# Exterminator: Automatically Correcting Memory Errors with High Probability

**Gene Novark** **Emery Berger**

University of Massachusetts Amherst

**Ben Zorn**

Microsoft Research

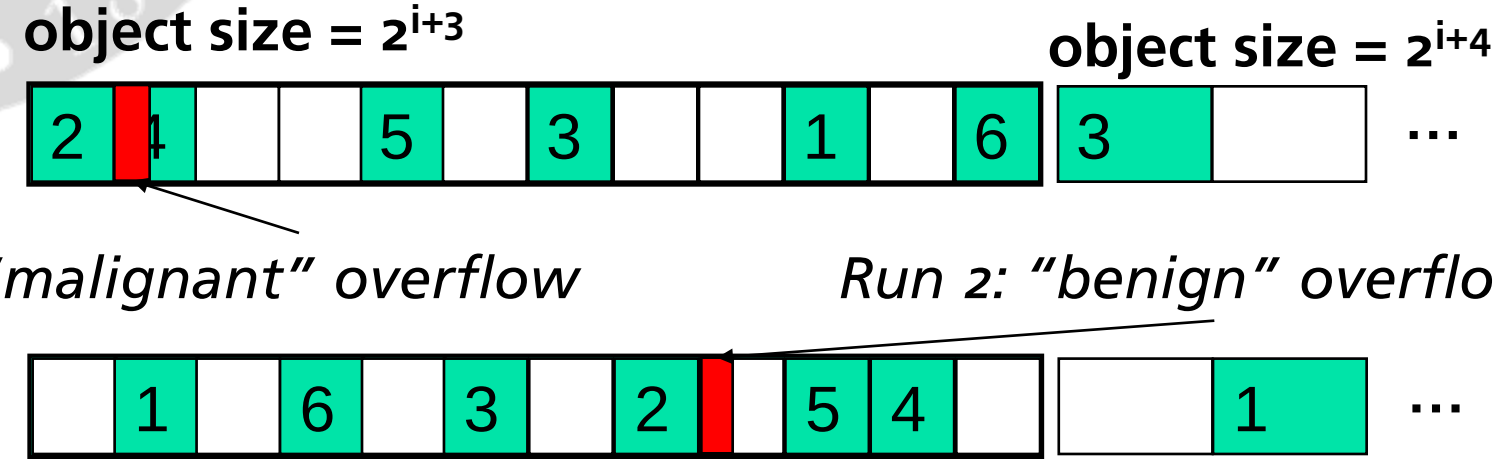
# *Problems with Unsafe Languages*

- C, C++: pervasive apps, but **unsafe**
- Numerous opportunities for security vulnerabilities, **errors**
  - Double/Invalid **`free`**
  - Uninitialized reads
  - Dangling pointers
  - Buffer overflows (stack & **heap**)
- DieHard: eliminates some, **probabilistically** avoids others [PLDI 2006]
  - Exterminator: builds on DieHard

# DieHard Overview

[PLDI 2006]

- Use randomization & (optionally) replication to reduce risk of memory errors
  - Objects randomly spread across heap
