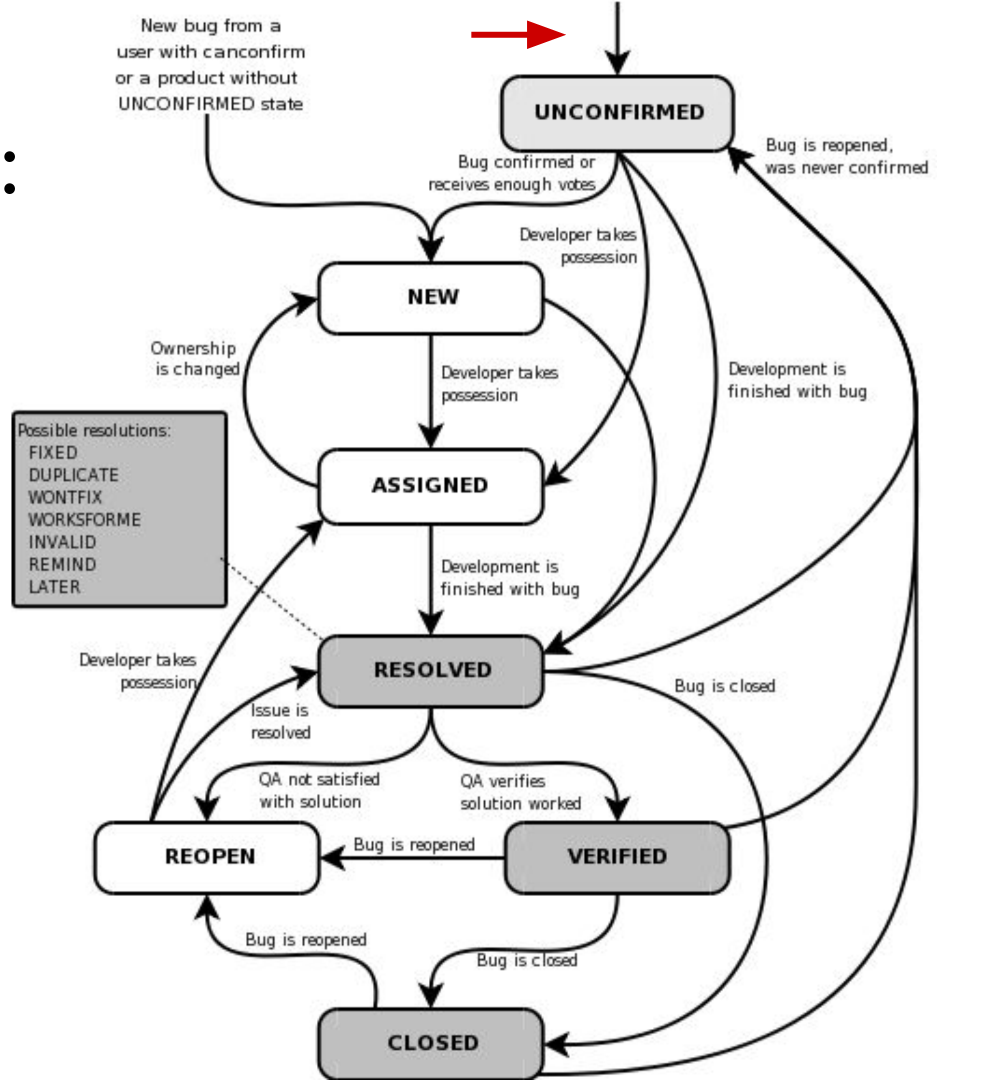

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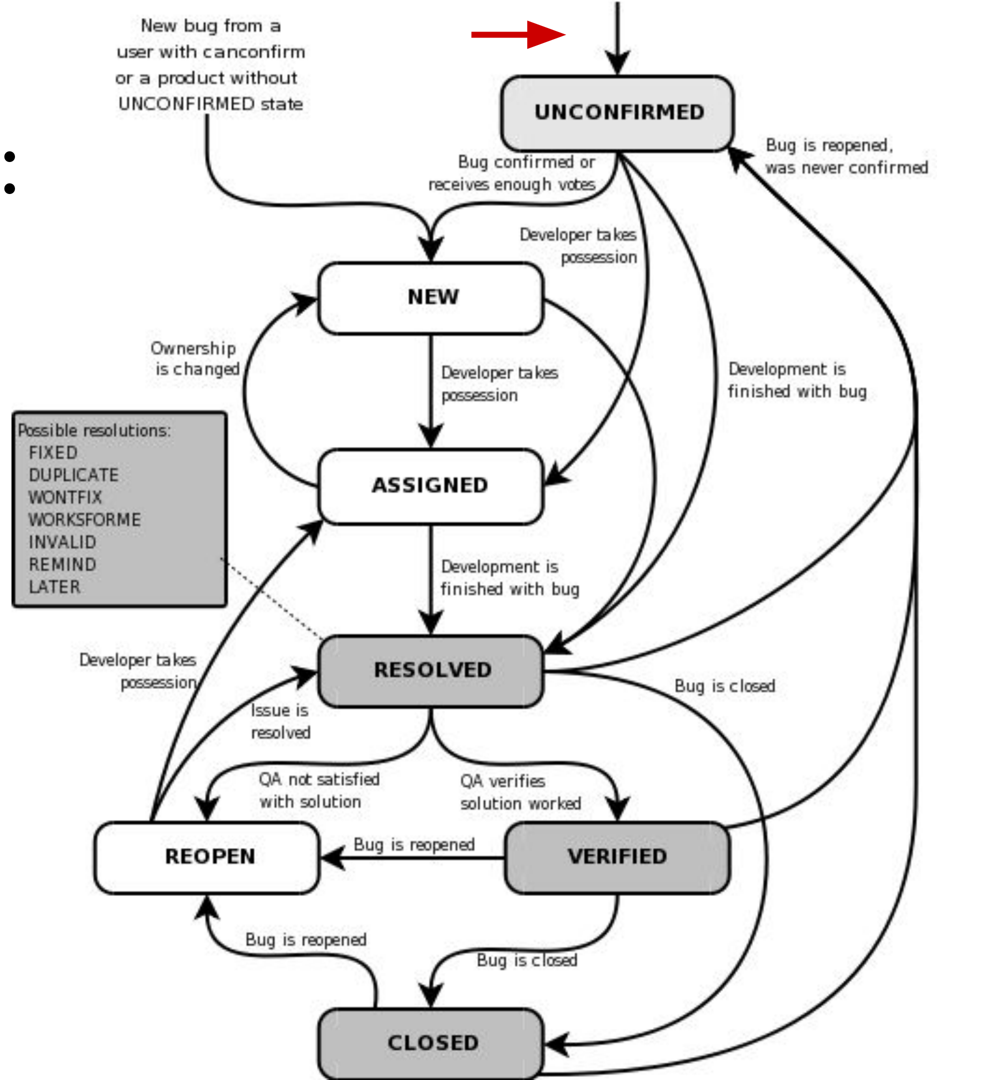

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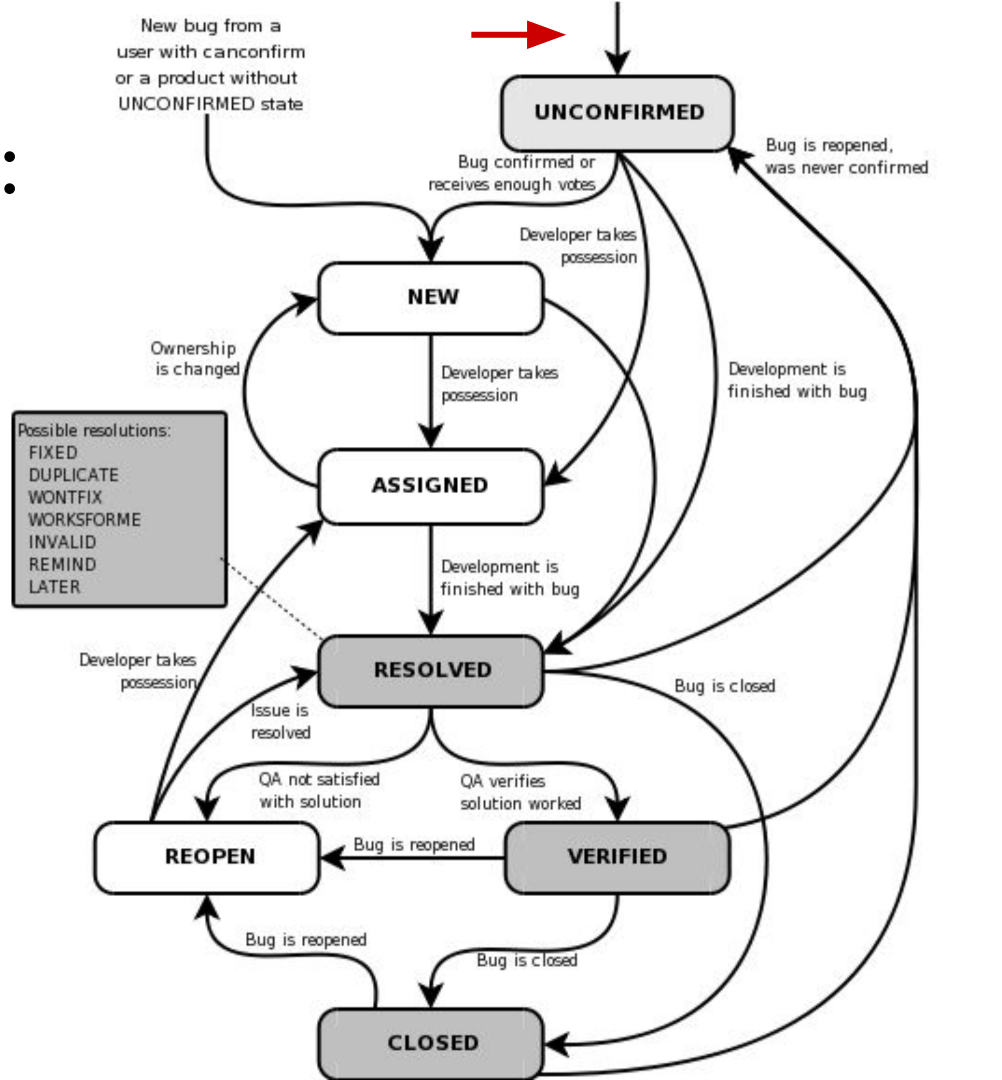

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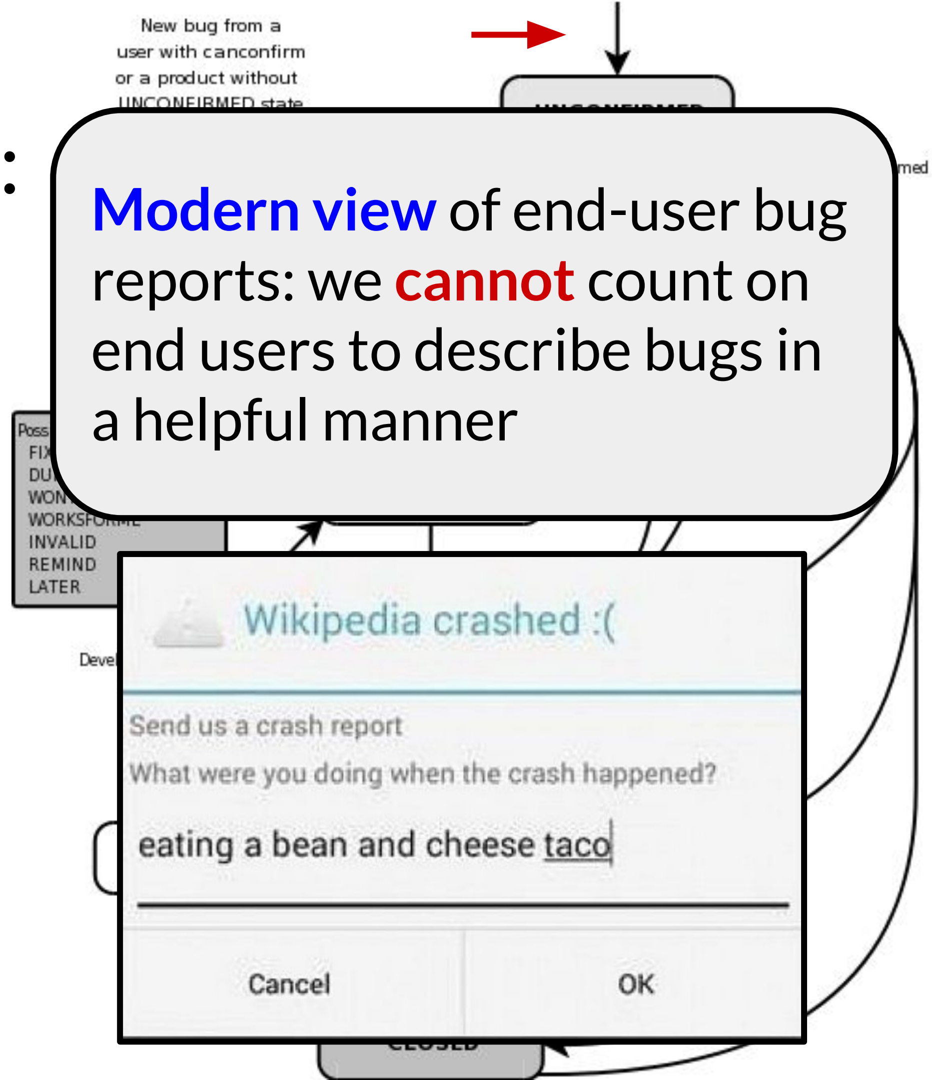
Modern view of end-user bug reports: we **cannot** count on end users to describe bugs in a helpful manner



Quick demo: GitHub issue tracker

example: https://github.com/typetools/checker-framework/issues

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Pet peeve of mine: never take a screenshot of your terminal! Always copy-paste text in bug reports.

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  - what you **expected** the program to do instead

