Cooperative Bug Isolation

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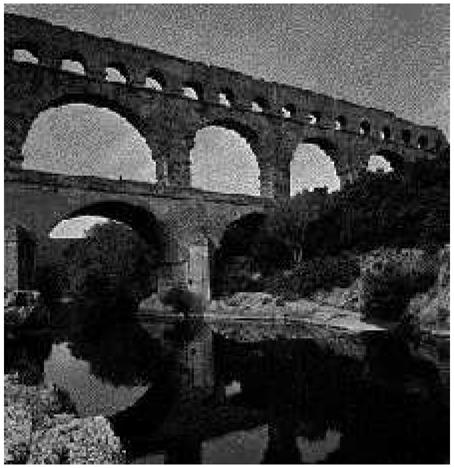
Build and Monitor



The Goal: Analyze Reality

- Where is the black box for software?
  - Historically, some efforts, but spotty
  - Now it's really happening: crash reporting systems

- Actual runs are a vast resource
  - Number of real runs >> number of testing runs
  - And the real-world executions are most important

- This talk: post-deployment bug hunting

Engineering Constraints

- Big systems
  - Millions of lines of code
  - Mix of controlled, uncontrolled code
  - Threads
- Remote monitoring
  - Limited disk & network bandwidth
- Incomplete information
  - Limit performance overhead
  - Privacy and security