- Different run = different heap
  - **Probabilistic memory safety**
    - Errors across heaps **independent**



# DieHard Limitations

- **DieHard:**
  - Fine for single error
    - But multiple errors eventually swamp probabilistic protection
    - Not great for large overflows
  - Tolerates errors
    - But doesn't find them
    - No information for programmer
- **Exterminator:**
  Automatically **isolate** and **fix** memory errors

# Diagnosing Buffer Overflows

- Canonical buffer overflow:
  - Allocate object – too small
  - Write past end $\Rightarrow$ nukes object $\delta$ bytes forward
    - Not *necessarily* contiguous

```
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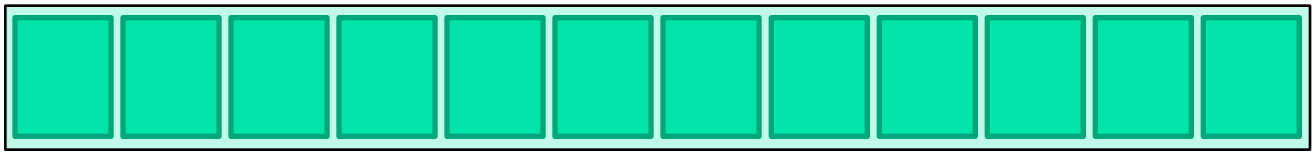