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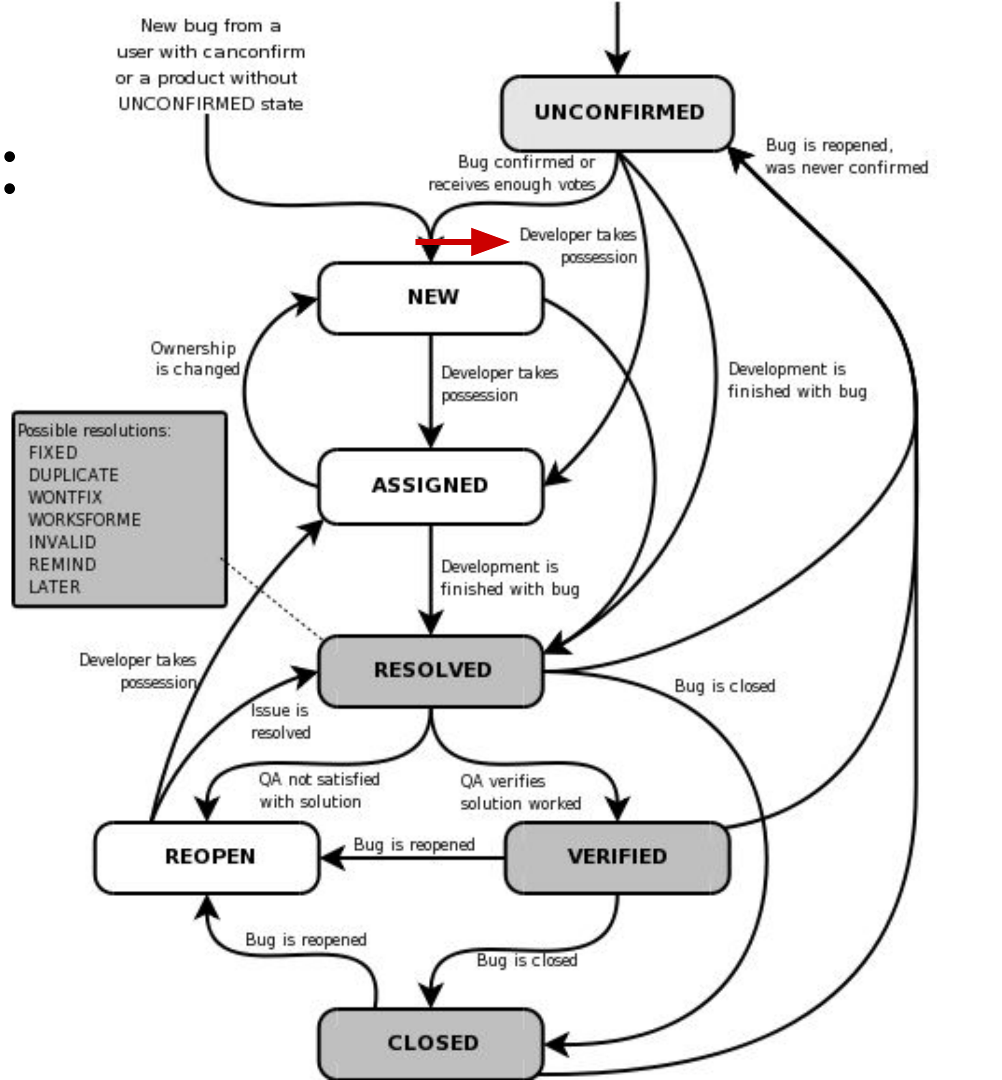
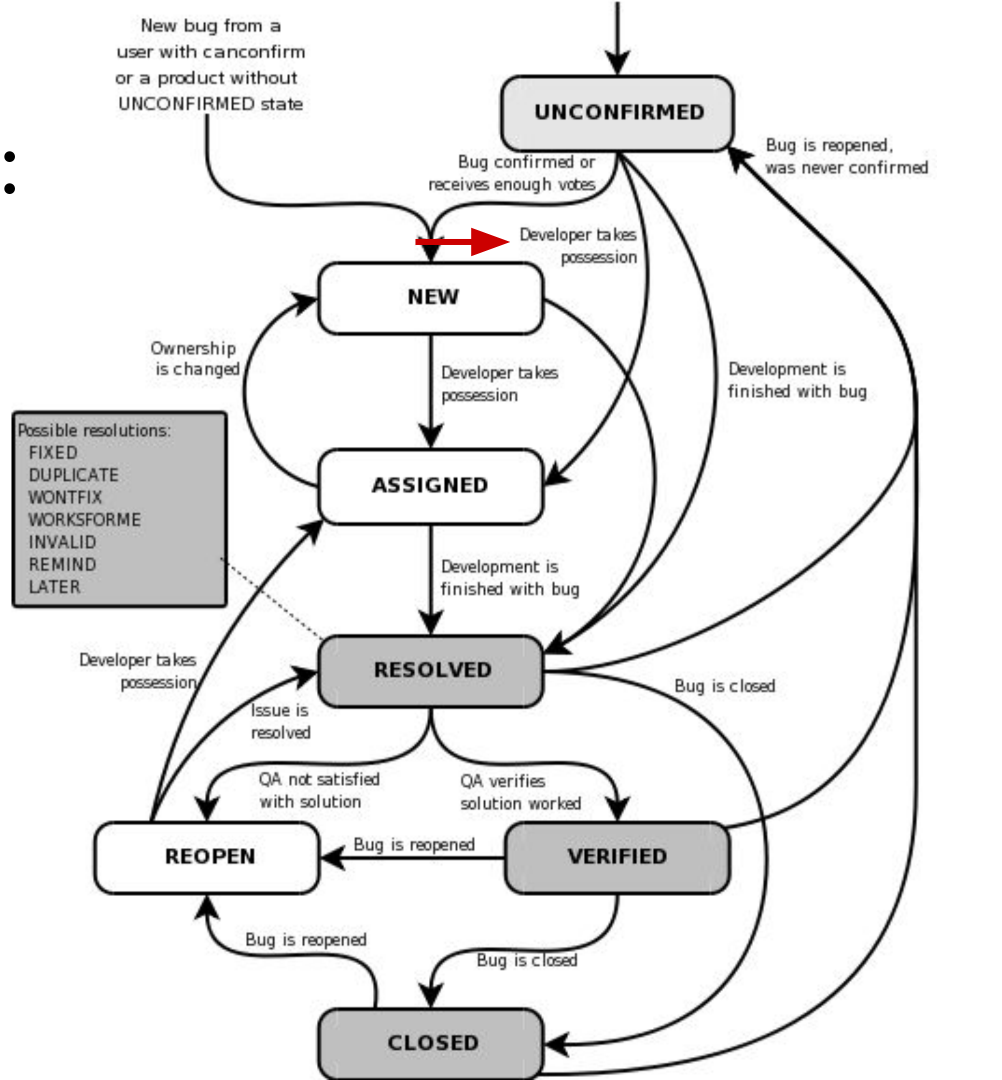


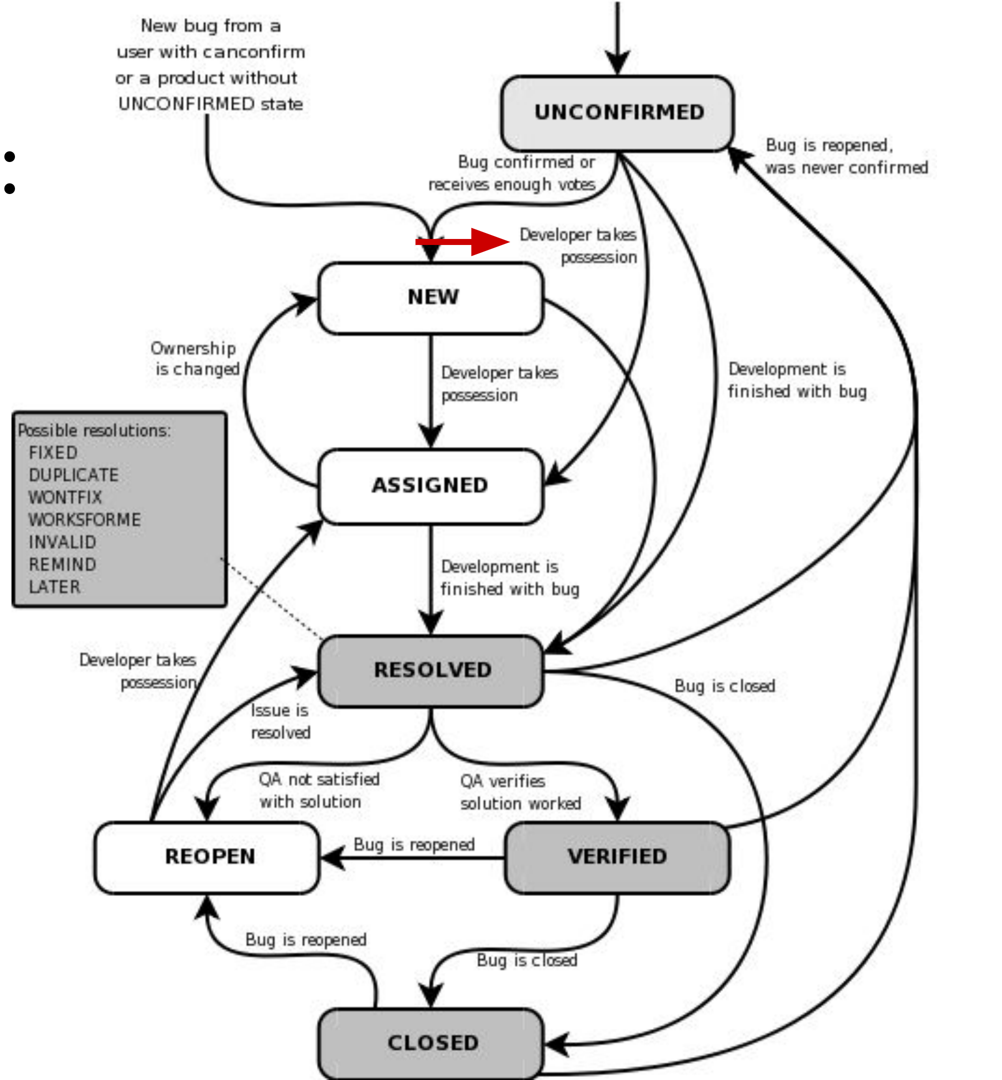
Defect report lifecycle: triage

- Key question: **which** bugs should we address first?



Defect report lifecycle: triage

- Key question: **which** bugs should we address first?
- "*triage*" is an analogy to **medicine**: which emergency room patient should you help first?



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- ***bug triage*** has the same definition, but with software defects instead of wounds/illnesses
- there are always **more defect reports than resources** available to address them
- we must do **cost-benefit** analysis:
  - How expensive is it to **fix** this bug?
  - How expensive is it to **not fix** this bug?

Defect report lifecycle: severity

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- BugZilla severity levels (varies by company/tool, but these typical):

Severity	Meaning
Blocker	Blocks further development and/or testing work.
Critical	Crashes, loss of data (internally, not your edit preview!) in a widely used and important component.
Major	Major loss of function in an important area.
Normal	Default/average.
Minor	Minor loss of function, or other problem that does not affect many people or where an easy workaround is present.
Trivial	Cosmetic problem like misspelled words or misaligned text which does not really cause problems.
Enhancement	Request for a new feature or change in functionality for an existing feature.

Defect report lifecycle: priority

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"As a rule of thumb, limit High priority task assignments for a single person to three, five in exceptional times."

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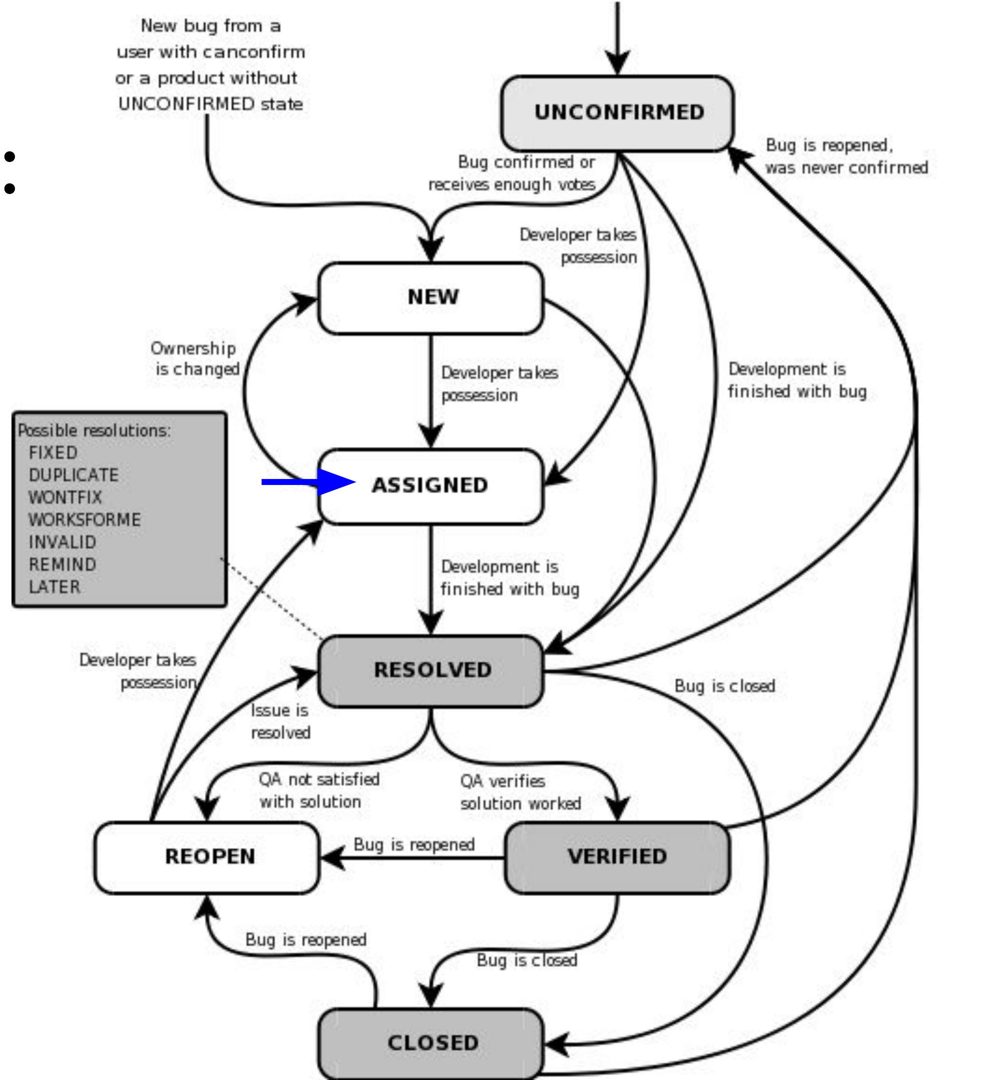
- severity and priority are used **together** (along with complexity, risk, etc.) to evaluate, prioritize and assign the resolution of reports
  - note that this is a bit of an **oversimplification**: "severity + priority = triage" is like "supply + demand = price"

Defect report lifecycle: assignment



Defect report lifecycle: assignment

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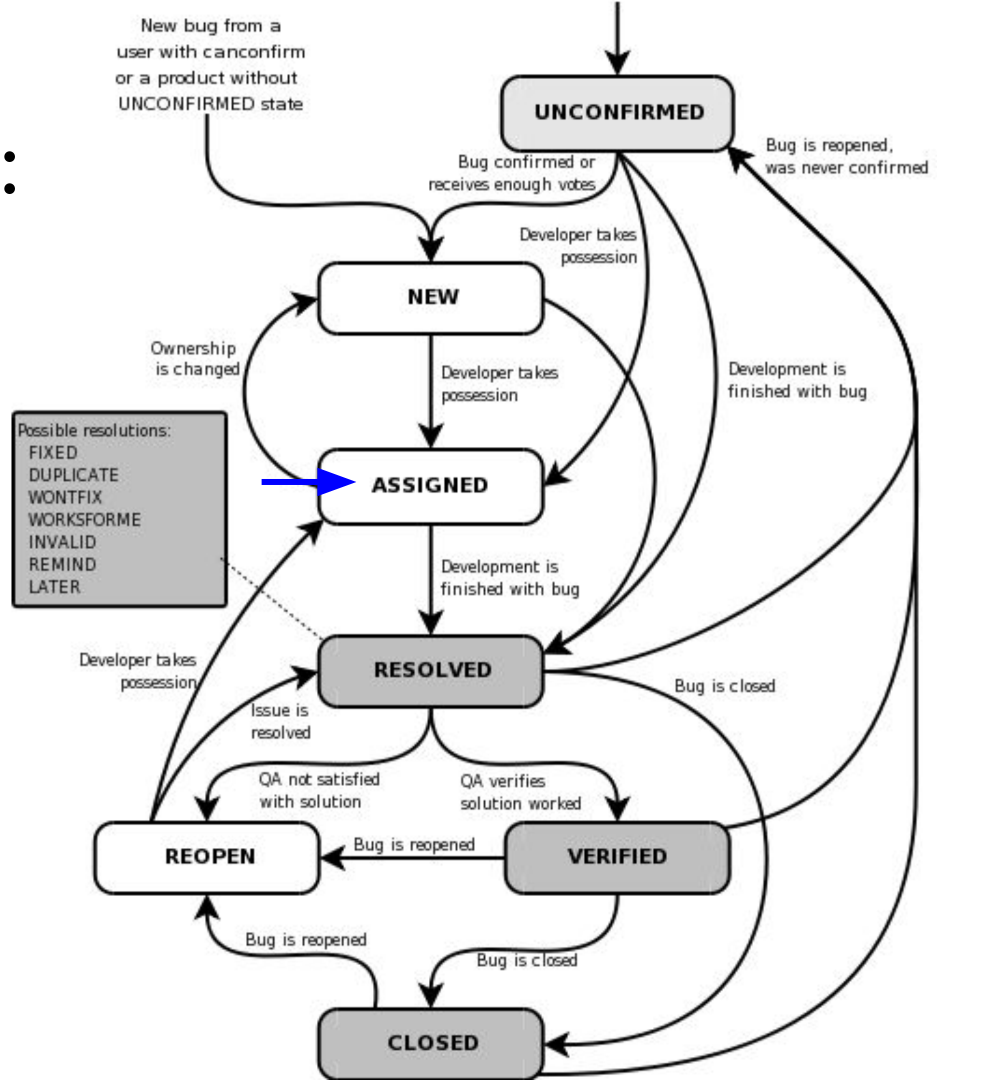