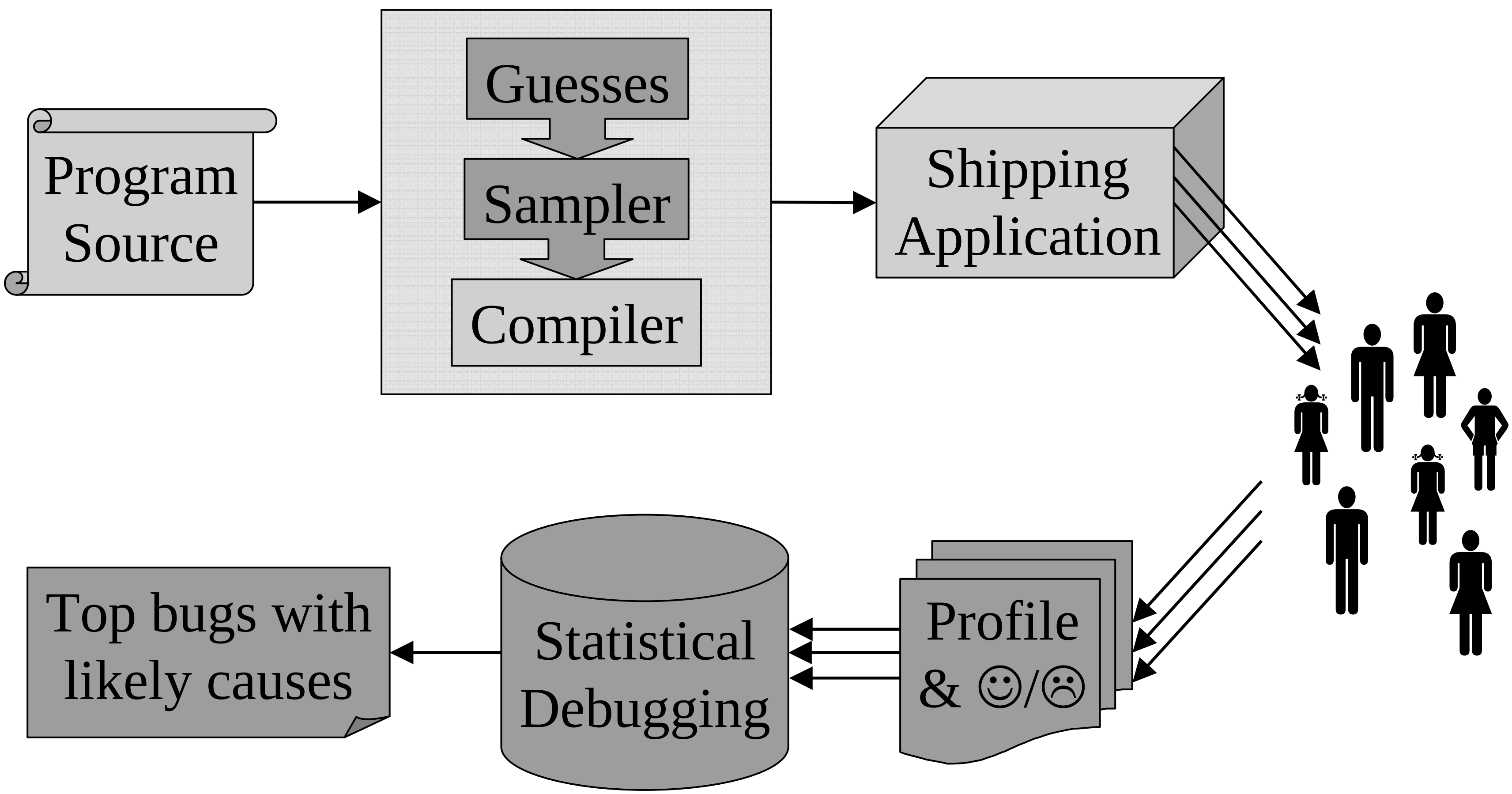
The Approach

1. Guess "potentially interesting" behaviors
   – Compile-time instrumentation

2. Collect sparse, fair subset of these behaviors
   – Generic sampling transformation
   – Feedback profile + outcome label

3. Find behavioral changes in good/bad runs
   – Statistical debugging

Bug Isolation Architecture



Our Model of Behavior

We assume any interesting behavior is expressible as a predicate P on program state at a particular program point.

Observation of behavior = observing P

Branches Are Interesting

```
if (p) …
else   …
```

Branch Predicate Counts

```
++branch_17[!!p];
if (p) …
else   …
```

- Predicates are folded down into counts
- C idiom: **`!!p`** ensures subscript is 0 or 1

Return Values Are Interesting

```
n = fprintf(…);
```

Returned Value Predicate Counts

```
n = fprintf(…);
++call_41[(n==0)+(n>=0)];
```

- Track predicates: **`n < 0`**, **`n == 0`**, **`n > 0`**

Scalar Relationships

```
int i, j, k;
…
i = …;
```

The relationship of `i` *to other integer-valued variables in scope after the assignment is potentially interesting . . .*

Pair Relationship Predicate Counts

```
int i, j, k;
…
```

Is $i < j$, $i = j$, or $i > j$?

```
i = …;
++pair_6[(i==j)+(i>=j)];
++pair_7[(i==k)+(i>=k)];
++pair_8[(i==5)+(i>=5)];
```

Test i against all other constants & variables in scope.

Summarization and Reporting

- Instrument the program with predicates
  - We have a variety of instrumentation schemes
- Feedback report is:
  - Vector of predicate counters
  - Success/failure outcome label

P1	P2	P3	P4	P5	. . .
0	0	4	0	1	. . .

- No time dimension, for good or ill
- Still quite a lot to measure
  - What about performance?

Sampling

- Decide to examine or ignore each site…
  - Randomly
  - Independently
  - Dynamically

- Why?
  - Fairness
  - We need accurate picture of rare events.

Problematic Approaches

- Sample every *k*th predicate
  - Violates independence
- Use clock interrupt
  - Not enough context
  - Not very portable
- Toss a coin at each instrumentation site
  - Too slow

Amortized Coin Tossing

- Observation
  - Samples are rare, say 1/100
  - Amortize cost by predicting time until next sample
- Randomized global countdown
  - Small countdown $\Rightarrow$ upcoming sample
- Selected from *geometric distribution*
  - Inter-arrival time for biased coin toss
  - How many tails before next head?

Geometric Distribution

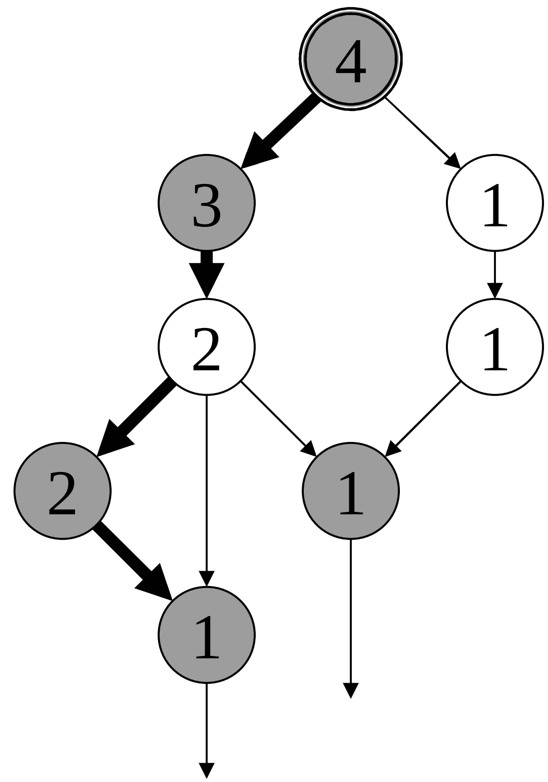
$$next = \left\lfloor \frac{\log(rand(0,1))}{\log(1-\frac{1}{D})} \right\rfloor + 1$$