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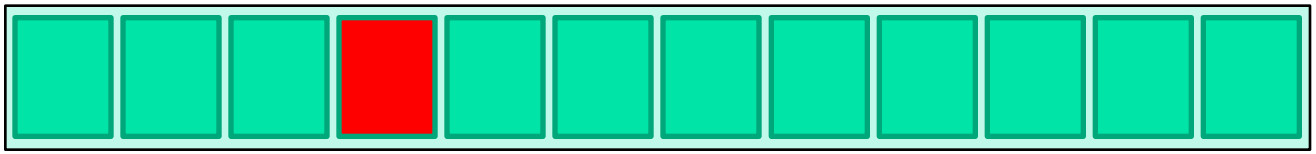

*bad object*
*(too small)*

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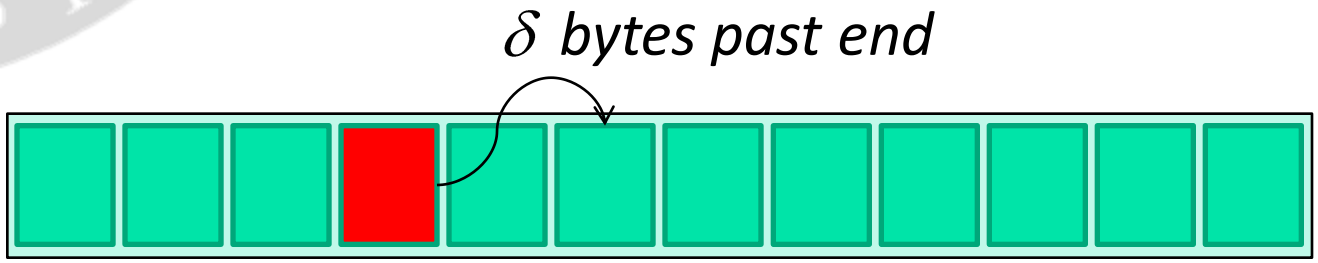

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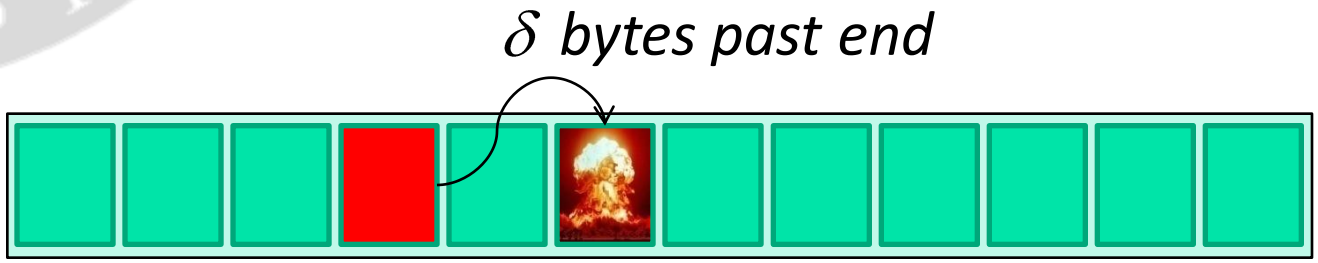

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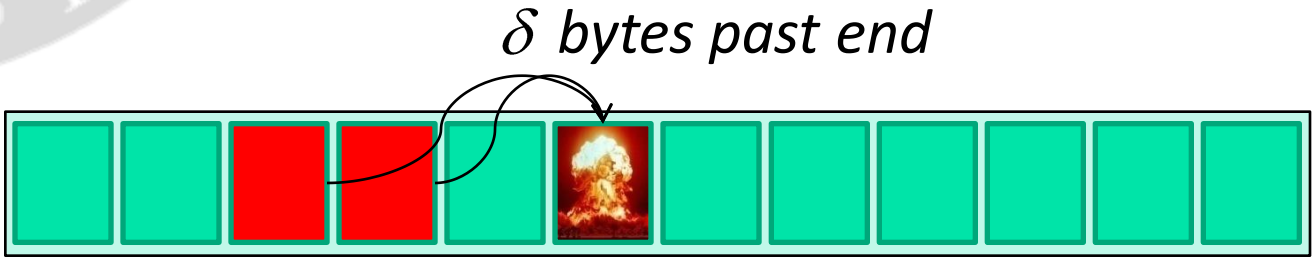

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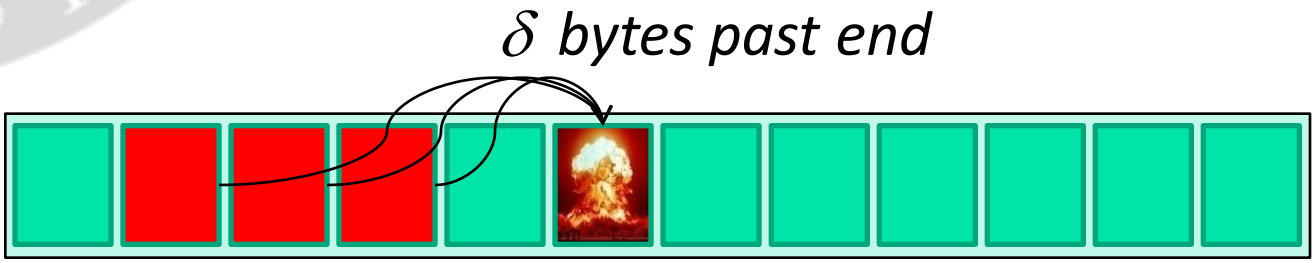

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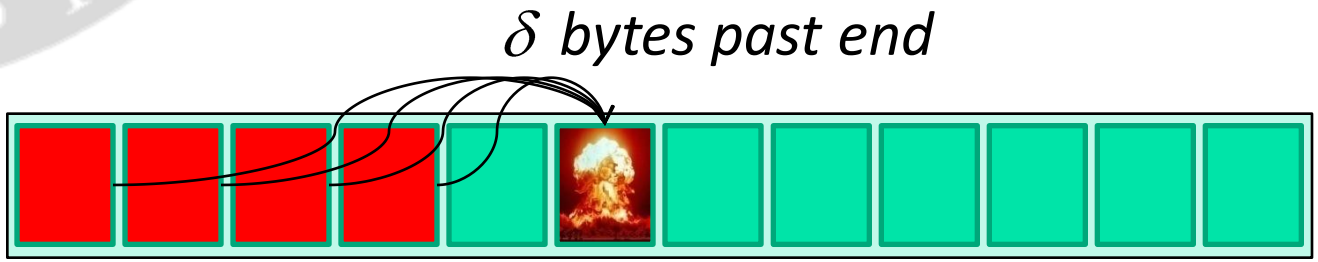

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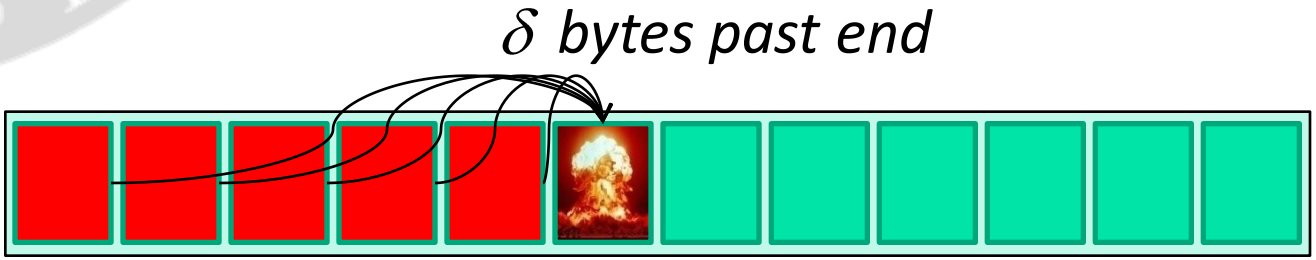

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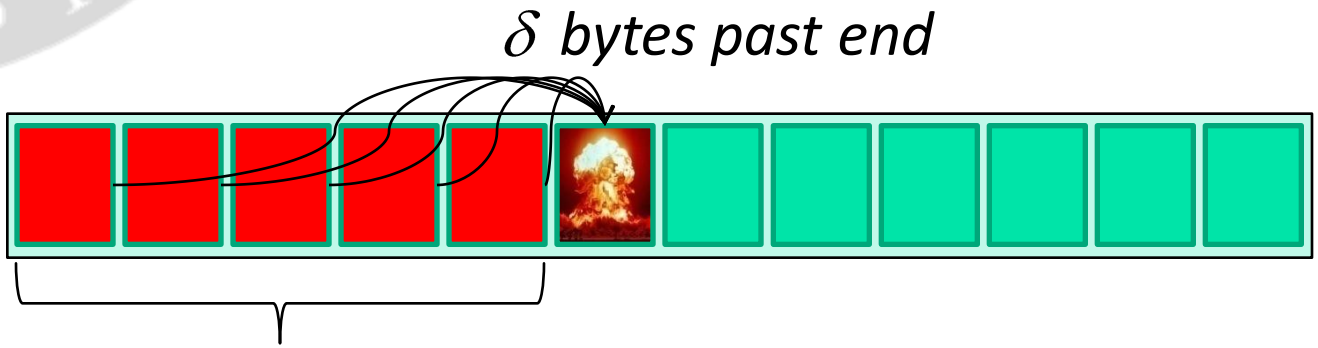