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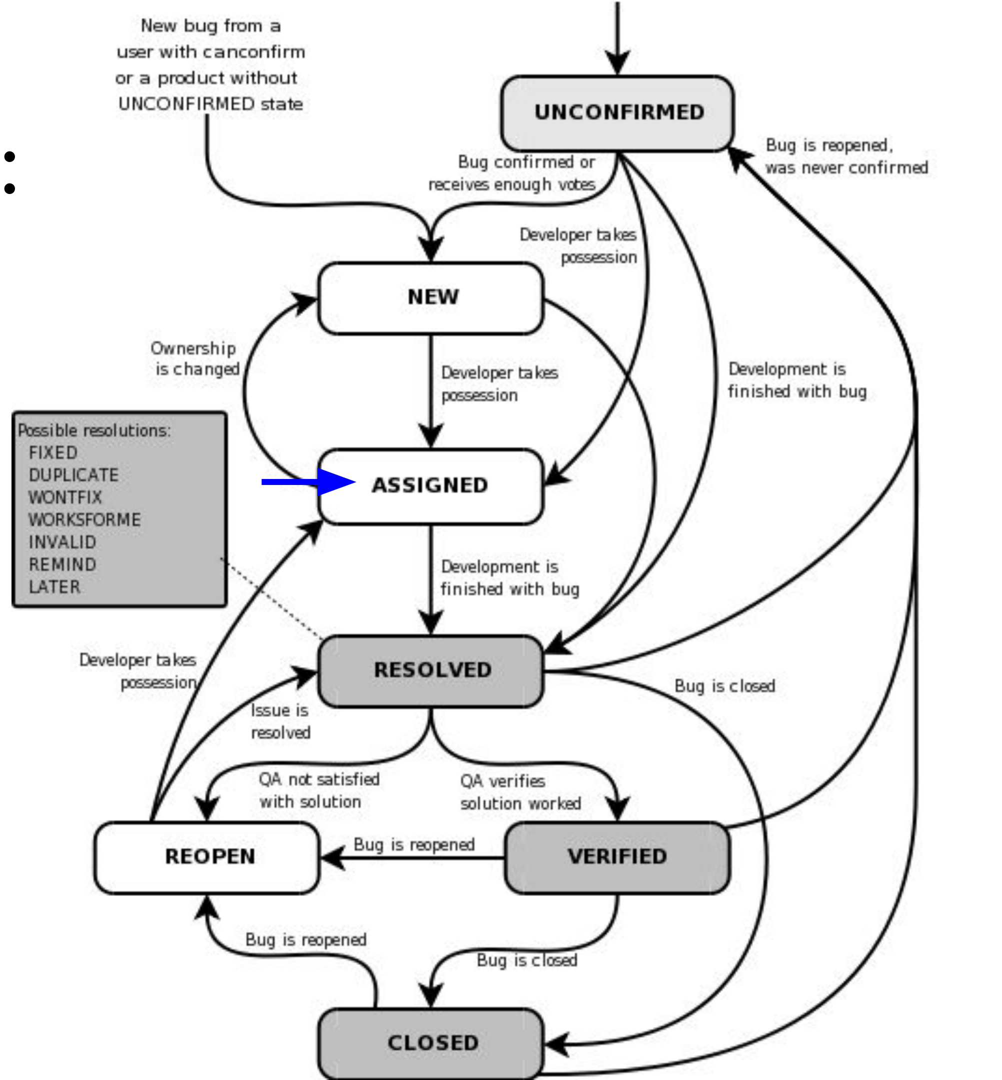

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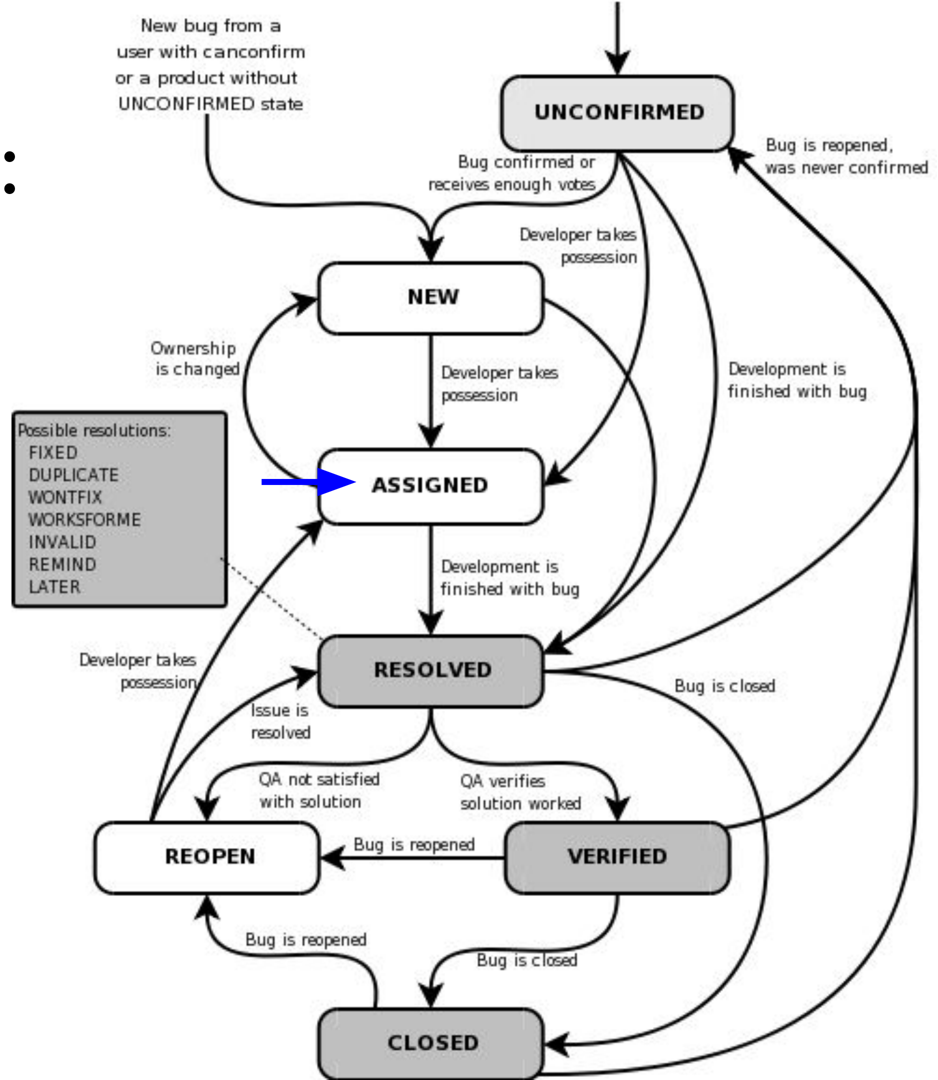

Defect report lifecycle: assignment

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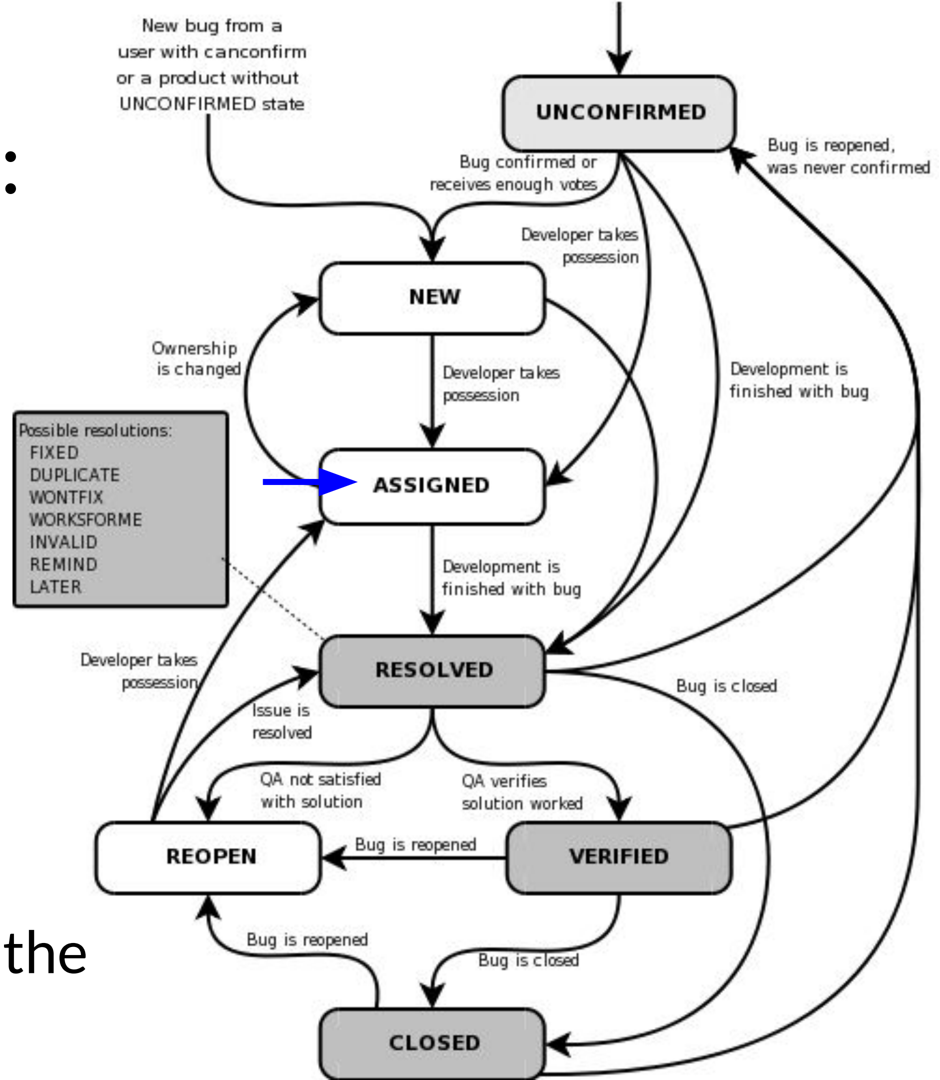
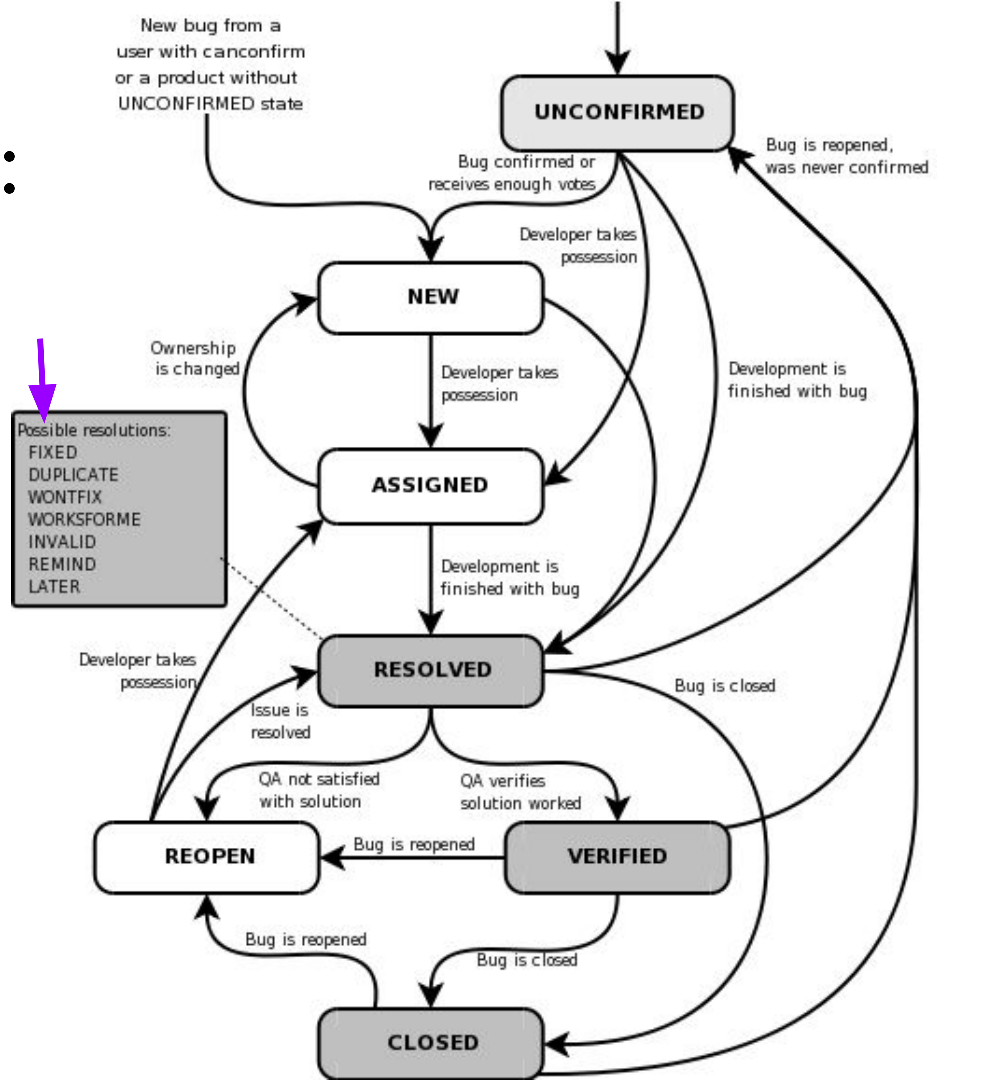


Defect report lifecycle: resolution



Defect report lifecycle: resolution

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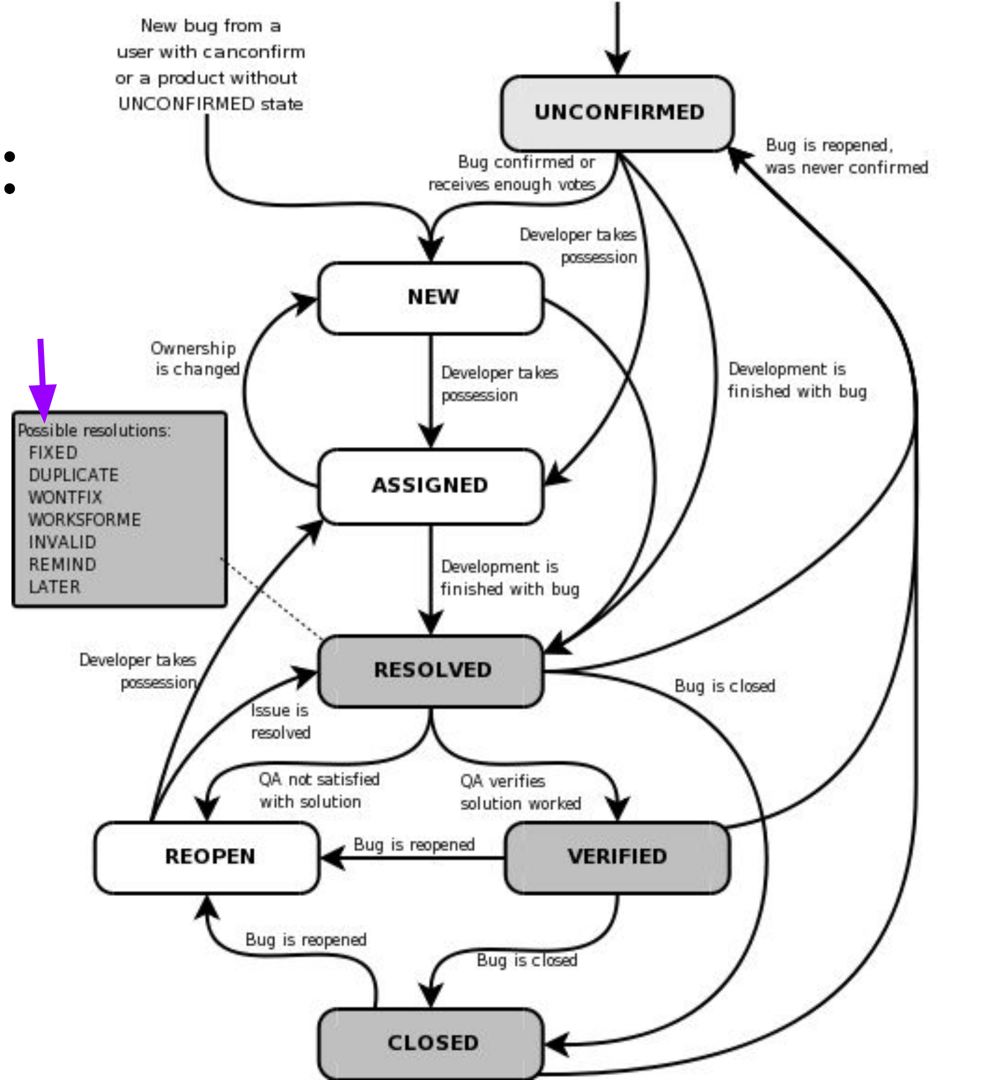