D = mean of distribution

= expected sample density

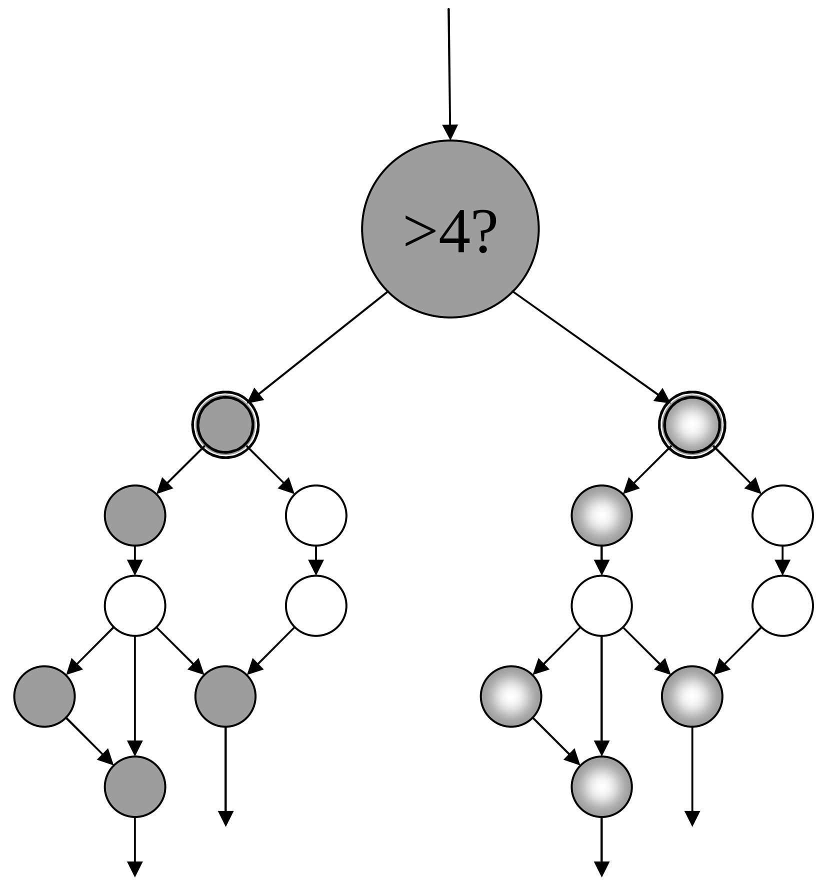
Weighing Acyclic Regions

- An acyclic region has:
- a finite number of paths
- a finite max number of instrumentation sites executed