**1. Heap provides no useful information**

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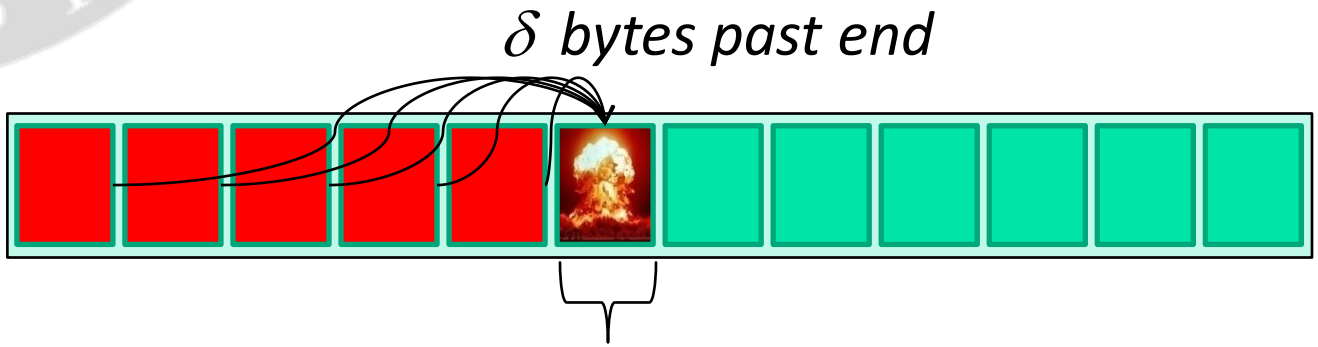


**2. No way to detect corruption**

# *Isolating Buffer Overflows*

- **Canaries** in freed space detect corruption

*known random value*

*dead canary = corruption*

**Red =** possible bad object


**Green =** *not* bad object

*# = object id (allocation time)*

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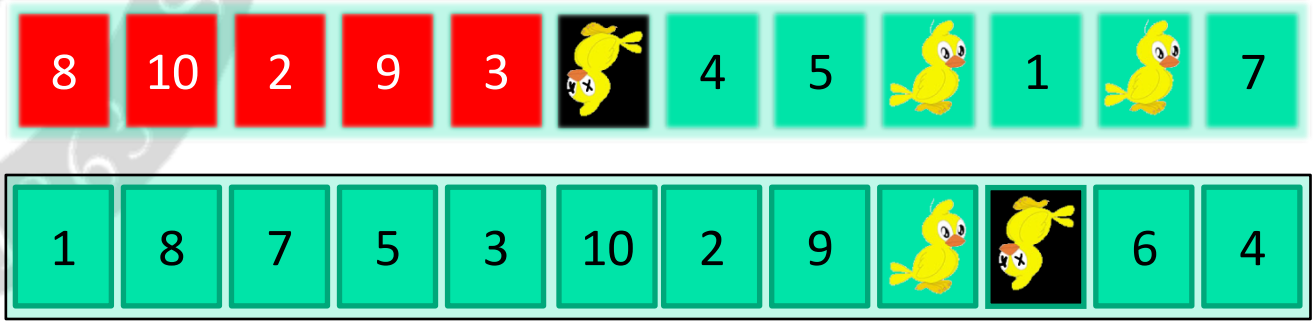


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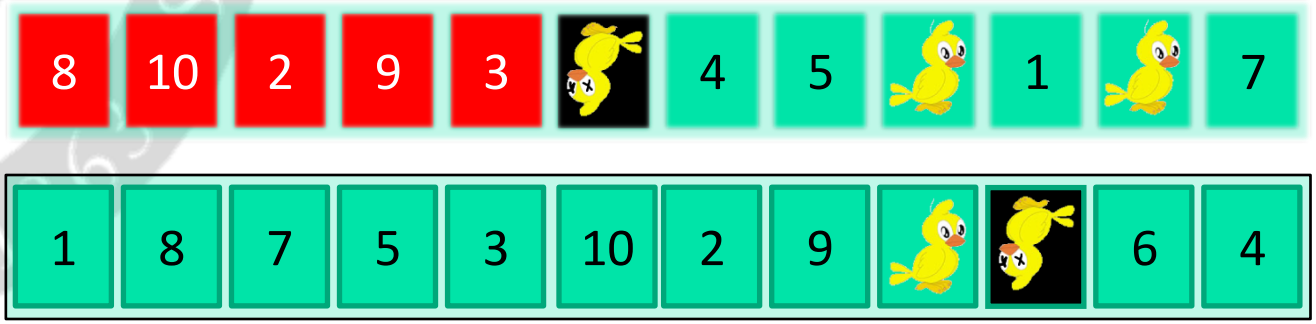


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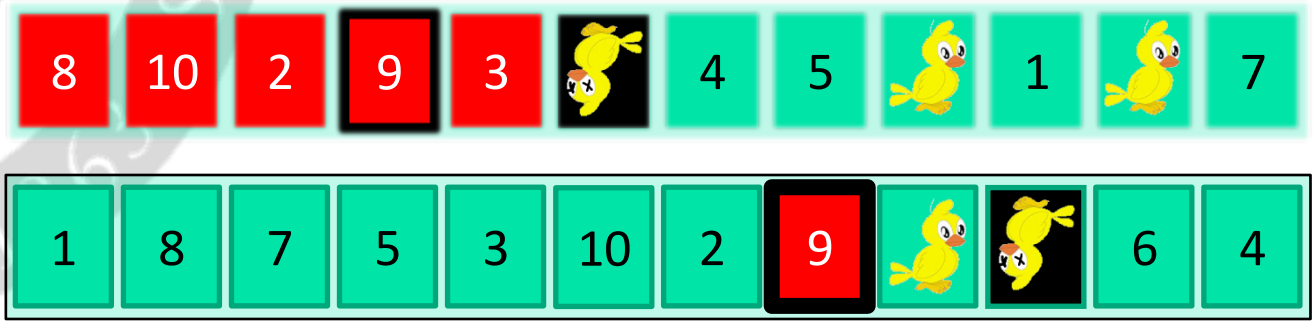


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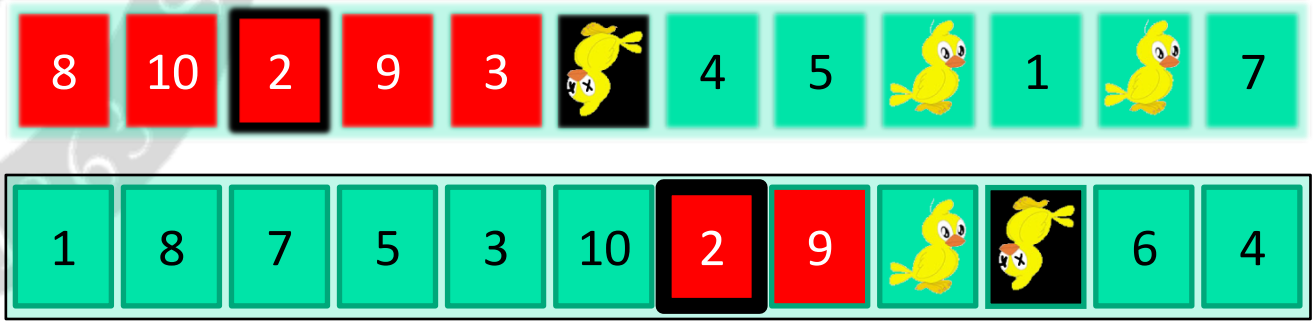