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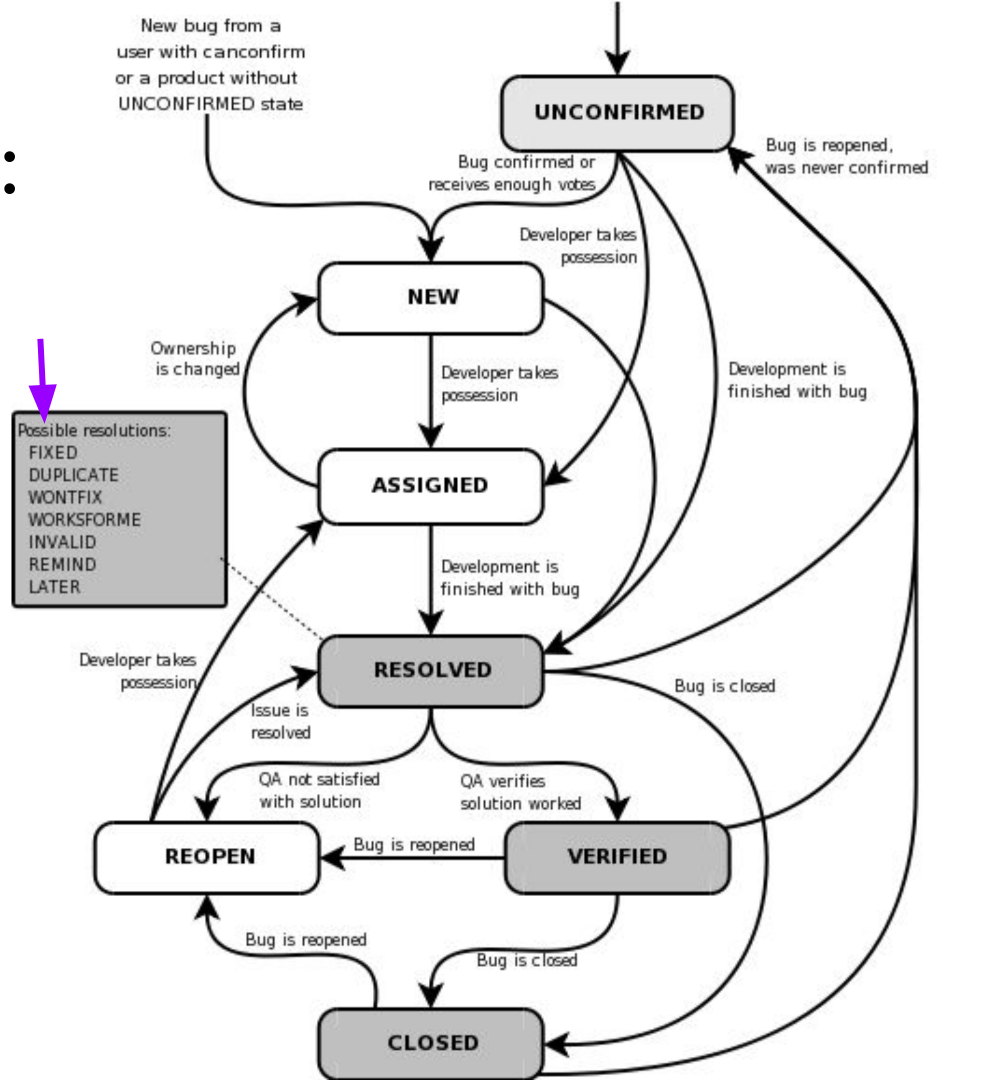

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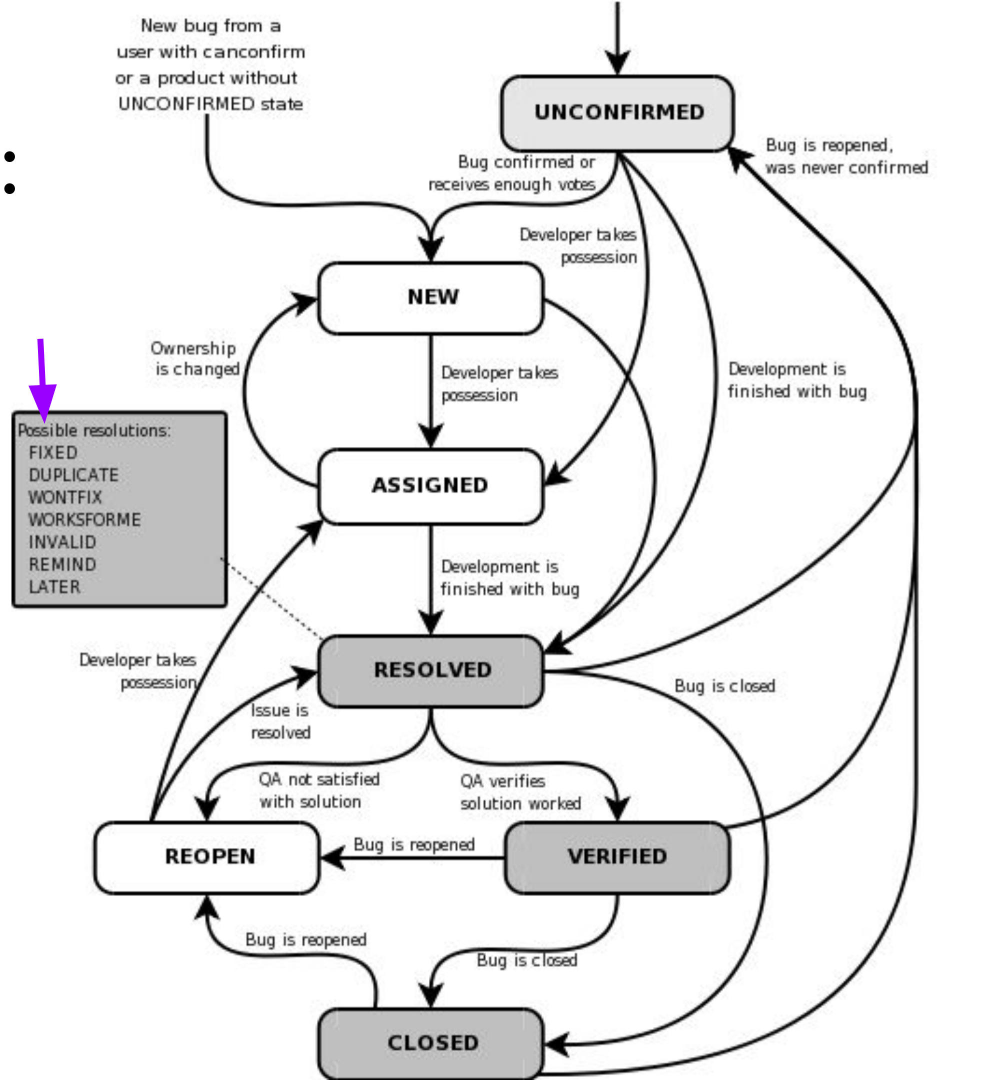
- **Important**: resolved **need not** mean "fixed"



Defect report lifecycle: possible resolutions

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- **DUPLICATE** (link to other bug report #)
- **WORKSFORME** (cannot reproduce, a.k.a. “WFM”)
- **MOVED** (give link: filed with wrong project)
- **NOTABUG** (report describes expected behavior)
- **NOTOURBUG** (is a bug, but not with our software)
- **INSUFFICIENTDATA** (cannot triage/fix w/o more)

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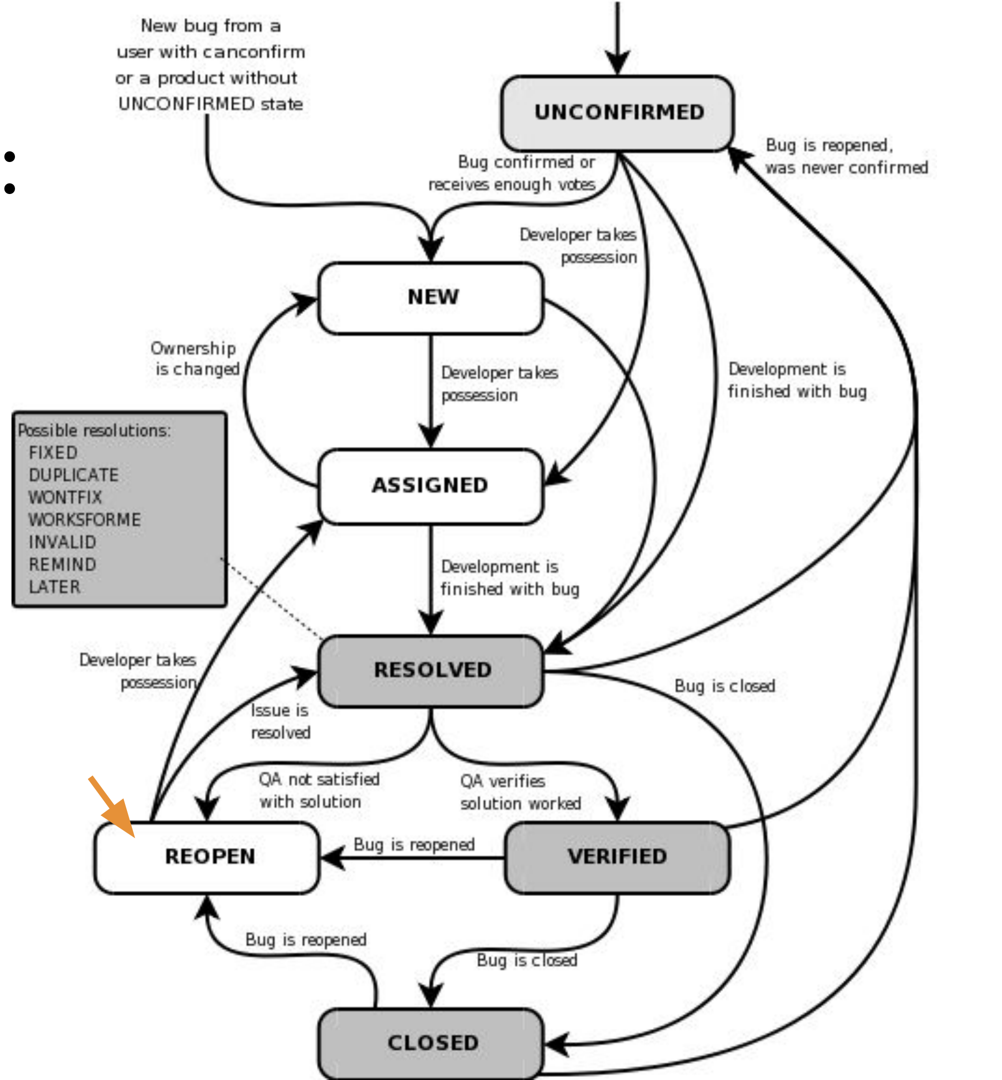
Thought question: what **fraction** of bug reports end up with each resolution?

Defect report lifecycle: possible resolutions

> A significant fraction of submitted bug reports are spurious duplicates that describe already-reported defects. Previous studies report that as many as 36% of bug reports were duplicates or otherwise invalid [2]. Of the 29,000 bug reports used in the experiments in this paper, 25.9% were identified as duplicates by the project developers.

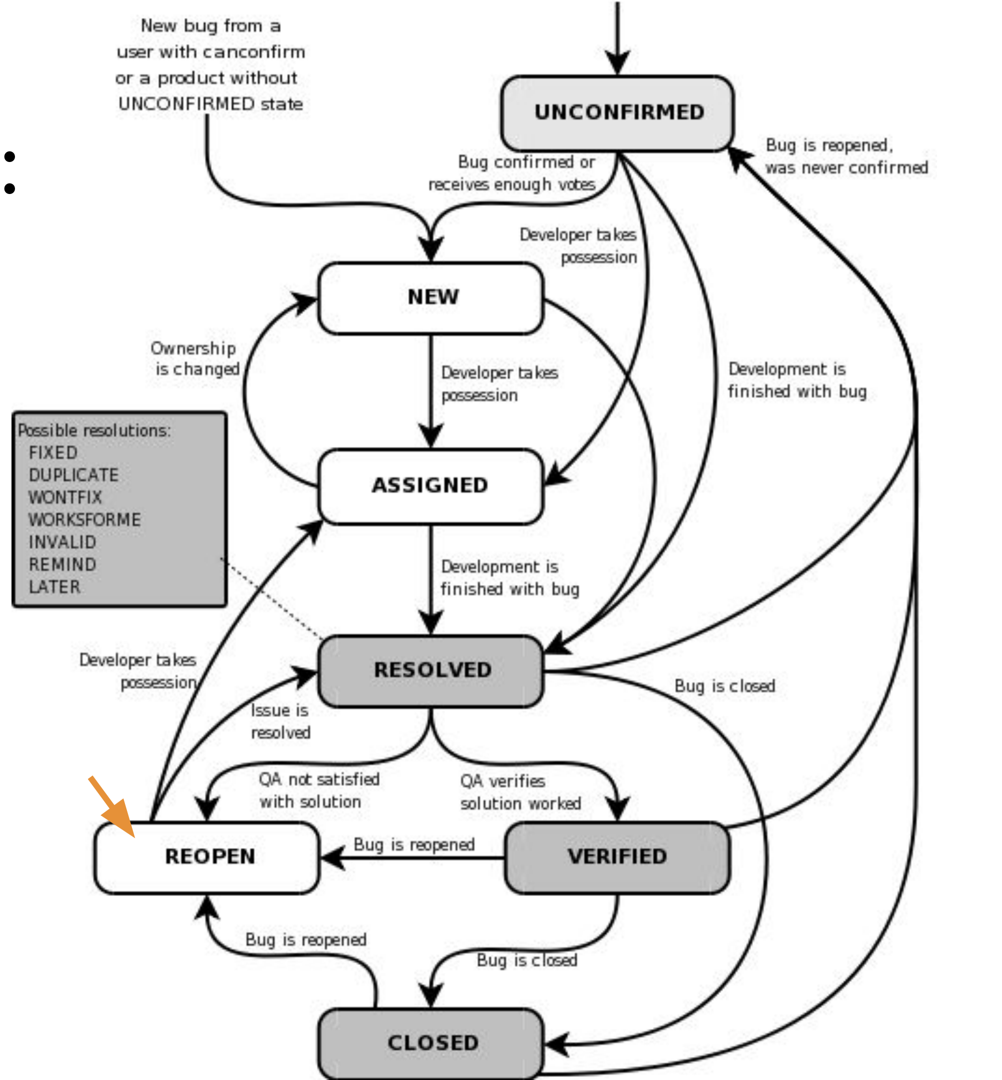
[Jalbert et al. Automated Duplicate Detection for Bug Tracking Systems. DSN 2008.]

Defect report lifecycle: reopening



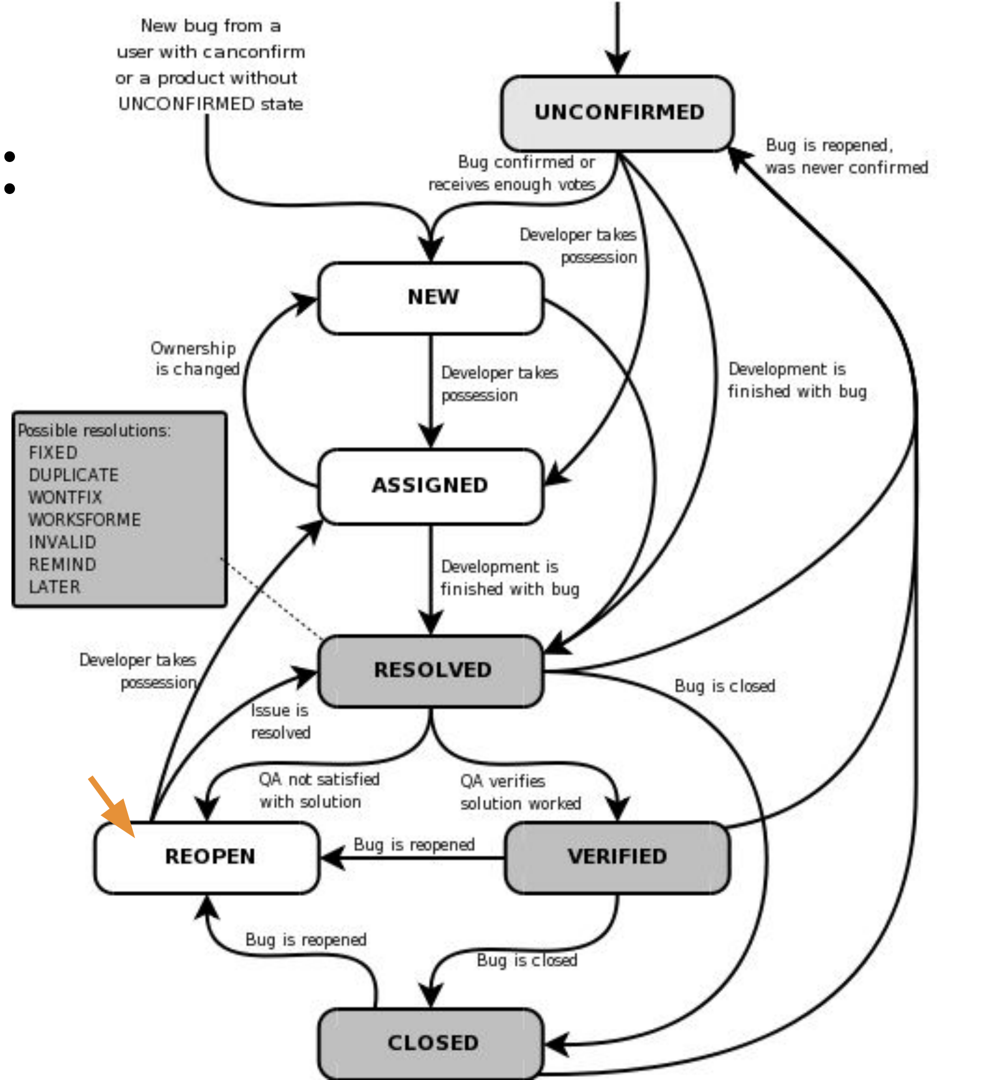
Defect report lifecycle: reopening

- A defect report that was previously resolved (e.g. “FIXED”) may be **reopened** if later evidence suggests the old resolution is no longer adequate



Defect report lifecycle: reopening

- A defect report that was previously resolved (e.g. “FIXED”) may be **reopened** if later evidence suggests the old resolution is no longer adequate
- Surely this only happens **rarely**?