Weighing Acyclic Regions

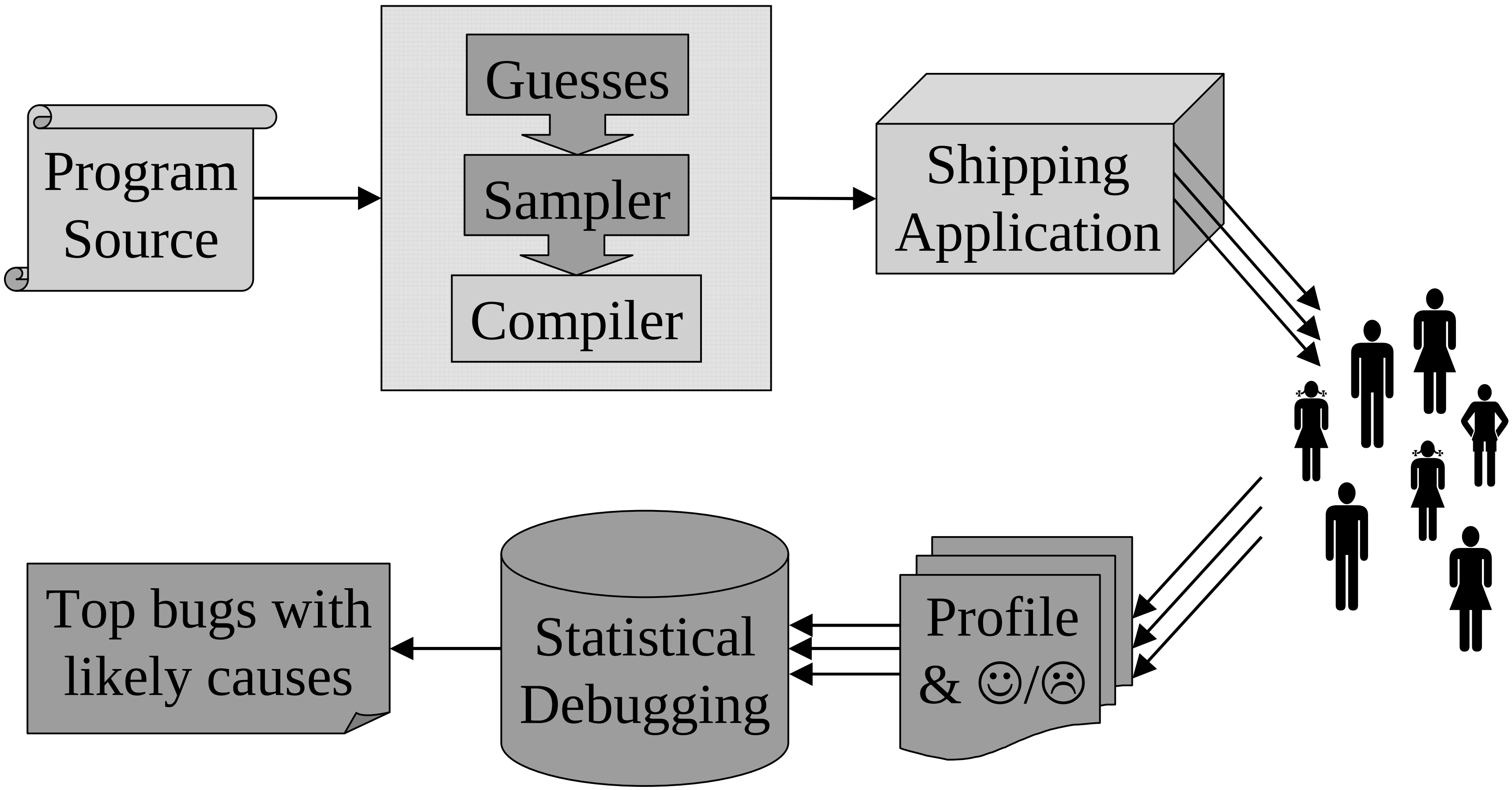
- Clone acyclic regions
  - “Fast” variant
  - “Slow” variant
- Choose at run time based on countdown to next sample



Summary: Feedback Reports

- Subset of dynamic behavior
  - Counts of true/false predicate observations
  - Sampling gives low overhead
    - Often unmeasurable at 1/100
  - Success/failure label for entire run
- Certain of what we did observe
  - But may have missed some events
- Given enough runs, samples $\approx$ reality
  - Common events seen most often
  - Rare events seen at proportionate rate

Bug Isolation Architecture



Find Causes of Bugs

- We gather information about *many* predicates.
  - 298,482 for **BC**

- Most of these are not predictive of anything.

- How do we find the useful predicates?

Finding Causes of Bugs

How likely is failure when P is observed true?

F(P) = # failing runs where P observed true

S(P) = # successful runs where P observed true

$$\text{Failure}(P) = \frac{F(P)}{F(P) + S(P)}$$

Not Enough . . .

```
if (f == NULL) {
  x = 0;
  *f;
}
```

Failure(`f == NULL`) = 1.0

Failure(`x == 0`) = 1.0

- Predicate `x == 0` is an innocent bystander
  - Program is already doomed

Context

What is the background chance of failure, regardless of P's value?

F(P observed) = # failing runs observing P
S(P observed) = # successful runs observing P

$$\text{Context}(P) = \frac{F(P\ \text{observed})}{F(P\ \text{observed}) + S(P\ \text{observed})}$$

A Useful Measure

Does the predicate being true increase the chance of failure over the background rate?

Increase(P) = Failure(P) – Context(P)

A form of likelihood ratio testing . . .