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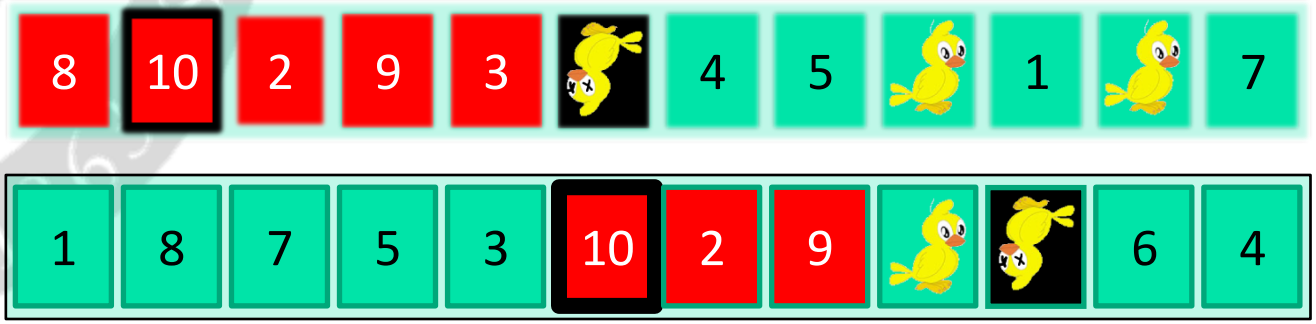


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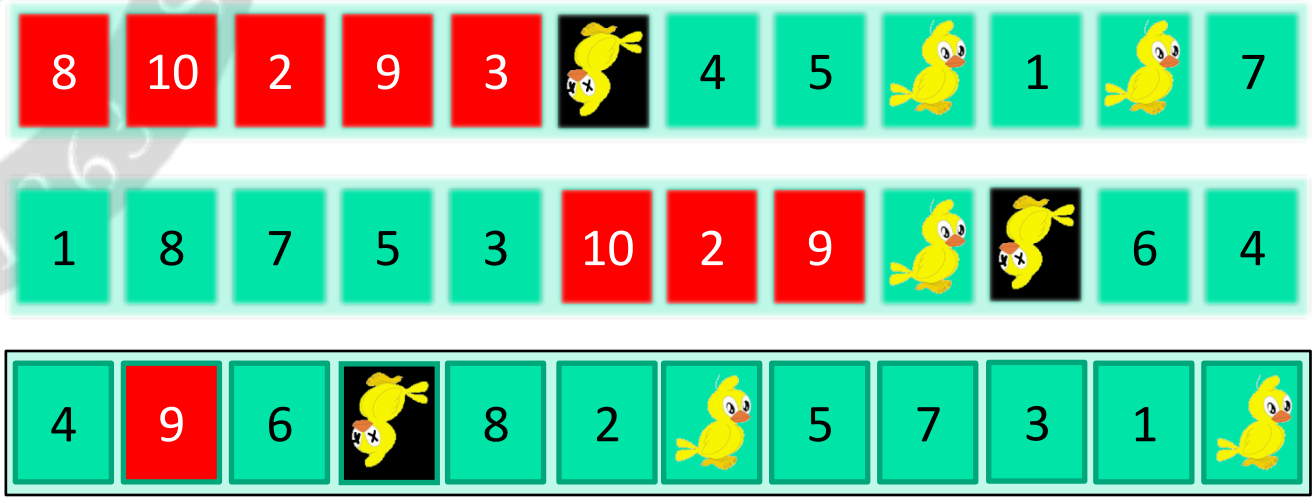
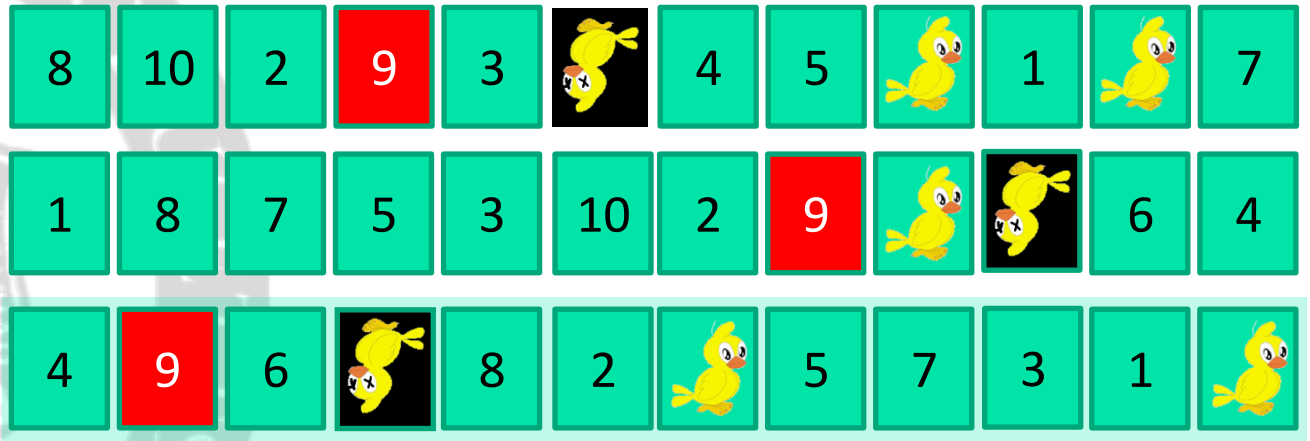



⇒ object 9 overflowed, *with high probability*

# Buffer Overflow Analysis




$$\mathrm{E}(\text{false positives}) = \frac{1}{(H-1)^{k-2}}$$

**H = # heap objects**
**K = # iterations**

- Example: H = 1,000,000 objects
  3 iterations $\approx \frac{1}{1{,}000{,}000}$ false positives
- **Iterations exponentially increase precision**

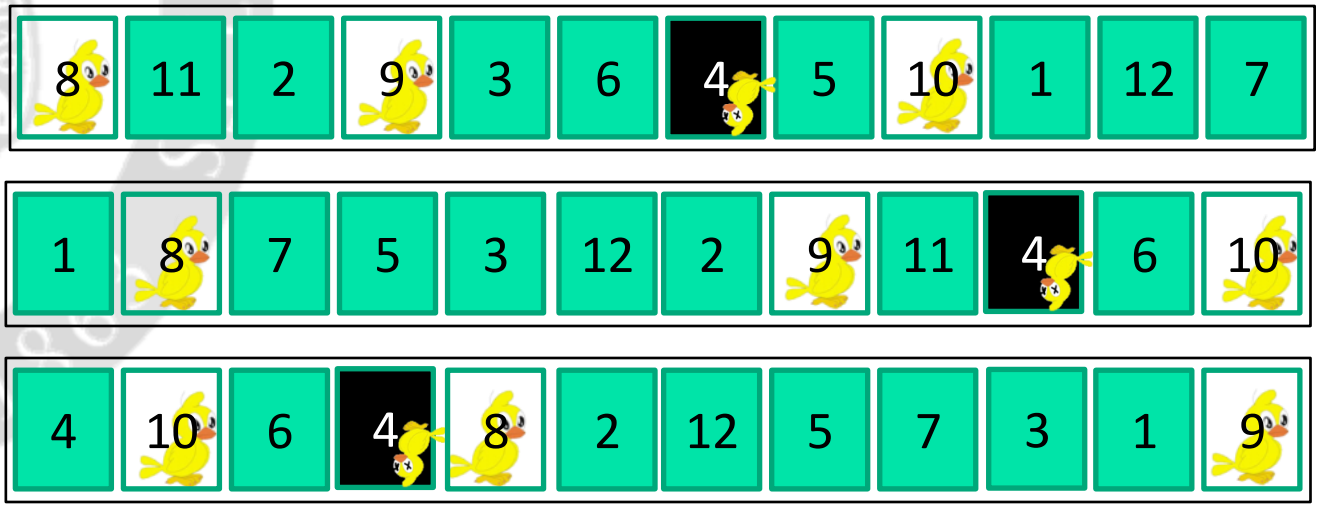
# *Isolating Dangling Pointers*

- Dangling pointer error:
  - Live object freed too soon
  - Overwritten by some other object