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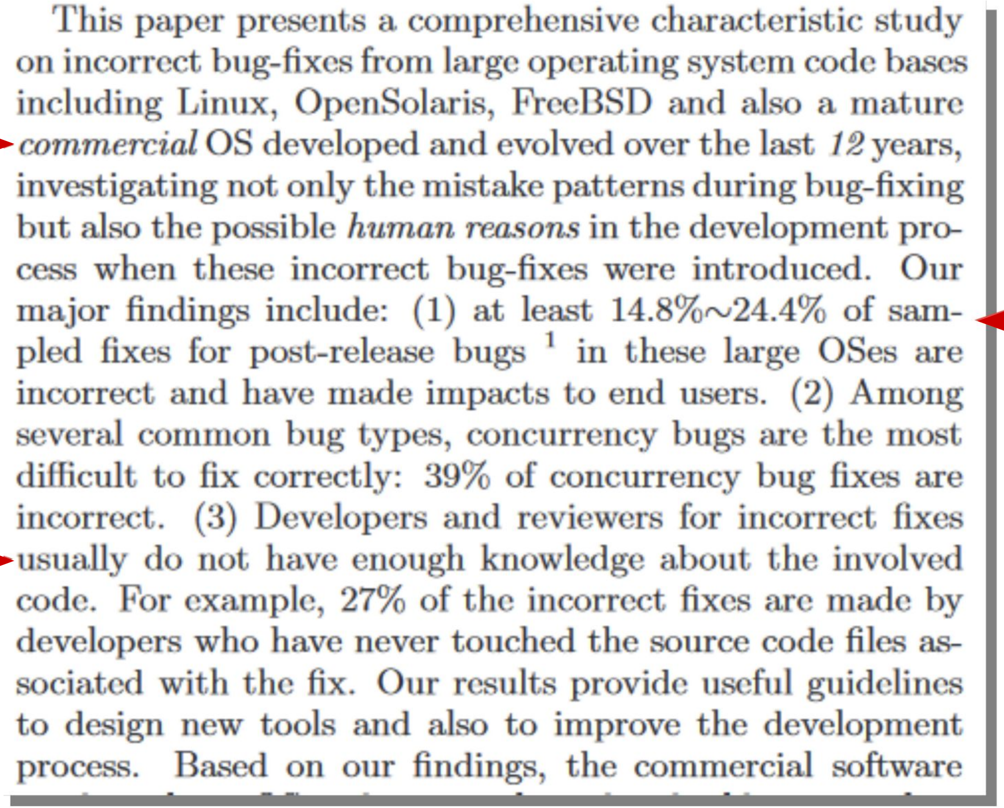

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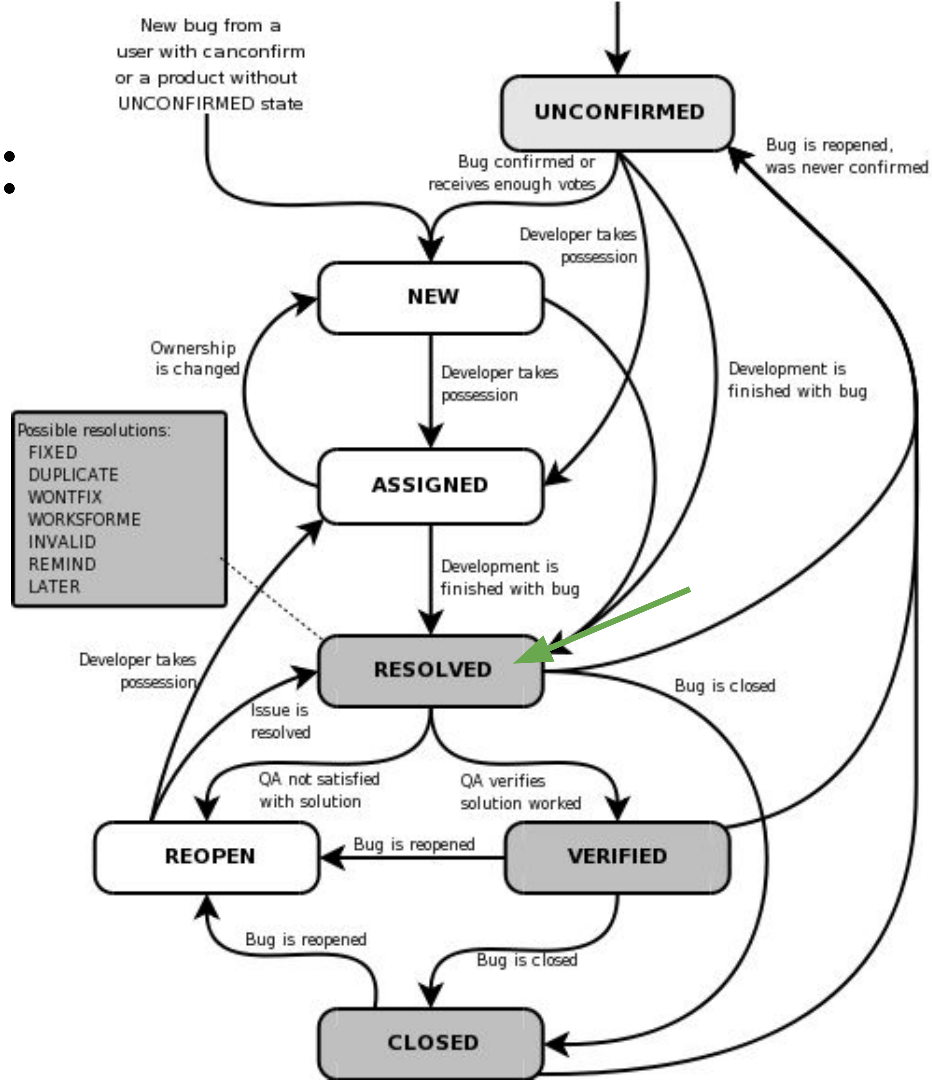

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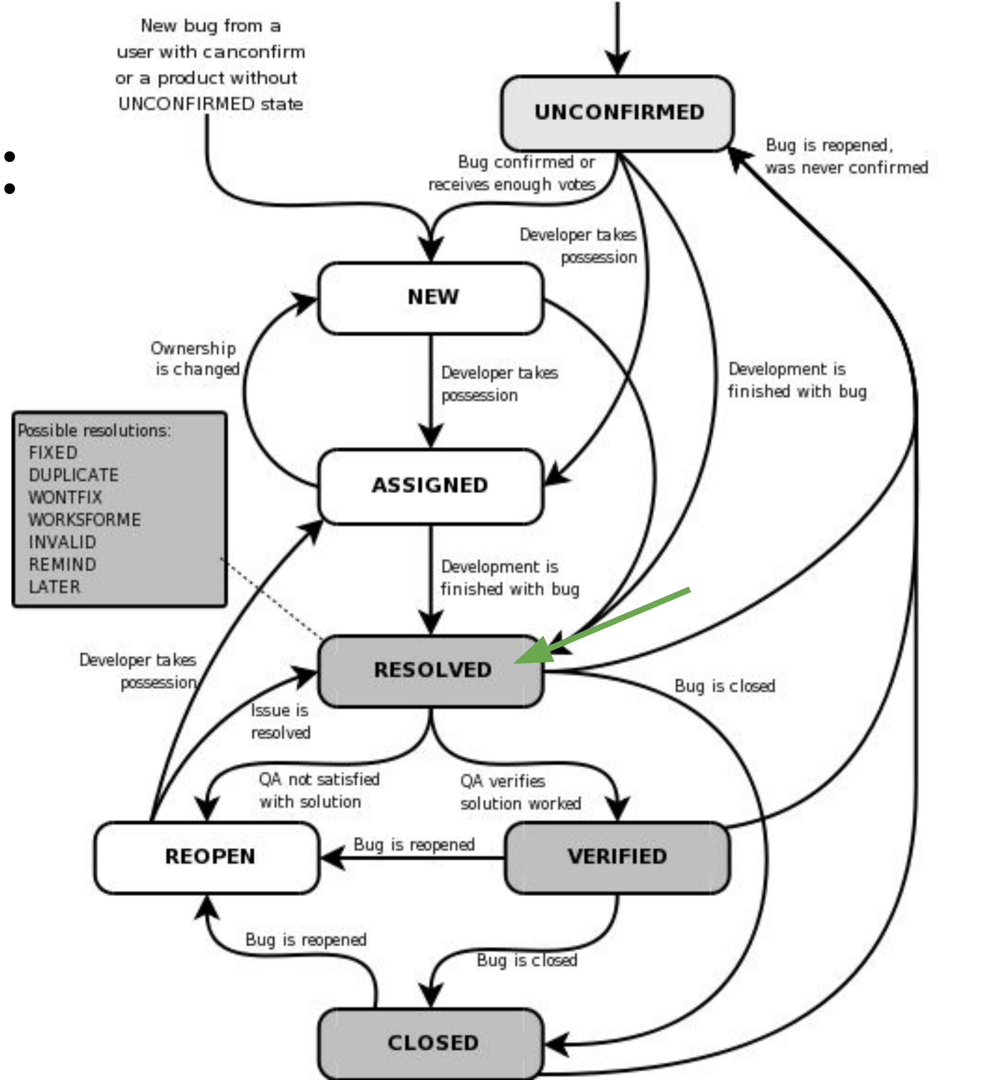

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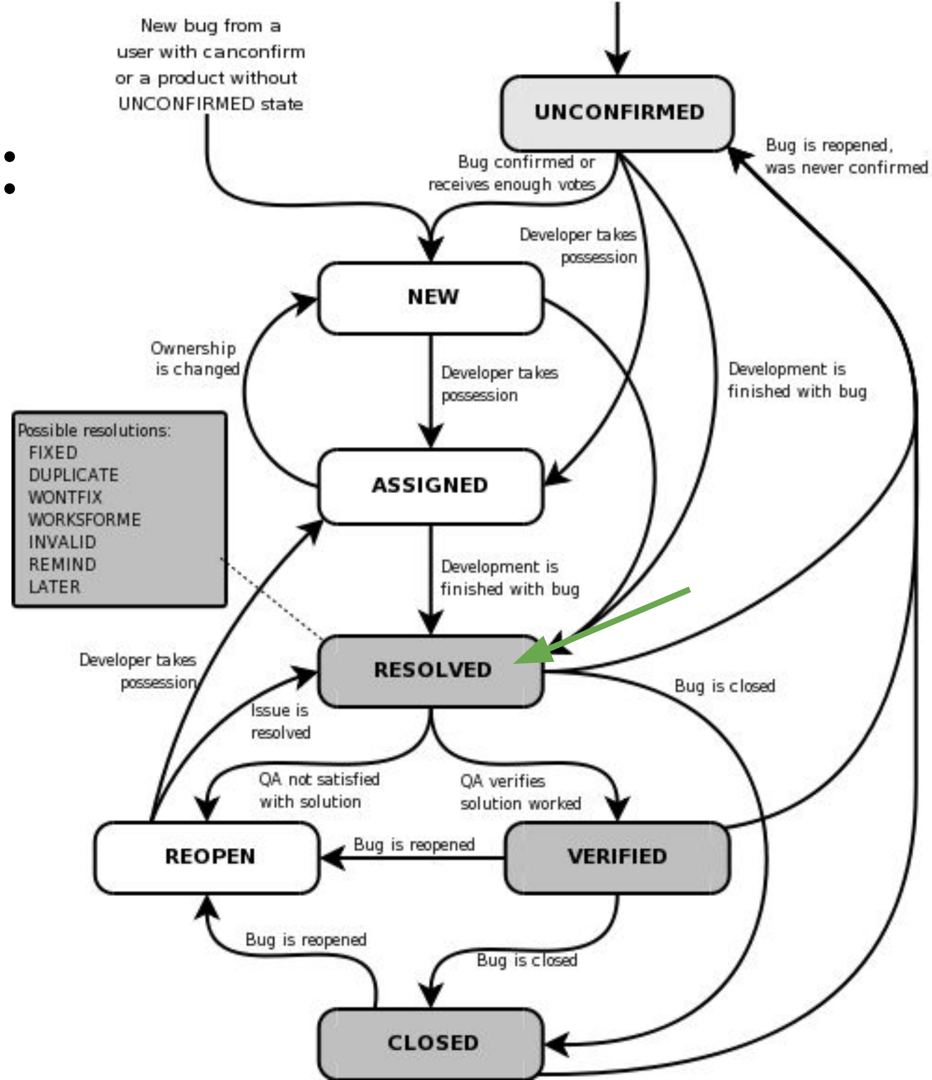

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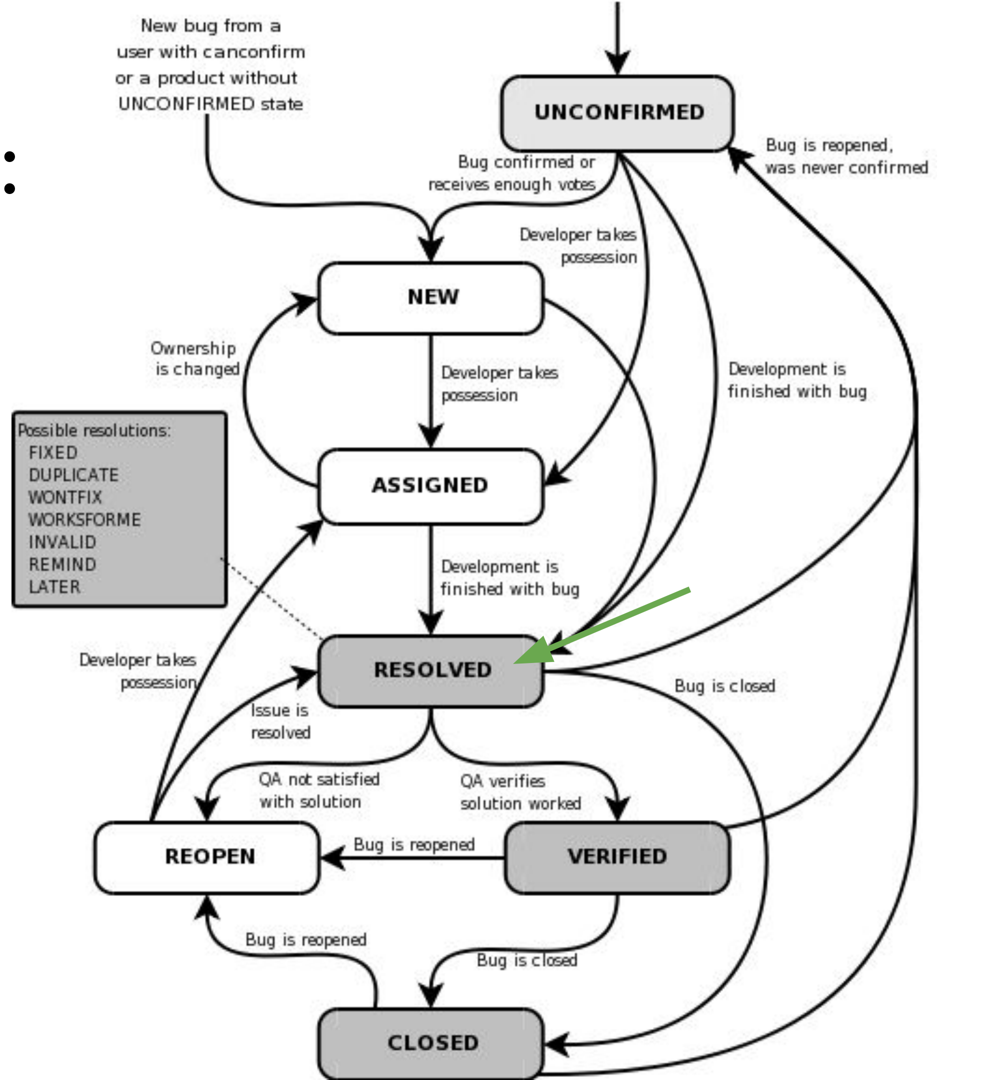
  - Rest of today's lecture + all of Wednesday's lecture on debugging



Debugging

Two-lecture agenda:

- What is a bug, anyway?
- Bug reports, triage, and the defect lifecycle
- **Debugging**
    - printf debugging and logging
    - delta debugging
    - debuggers

Debugging: what makes it difficult?