Increase() Works . . .

```
if (f == NULL) {
  x = 0;
  *f;
}
```

Increase(`f == NULL`) = 1.0

Increase(`x == 0`) = 0.0

A First Algorithm

1. Discard predicates having Increase(P) ≤ 0
   - E.g. dead, invariant, bystander predicates
   - Exact value is sensitive to small F(P)
   - Use lower bound of 95% confidence interval

2. Sort remaining predicates by Increase(P)
   - Again, use 95% lower bound
   - Likely causes with determinacy metrics

Isolating a Single Bug in BC

```
void more_arrays ()
{
  …

  /* Copy the old arrays. */
  for (indx = 1; indx < old_count; indx
    arrays[indx] = old_ary[indx];

  /* Initialize the new elements. */
  for (; indx < v_count; indx++)
    arrays[indx] = NULL;

  …
}
```

```
#1: indx > scale
#2: indx > use_math
#3: indx > opterr
#4: indx > next_func
#5: indx > i_base
```

It Works!

- Well . . . at least for a program with 1 bug.

- But
  - Need to deal with multiple, unknown bugs.
  - Redundancy in the predicate list is a major problem.

Using the Information

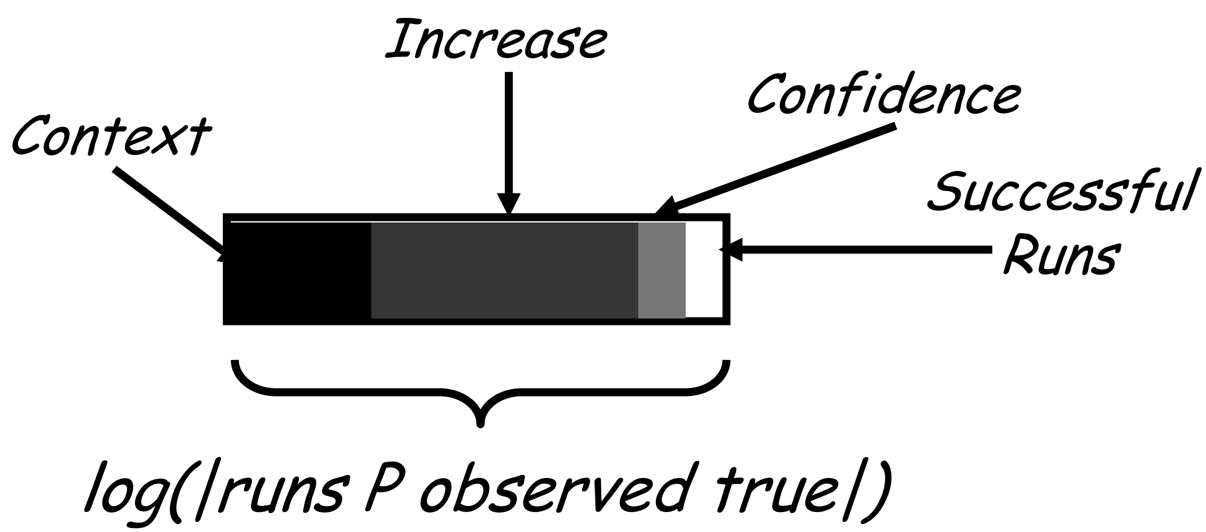
- Multiple predicate metrics are useful
  - Increase(P), Failure(P), F(P), S(P)