```
int * v = new int[4];
…
delete [] v; // oops
…
char * str = new char[16];
strcpy (str, “die, pointer”);
v[3] = 12;
… use of v[0]
```

# Isolating Dangling Pointers

- Unlike buffer overflow:
  - dangling pointer ⇒ **same** corruption in all



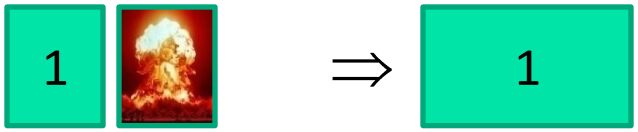

$$\mathrm{P}(\text{identical overflow}) \leq \left(\frac{1}{H-1}\right)^{k-1}$$

  - k = 3 ⇒ *false negatives* $\approx \left(\frac{1}{1{,}000{,}000}\right)^{2}$

# Correcting Allocator

- Generate **runtime patches** to **correct** errors
  - Track object call sites in allocator
- *Prevent overflows*: **pad** overflowed objects

`malloc(8)` ⇒ `malloc(8 + δ)`




- *Prevent dangling pointers*: **defer** frees

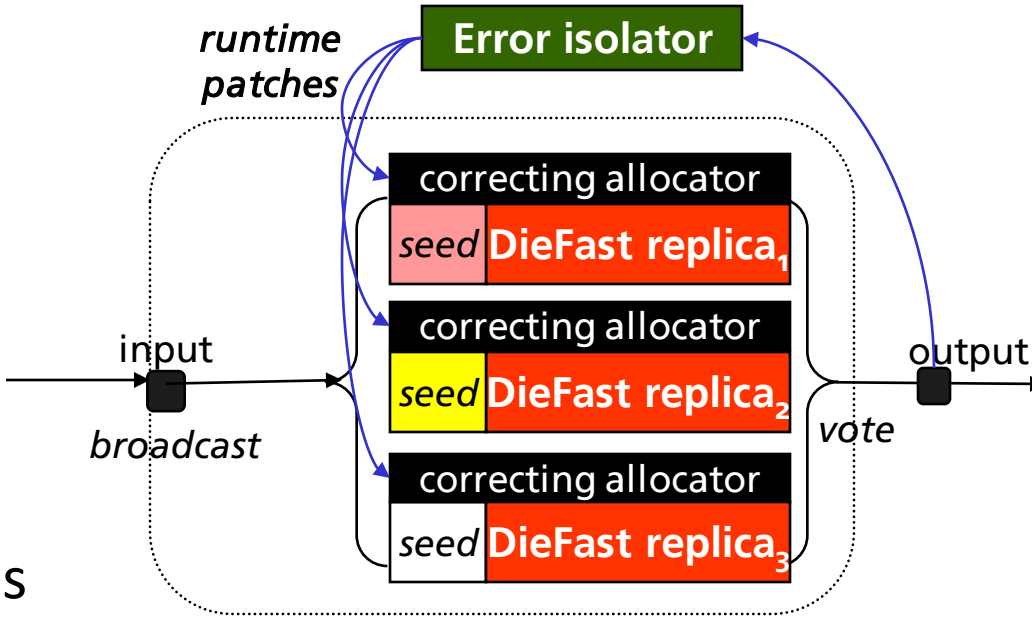
```