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  - Techniques from the 1980s or your habits from classes

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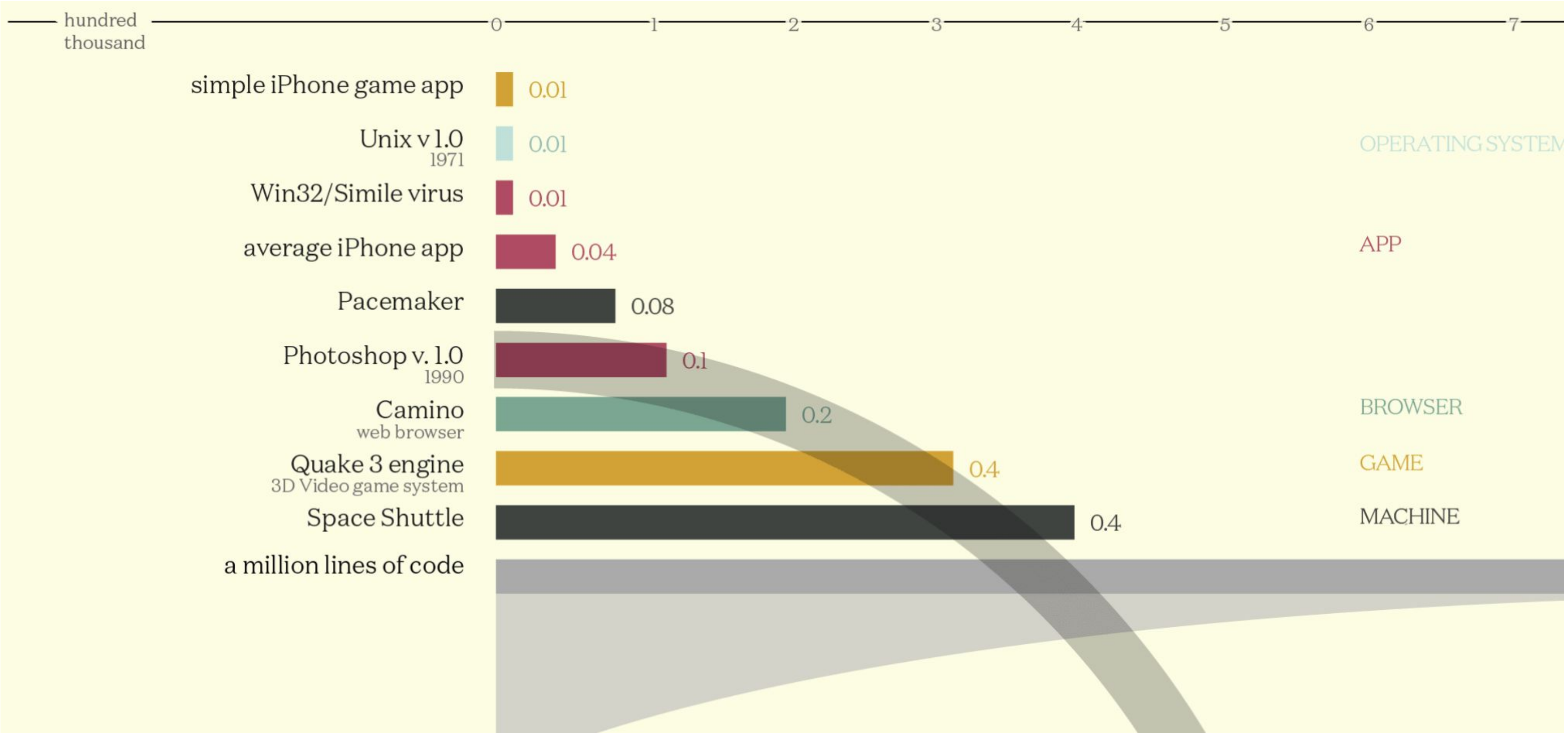

https://www.informationisbeautiful.net/visualizations/million-lines-of-code/

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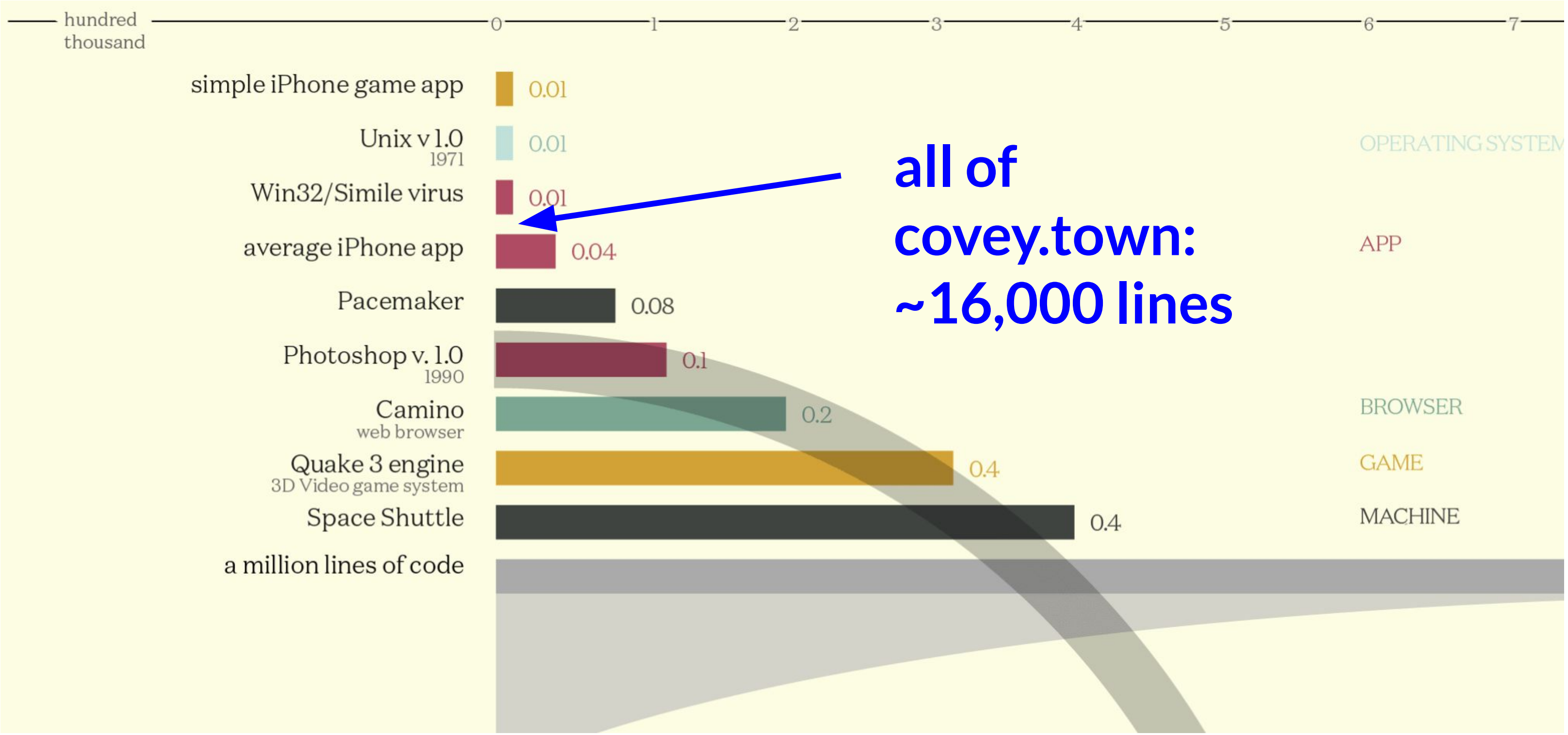

all of covey.town: ~16,000 lines

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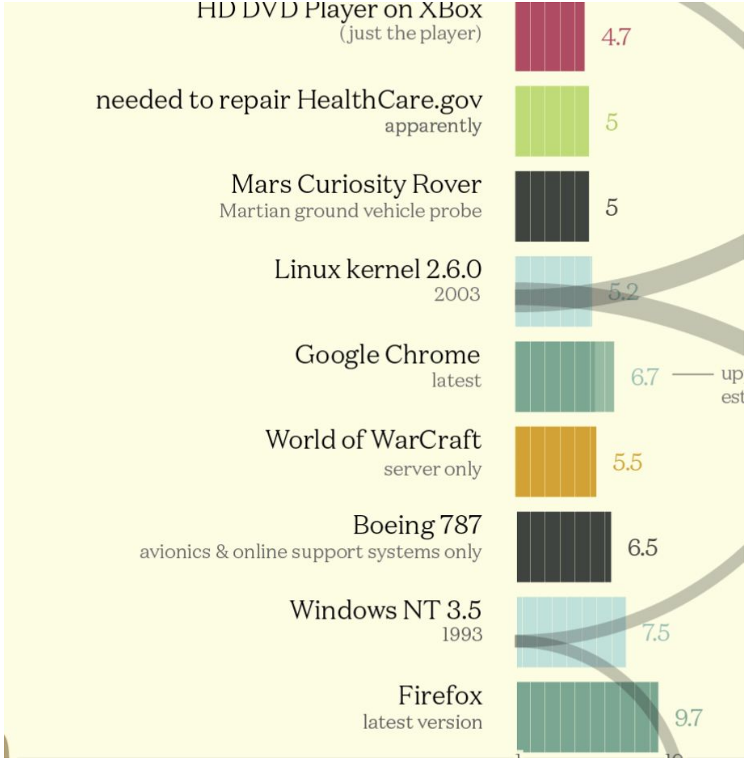

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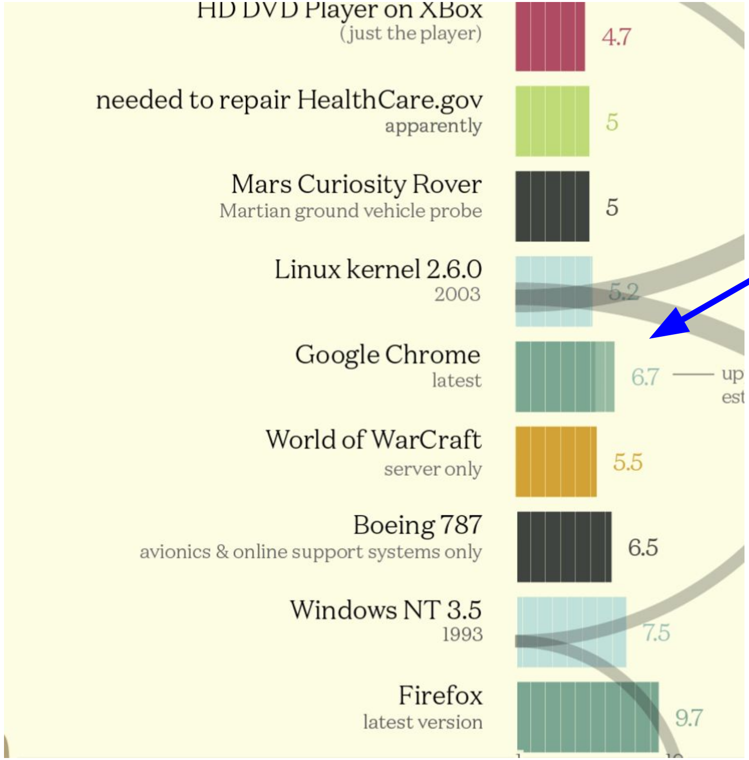

Chrome at ~7M LoC is ~400x bigger than covey.town

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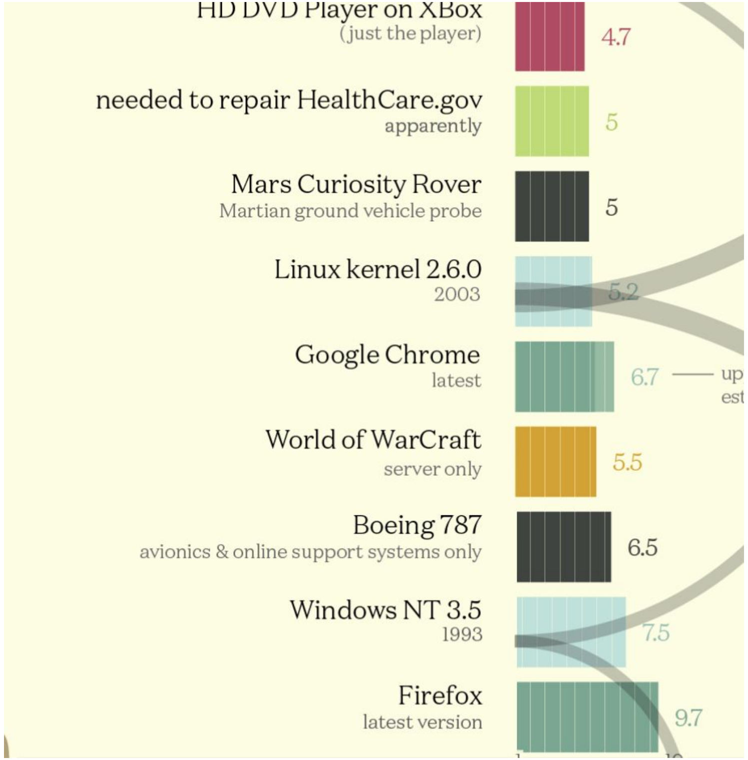