[redacted]ext(P) = .25

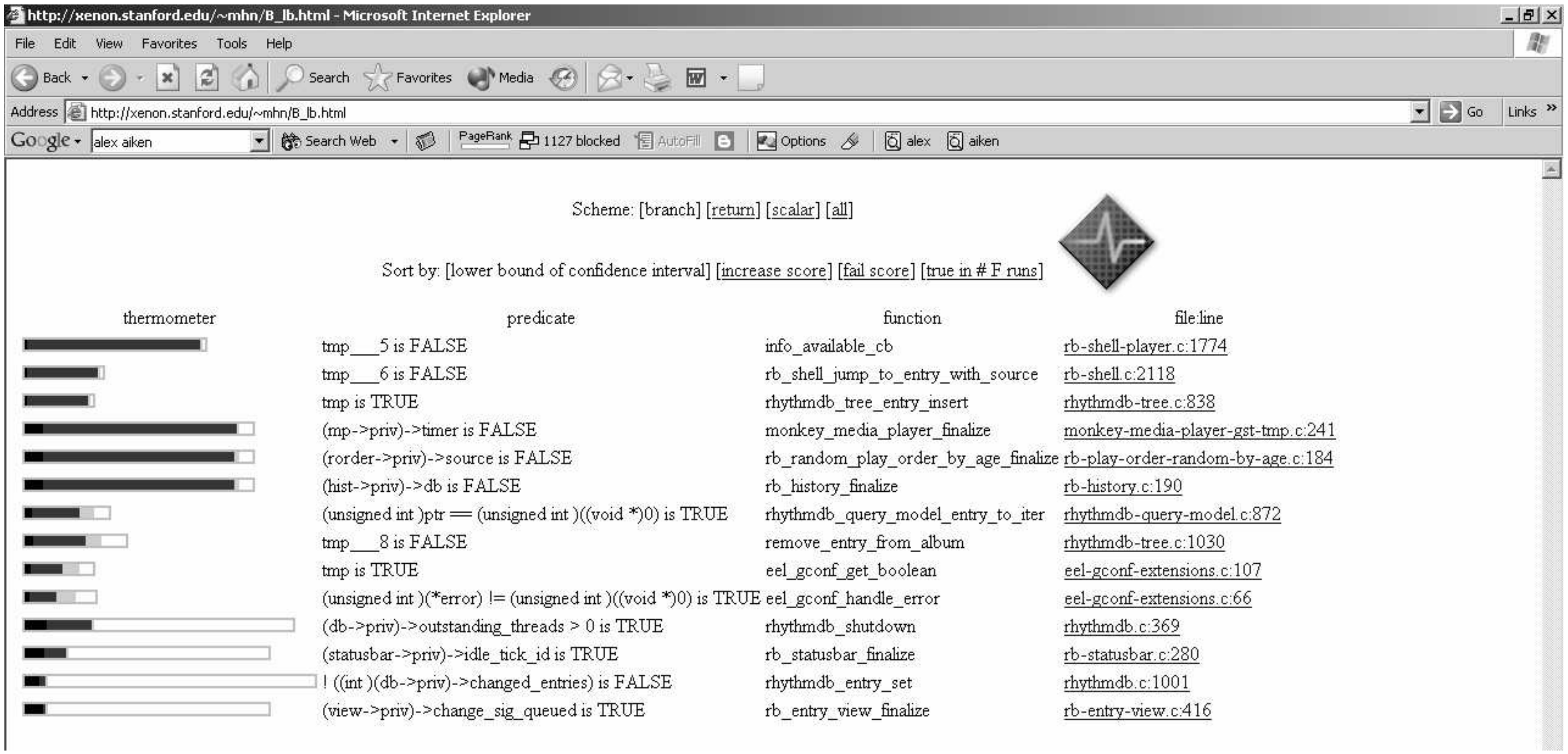
[redacted]

$\boxed{F(P) + S(P) = 349}$

The Bug Thermometer



Sample Report



http://xenon.stanford.edu/~mhn/B_lb.html - Microsoft Internet Explorer

Scheme: [branch] [return] [scalar] [all]

Sort by: [lower bound of confidence interval] [increase score] [fail score] [true in # F runs]

thermometer	predicate	function	file:line
	tmp___5 is FALSE	info_available_cb	rb-shell-player.c:1774
	tmp___6 is FALSE	rb_shell_jump_to_entry_with_source	rb-shell.c:2118
	tmp is TRUE	rhythmdb_tree_entry_insert	rhythmdb-tree.c:838
	(mp->priv)->timer is FALSE	monkey_media_player_finalize	monkey-media-player-gst-tmp.c:241
	(rorder->priv)->source is FALSE	rb_random_play_order_by_age_finalize	rb-play-order-random-by-age.c:184
	(hist->priv)->db is FALSE	rb_history_finalize	rb-history.c:190
	(unsigned int)ptr == (unsigned int)((void *)0) is TRUE	rhythmdb_query_model_entry_to_iter	rhythmdb-query-model.c:872
	tmp___8 is FALSE	remove_entry_from_album	rhythmdb-tree.c:1030
	tmp is TRUE	eel_gconf_get_boolean	eel-gconf-extensions.c:107
	(unsigned int)(*error) != (unsigned int)((void *)0) is TRUE	eel_gconf_handle_error	eel-gconf-extensions.c:66
	(db->priv)->outstanding_threads > 0 is TRUE	rhythmdb_shutdown	rhythmdb.c:369
	(statusbar->priv)->idle_tick_id is TRUE	rb_statusbar_finalize	rb-statusbar.c:280
	! ((int)(db->priv)->changed_entries) is FALSE	rhythmdb_entry_set	rhythmdb.c:1001
	(view->priv)->change_sig_queued is TRUE	rb_entry_view_finalize	rb-entry-view.c:416

Multiple Bugs: The Goal

Isolate the best predictor for each bug, with no prior knowledge of the number of bugs.