free(ptr) ⇒ delay δ mallocs;
            free(ptr)
```

# *Exterminator Architecture*

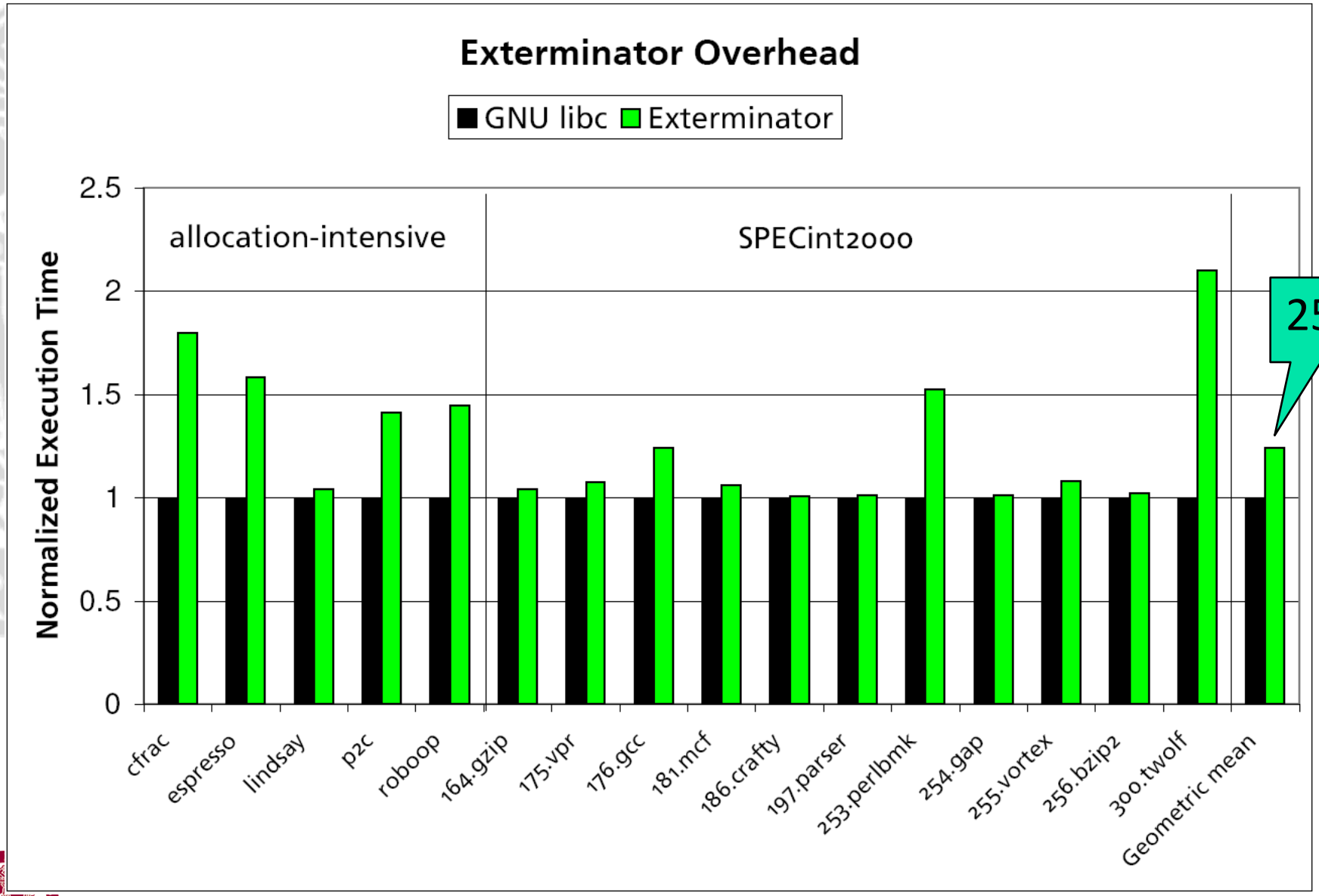
- Three main pieces:
  - DieHard-based **allocator** (DieFast)
    - Reveals bugs
  - **Error isolator**
    - Finds bugs across multiple heaps w.h.p.
  - **Correcting allocator**
    - Fixes bugs
- Multiple modes suitable for testing (debugging) or deployment

# Exterminator Modes

- **Iterative**
  - Run multiple times
  - Same inputs
  - Debugging
- **Replicated**
  - Run simultaneously
  - Deployable w/limitations
  - Can fix errors on-the-fly
- **Cumulative**
  - Different inputs, nondeterminism
  - Deployable; see paper for details



# Exterminator Runtime Overhead

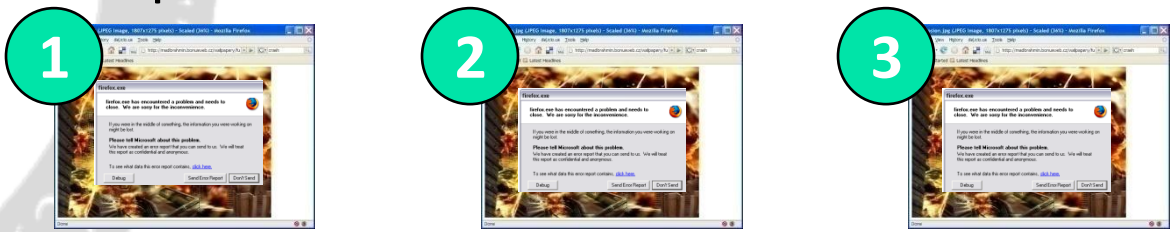