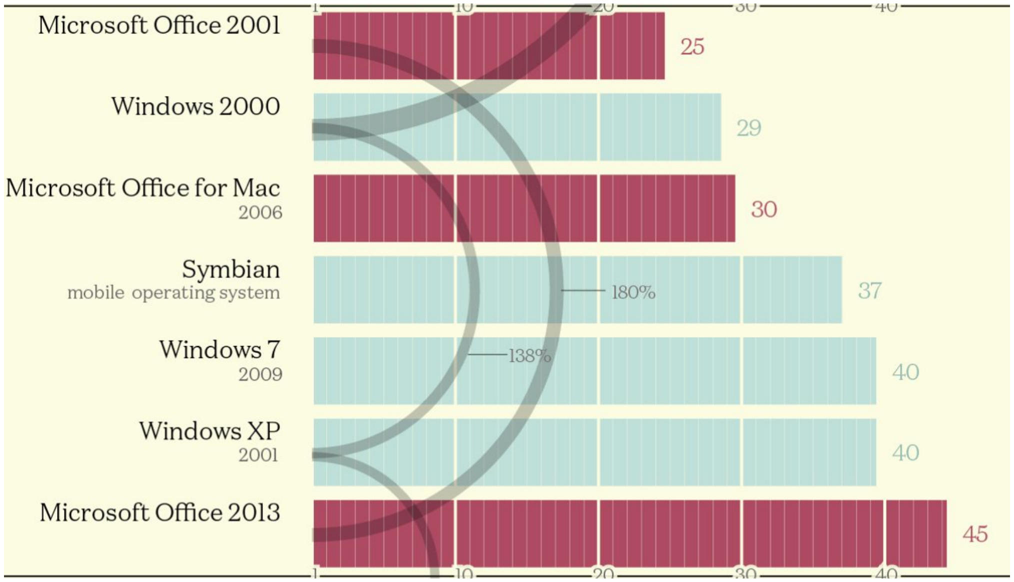

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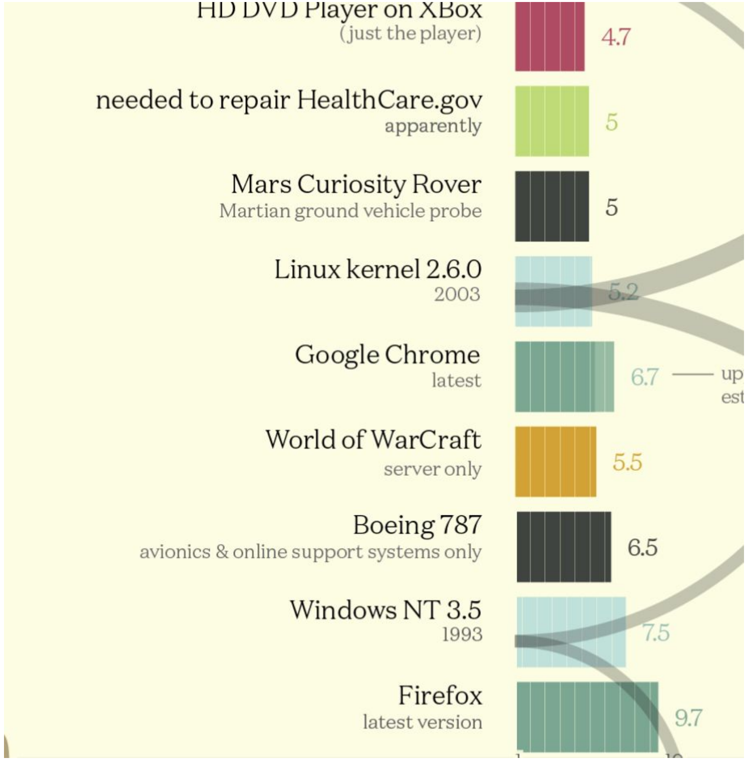
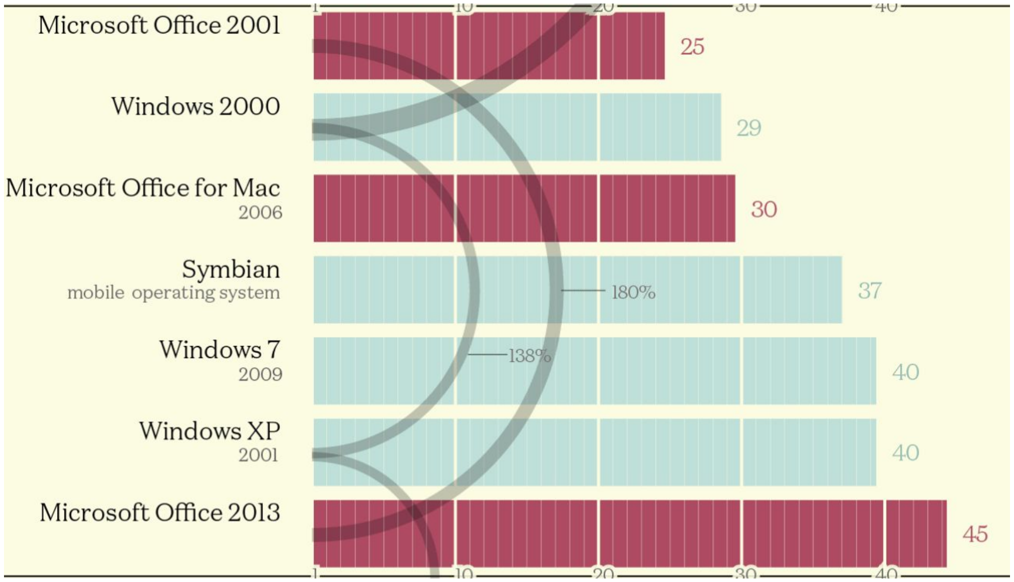


Chrome is small compared to even old versions of Windows!



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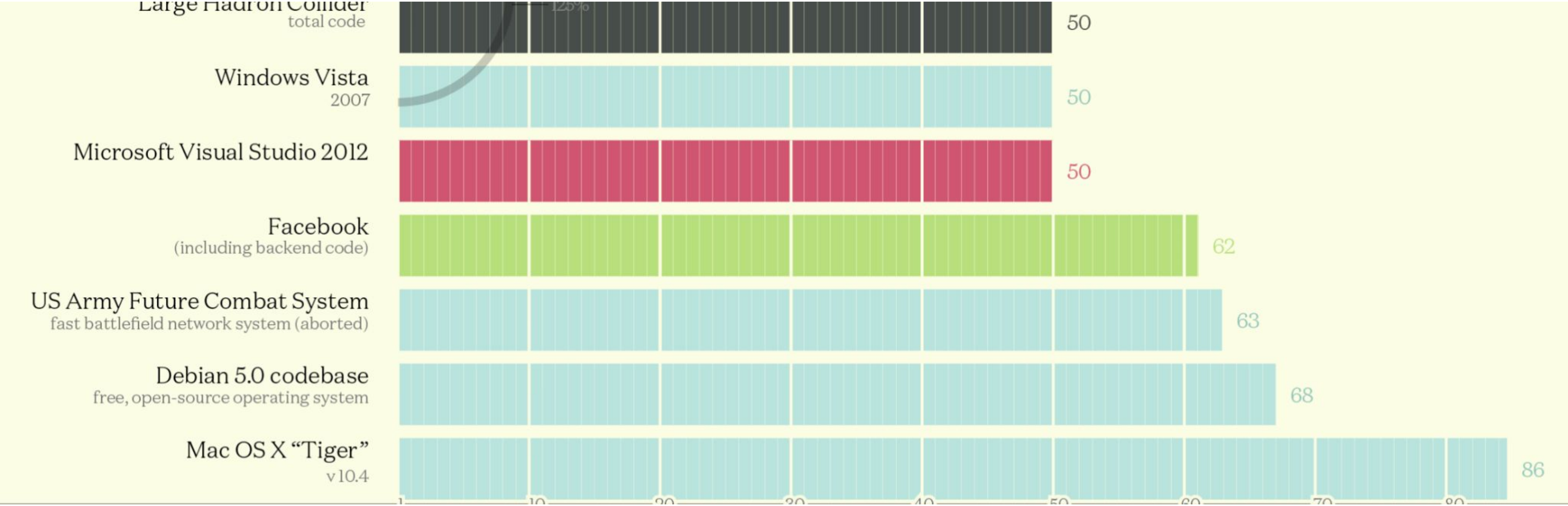

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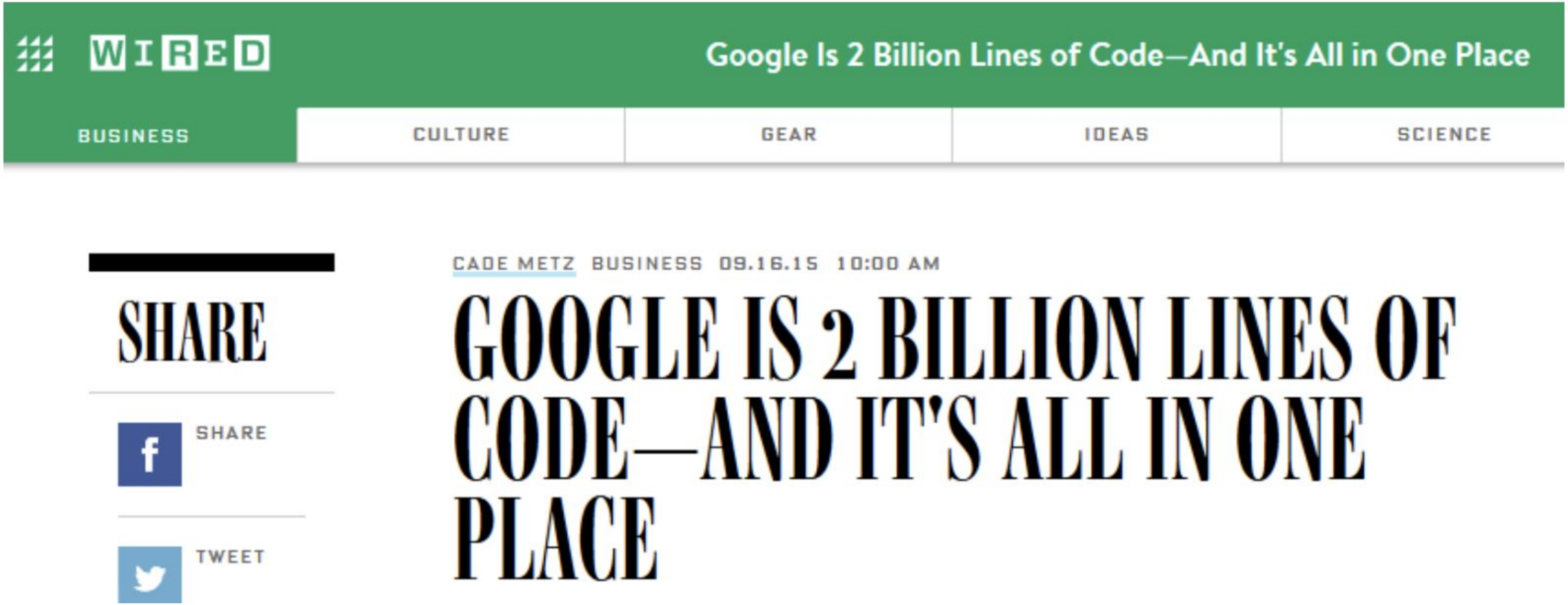

WIRED

Google Is 2 Billion Lines of Code—And It's All in One Place

BUSINESS | CULTURE | GEAR | IDEAS | SCIENCE

SHARE

SHARE

TWEET

CADE METZ BUSINESS 09.16.15 10:00 AM

GOOGLE IS 2 BILLION LINES OF CODE—AND IT'S ALL IN ONE PLACE

https://www.wired.com/2015/09/google-2-billion-lines-codeand-one-place/

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  - a one-hour bug on covey.town would take **years** on google!

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  - **confirm** that your fix actually resolves the issue

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  - especially bugs reported by users often do not get past this stage: **not enough information** to reproduce the fault

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> Minimizing the reproduction is **sometimes unnecessary**: a small (but not minimal) input is often good enough

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    - best practice: commit tests separately (and see them fail in CI)

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    - hypothesis testing is one of the key components of the **scientific method**:
        1. guess why something happens, devise an experiment to test if your guess is correct, then run the experiment
        2. repeat step 1 until you've figured it out

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Big difference between you ("**computer scientist**") and anyone who knows how to program: the ability to apply the **scientific method** to coding

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

Remaining agenda:

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

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  - sometimes considered “unprofessional”

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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.

Logging

Definition: *logging* is the process of recording information about the program's internal state as it runs via a printf-like interface

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- 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

Debugging (2/2)

Martin Kellogg

Reading Quiz: debugging 2

Q1: **TRUE** or **FALSE**: Delta debugging, as described in the first reading, requires a test to prove that each circumstance is really failure inducing.

Q2: Which of these would the author of the second article describe as a “good” TODO?

A. // TODO: Write the second half of this file so next week's launch won't explode
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Debugging

Remaining agenda:

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

Debugging

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Announcements:

- there is a midterm on Monday
- review session Friday 1pm
  - via Zoom
- my research group is recruiting undergrads for a study
  - look for our posters or talk to me after class

Review: Printf Debugging and Logging

- Key idea of ***printf debugging***: instrument the program so that it prints the values of key variables at a particular point
    - probably your most common debugging strategy already!
    - one of many debugging strategies in an engineer's arsenal

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- Key idea of ***printf debugging***: instrument the program so that it prints the values of key variables at a particular point
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        - e.g., via tools like Log4j, slf4j, etc.
    - logs play an important role in debugging distributed systems

Logging: levels

Typical example of a (Java) logging statement:

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

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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

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.

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!

Debugging (Part 2/2)

Today's agenda:

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

Delta debugging: summary

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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

- Having a **test input** may not be enough

Delta debugging: motivation: inputs

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  - Even if you know the suspicious code, the input may be **too large** to step through

Delta debugging: motivation: inputs

- 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
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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

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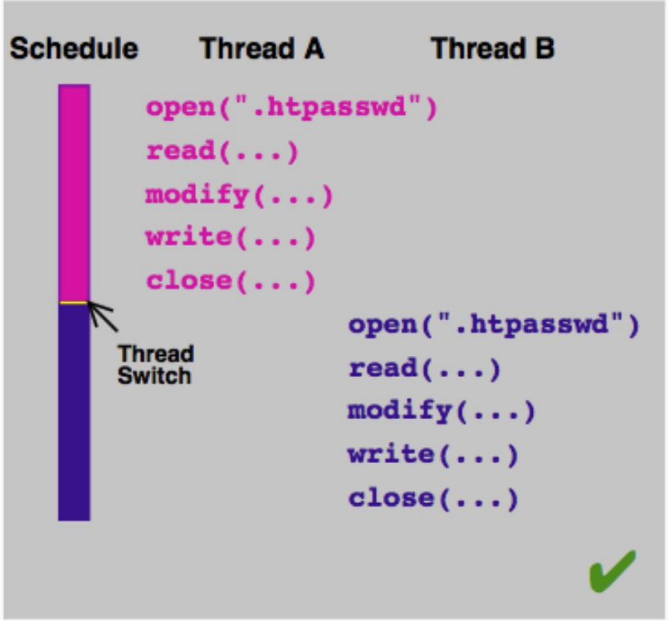
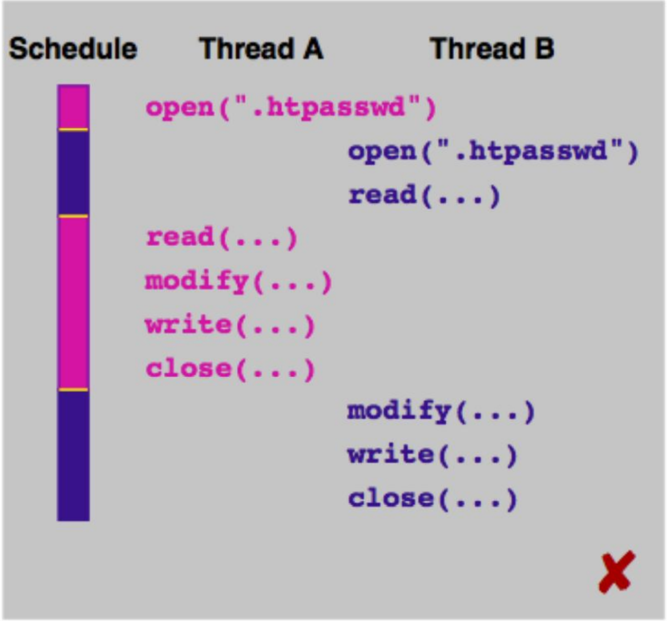
- Multithreaded programs can be **nondeterministic**





Delta debugging: motivation: thread schedules

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

Delta debugging: motivation: code changes

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- A new version of GDB has a UI bug

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    - … and **which commit** is responsible for introducing it?

Delta debugging: motivation: code changes

- A new version of GDB has a UI bug
  - The old version does not have that bug (it is a **regression**)
- 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

Definition: With respect to debugging, a ***difference*** is a change in the program configuration or state that may lead to alternate observations

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- Difference in **thread schedule**: difference in the time before a given thread preemption is performed
- Difference in **code**: different statements or expressions in two versions of a program
- Difference in **program state**: different values of internal variables

Delta debugging: unified solution

- Define the ***Abstract Debugging Problem*** as:

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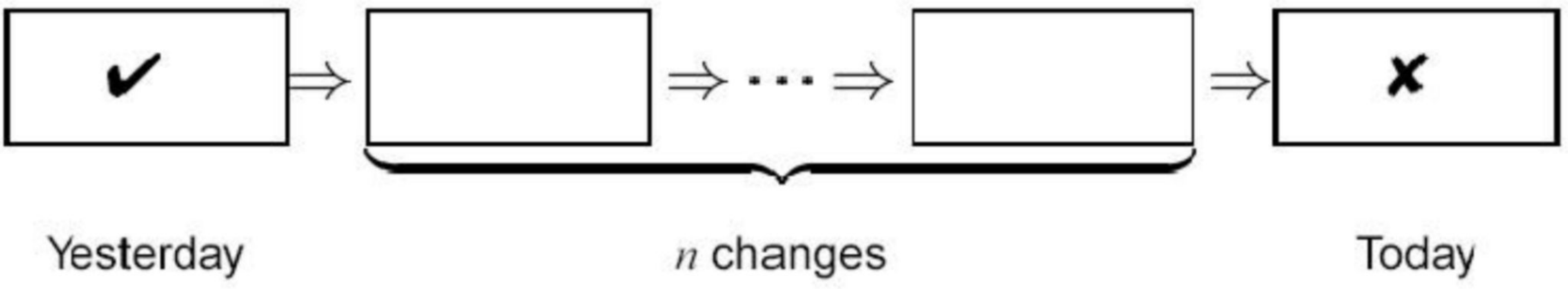
  - **key idea**: split up the set into two subsets, check which of the two is still "**interesting**"
  - can be applied to working and failing inputs, code versions, thread schedules, program states, etc.

Delta debugging: unified solution

"Yesterday, my program worked. Today, it does not."