Multiple Bugs: Some Issues

- A bug may have many redundant predictors
  - Only need one
  - But would like to know correlated predictors

- Bugs occur on vastly different scales
  - Predictors for common bugs may dominate, hiding predictors of less common problems

An Idea

- Simulate the way humans fix bugs
- Find the first (most important) bug
- Fix it, and repeat

An Algorithm

Repeat the following:

1. Compute Increase(), Context(), etc. for all preds.
2. Rank the predicates
3. Add the top-ranked predicate P to the result list
4. Remove P & discard all runs where P is true
   - Simulates fixing the bug corresponding to P
   - Discard reduces rank of correlated predicates

Bad Idea #1: Ranking by Increase(P)

Thermometer	Context	Increase	S	F
	0.065	0.935 ± 0.019	0	23
	0.065	0.935 ± 0.020	0	10
	0.071	0.929 ± 0.020	0	18
	0.073	0.927 ± 0.020	0	10
	0.071	0.929 ± 0.028	0	19
	0.075	0.925 ± 0.022	0	14
	0.076	0.924 ± 0.022	0	12
	0.077	0.923 ± 0.023	0	10

High Increase() but very few failing runs!

These are all *sub-bug predictors*: they cover a special case of a more general problem.

Bad Idea #2: Ranking by Fail(P)

Thermometer	Context	Increase	S	F
	0.176	0.007 ± 0.012	22554	5045
	0.176	0.007 ± 0.012	22566	5045
	0.176	0.007 ± 0.012	22571	5045
	0.176	0.007 ± 0.013	18894	4251
	0.176	0.007 ± 0.013	18885	4240
	0.176	0.008 ± 0.013	17757	4007
	0.177	0.008 ± 0.014	16453	3731
	0.176	0.261 ± 0.023	4800	3716

Many failing runs but low Increase()!

Tend to be *super-bug predictors*: predicates that cover several different bugs rather poorly.

A Helpful Analogy

- In the language of information retrieval
  - Increase(P) has high precision, low recall
  - Fail(P) has high recall, low precision
- Standard solution:
  - Take the harmonic mean of both
  - Rewards high scores in both dimensions

Ranking by the Harmonic Mean

Thermometer	Context	Increase	S	F
	0.176	0.824 ± 0.009	0	1585
	0.176	0.824 ± 0.009	0	1584
	0.176	0.824 ± 0.009	0	1580
	0.176	0.824 ± 0.009	0	1577
	0.176	0.824 ± 0.009	0	1576
	0.176	0.824 ± 0.009	0	1573
	0.116	0.883 ± 0.012	1	774
	0.116	0.883 ± 0.012	1	776

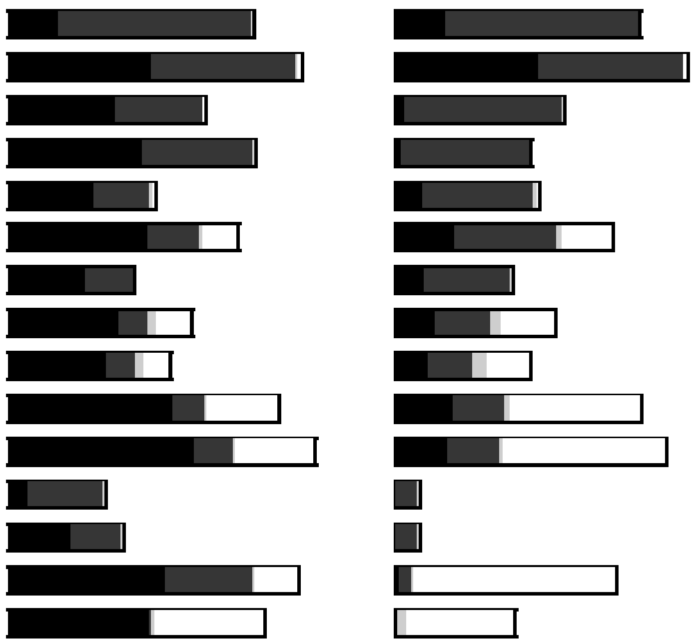
It works!