# *Empirical Results: Real Faults*

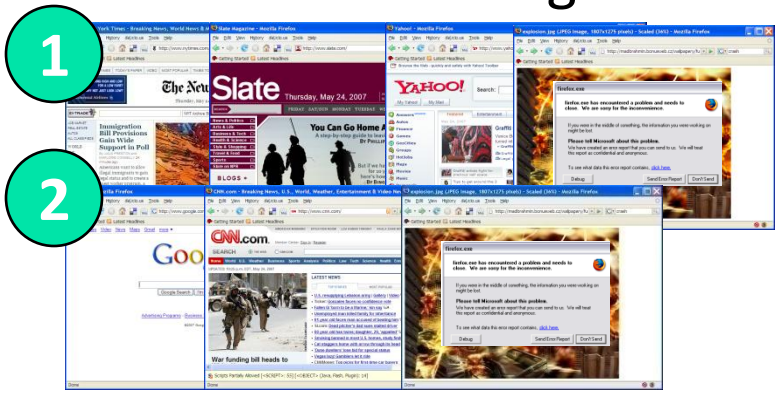
- Squid heap overflow
  - Crashes glibc 2.8.0 and BDW collector
  - 3 iterations to fix $\Rightarrow$ 6 byte pad
    - Prevents overflow for all subsequent executions

# Empirical Results: Real Faults

- Mozilla 1.7.3 buffer overflow
  - **Debug scenario:**
    - repeated load of PoC: 23 runs to fix overflow




  - **Deployed scenario**:
    - different browsing sessions: 34 runs to fix



# *Exterminator Conclusion*

- Exterminator: **automatic error correction** w.h.p.
  - **Randomization** ⇒ bugs have *different* effects
  - **Statistical analysis** combines information from multiple runs to isolate error
  - **Correcting allocator** eliminates bugs at runtime

http://www.cs.umass.edu/~gnovark/