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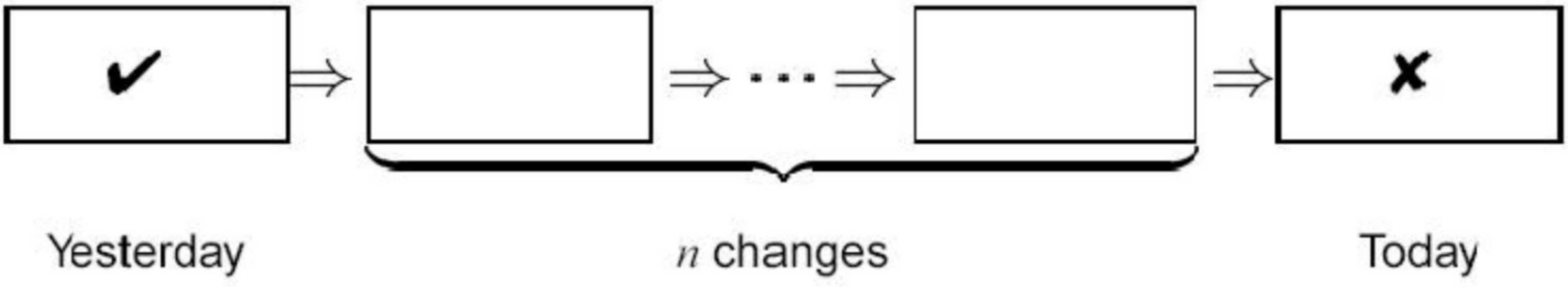

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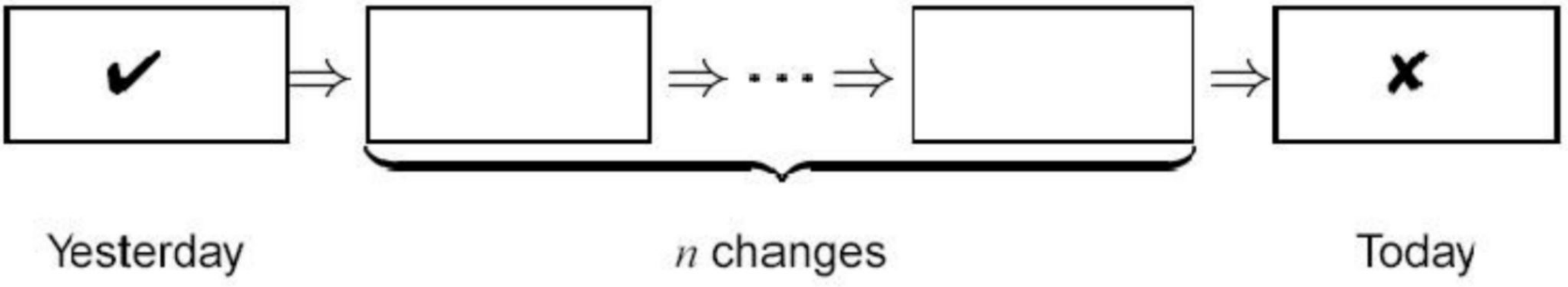

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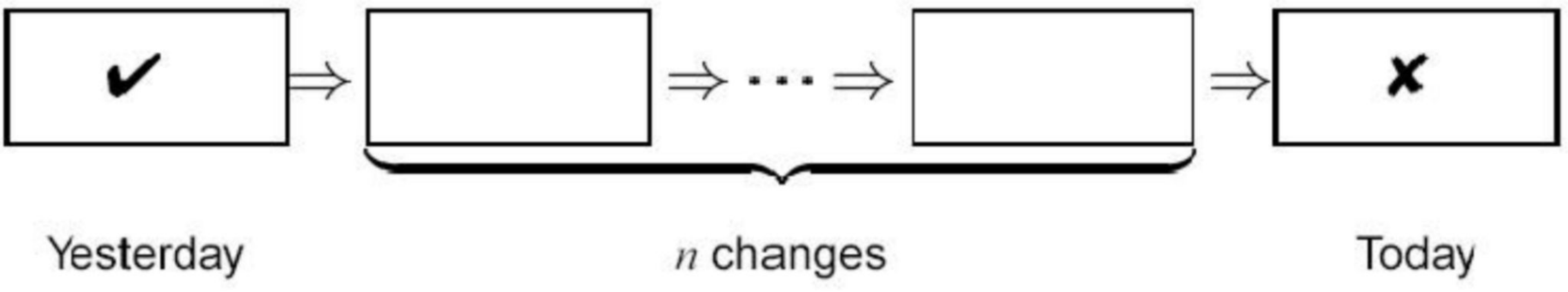

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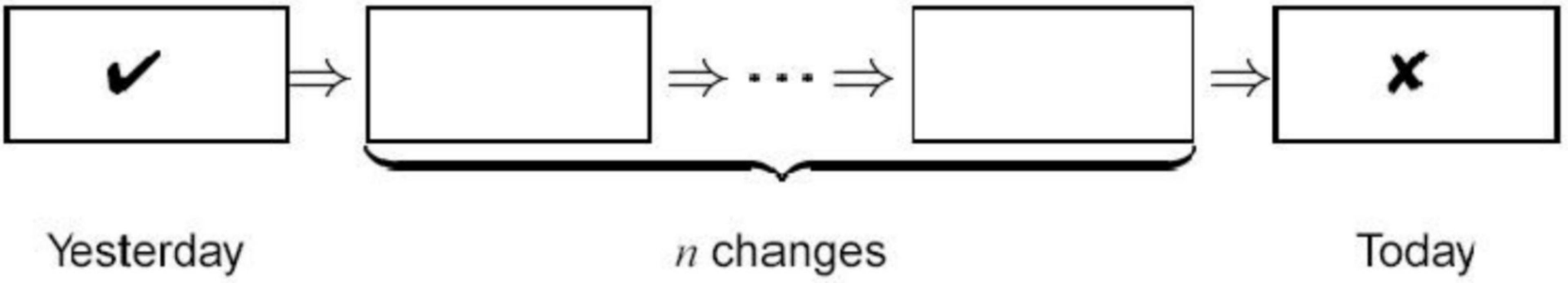

- We will iteratively:
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    - e.g., the subset of changes {1, 3, 8} causes the bug
  - run tests to **falsify** our hypothesis

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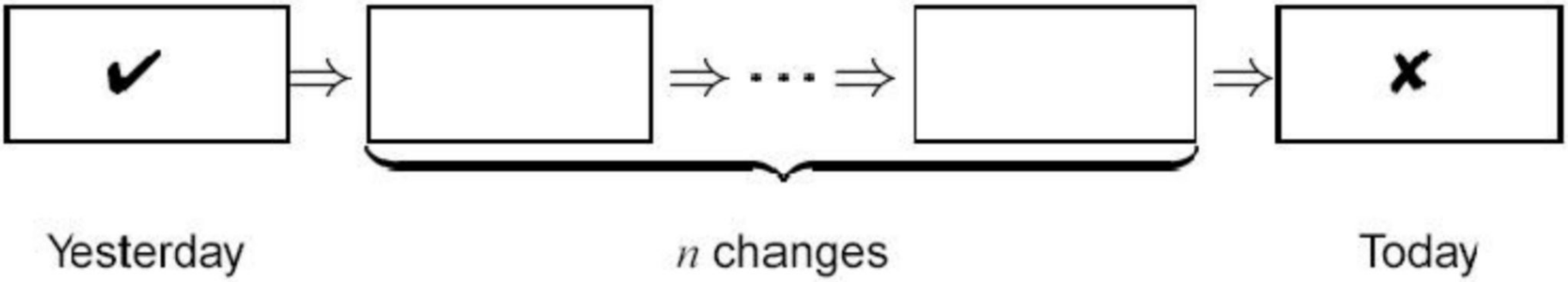
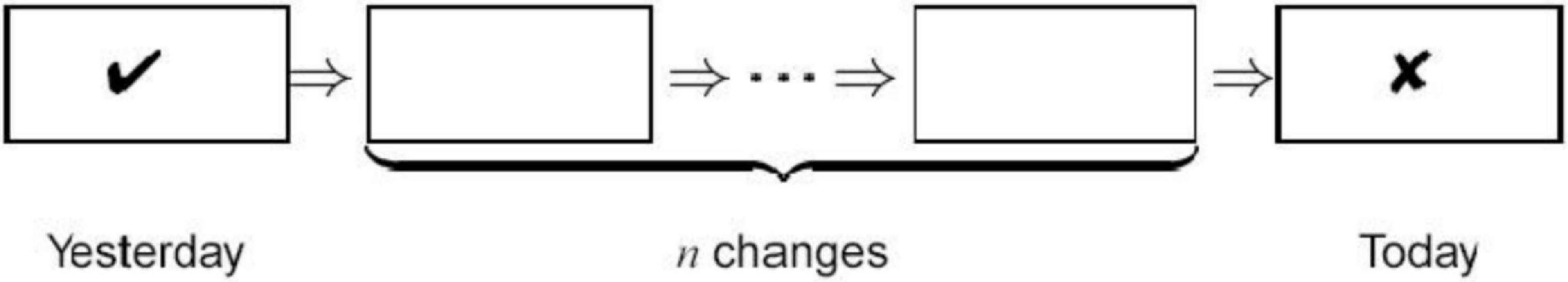
  - Interesting(M) = Yes
  - Forall m $\subset$ M, Interesting(M - m) = No

Delta debugging: example



- C =
- Interesting(X) =

Delta debugging: example



- C = set of *n* changes
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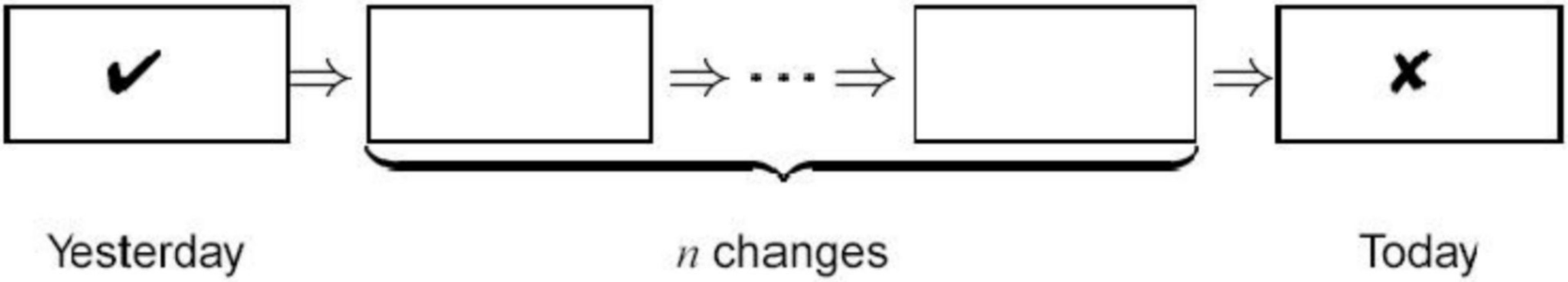

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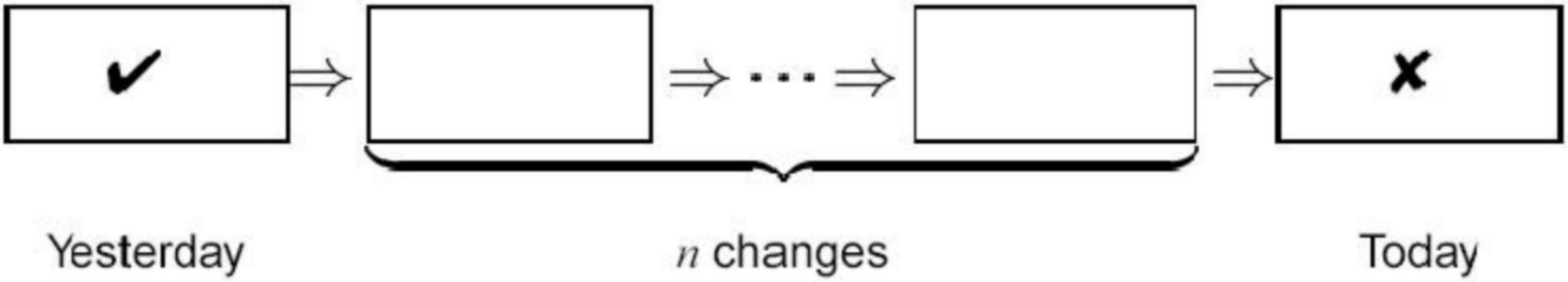

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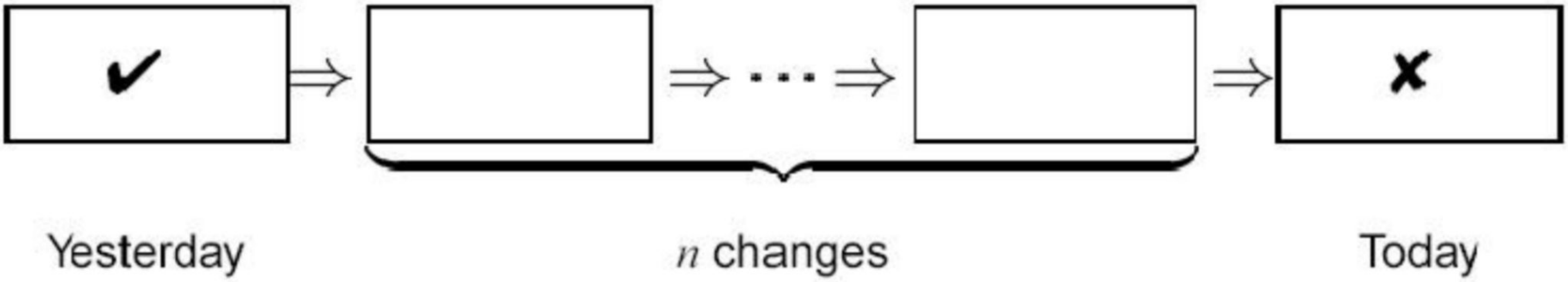

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  - If the tests **fail**, Interesting(X) = **True**.
  - If the tests **pass**, Interesting(X) = **False**.

Delta debugging: algorithm: naive

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

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    - **Problem**: if $|C| = N$, this takes 2^N time

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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($\{c_1 \dots c_n\}$) = True

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

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

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

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

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

then return DD(P_1)

else return DD(P_2)

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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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  - Not just singleton subsets of size 1 (cf. binary search)

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  - Interesting(X) & Interesting(Y) $\rightarrow$ Interesting(X $\cap$ Y)
- Interesting is **Consistent**
  - Interesting(X) = True xor Interesting(X) = False
  - (Some formulations also allow: Interesting(X) = Unknown)

Delta debugging: algorithm: insights

- Basic Binary Search:
  - Divide C into P_1 and P_2
  - If Interesting(P_1) = True then recurse on P_1
  - If Interesting(P_2) = True then recurse on P_2

Delta debugging: algorithm: insights

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Unambiguous =
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- At most one case can apply (by **Unambiguous**)
- By **Consistency**, the only other possibility is:

Delta debugging: algorithm: insights

- Basic Binary Search:
  - Divide C into P_1 and P_2
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- By **Monotonicity**
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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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        - 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

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1 2 3 4 5 6 7 8 = Interesting

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5 6 7 8

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

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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

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- Let's use DD to find it

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

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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

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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($\{c_1 \dots c_n\}$) = True

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

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

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

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

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**($P \cup P_1, P_2$)

Delta debugging: algorithmic complexity

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

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  - Assuming constant time per Interesting() check
  - Is this realistic?

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  - DD is **logarithmic**: 2 * log |C|
  - Why? (Equivalent to binary search.)
- 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**
- Interesting is **Monotonic**
  - $\text{Interesting}(X) \rightarrow \text{Interesting}(X \cup \{c\})$
- Interesting is **Unambiguous**
  - $\text{Interesting}(X)\ \&\ \text{Interesting}(Y) \rightarrow \text{Interesting}(X \cap Y)$
- Interesting is **Consistent**
  - Interesting(X) = True xor Interesting(X) = False
  - (Some formulations also allow: Interesting(X) = Unknown)

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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)

Assumptions restated on this slide for convenience

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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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- A *signal* is an **asynchronous** notification sent to a process about an event:
  - User pressed Ctrl-C (or did kill %pid)
    - Or asked the Windows Task Manager to terminate it
  - Exceptions (divide by zero, null pointer)
  - From the OS (SIGPIPE)

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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

```
#define BREAKPOINT *(0)=0
int global = 11;
int debugger_signal_handler() {
  printf("debugger prompt: \n");
  // debugger code goes here!
}
void main() {
  signal(SIGSEGV, debugger_signal_handler) ;
  global = 33;
  BREAKPOINT;
  global = 55;
  printf("Outside, global = %d\n", global);
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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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at the user-specified breakpoint, the debugger **forces** a SIGSEGV (which its handler will intercept)

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- 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

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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