Experimental Results: Exif

Initial	Effective	Predicate
		`i < 0`
		`maxlen > 1900`
		`o + s > buf_size is TRUE`

- Three predicates selected from 156,476
- Each predicate predicts a distinct crashing bug
- We found the bugs quickly using these predicates

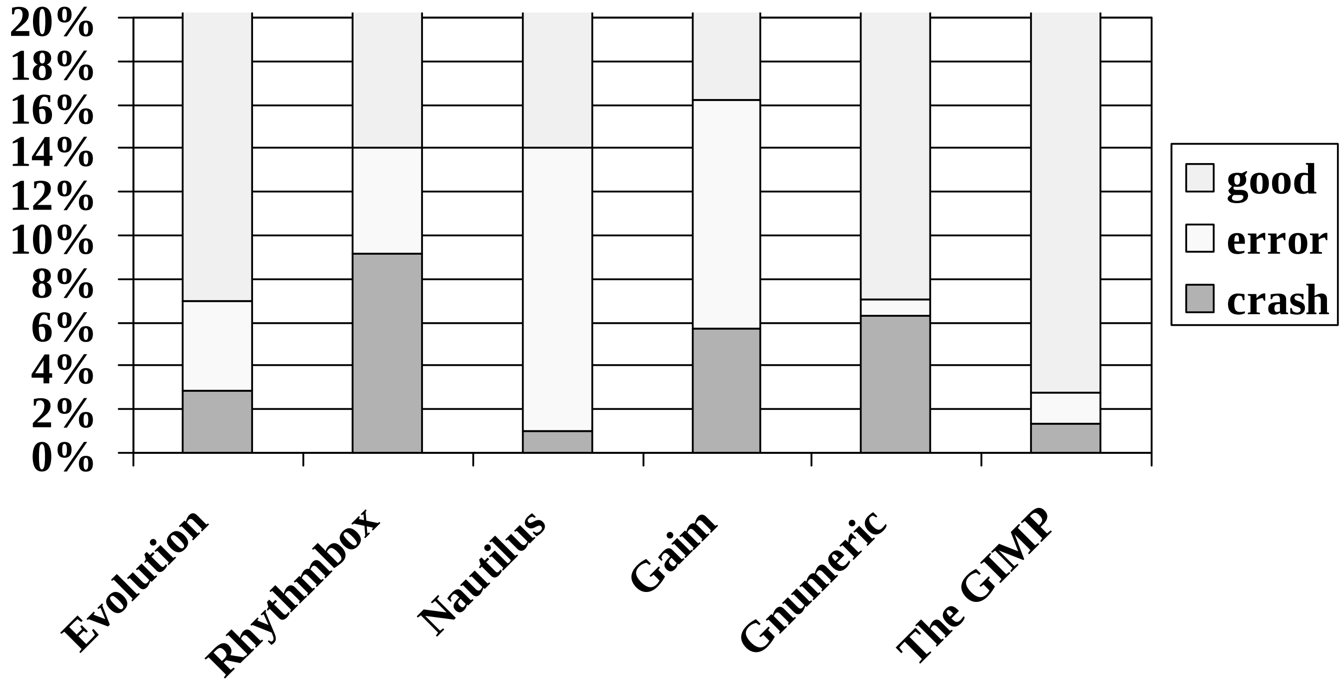
Experimental Results: Rhythmbox



Initial	Effective	Predicate
		tmp is FALSE
		(mp->priv)->timer is FALSE
		(view->priv)->change_sig_queued is TRUE
		(hist->priv)->db is TRUE
		rb_playlist_manager_signals[0] > 269
		(db->priv)->thread_reaper_id >= 12
		entry == entry
		fn == fn
		klass > klass
		genre < artist
		vol <= (float)0 is TRUE
		(player->priv)->handling_error is TRUE
		(statusbar->priv)->library_busy is TRUE
		shell < shell
		len < 270

- 15 predicates from 857,384
- Also isolated crashing bugs . . .

Public Deployment in Progress



Lessons Learned

- A lot can be learned from actual executions
  - Users are executing them anyway
  - We should capture some of that information
- Crash reporting is a step in the right direction
  - But doesn't characterize successful runs
  - Stack is useful for only about 50% of bugs
- Bug finding is just one possible application
  - Understanding usage patterns
  - Understanding performance in different environments

Related Work

- Gamma
  - Georgia Tech
- Daikon
  - MIT/U. Washington
- Diduce
  - Stanford

The Cooperative Bug Isolation Project

http://www.cs.wisc.edu/cbi/