Tolerating and Correcting Memory Errors in C and C++

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In collaboration with:

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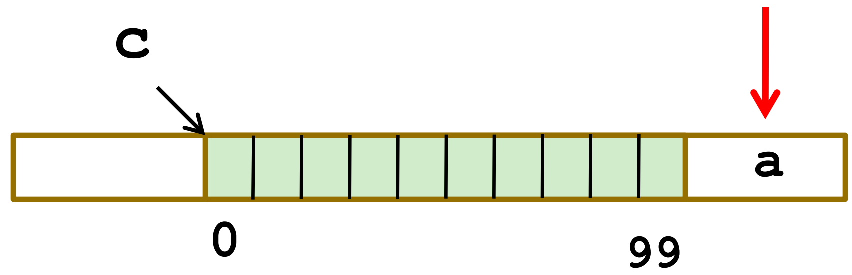
Focus on Heap Memory Errors

- Buffer overflow

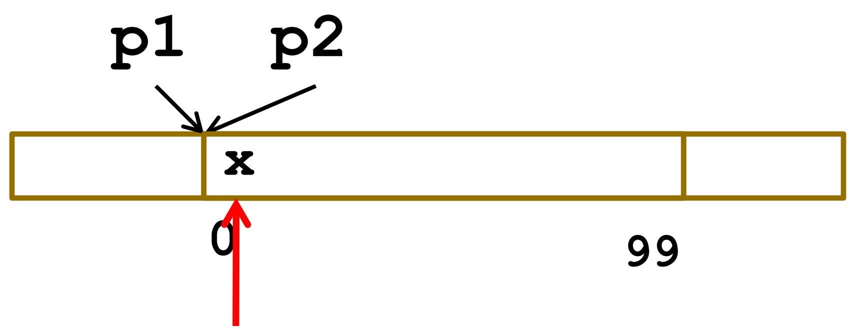
```
char *c = malloc(100);
c[100] = ‘a’;
```



- Dangling reference

```
char *p1 = malloc(100);
char *p2 = p1;

free(p1);
p2[0] = ‘x’;
```



Approaches to Memory Corruptions

- Rewrite in a safe language
- Static analysis / safe subset of C or C++
  - SAFECode [Adve], PREfix, SAL, etc.
- Runtime detection, fail fast
  - Jones & Lin, CRED [Lam], CCured [Necula], etc.
- <u>Tolerate Corruption and Continue</u>
  - Failure oblivious [Rinard] (unsound)
  - Rx, Boundless Memory Blocks, ECC memory
    DieHard / Exterminator, Samurai

Fault Tolerance and Platforms

- Platforms necessary in computing ecosystem
  - Extensible frameworks provide lattice for 3rd parties
  - Tremendously successful business model
  - Examples: Window, iPod, browser, etc.
- Platform power derives from extensibility
  - Tension between isolation for fault tolerance, integration for functionality
  - **Platform only as reliable as weakest plug-in**
  - Tolerating bad plug-ins necessary by design

Research Vision

- Increase robustness of installed code base
  - Potentially improve millions of lines of code
  - Minimize effort – ideally no source mods, no recompilation
- Reduce requirement to patch
  - Patches are expensive (detect, write, deploy)
  - Patches may introduce new errors
- Enable trading resources for robustness
  - E.g., more memory implies higher reliability

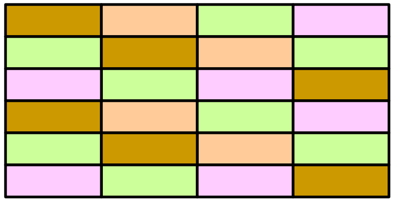
Outline

- Motivation
- Exterminator
  - Collaboration with Emery Berger, Gene Novark
  - Automatically corrects memory errors
  - Suitable for large scale deployment
- Critical Memory / Samurai
  - Collaboration with Karthik Pattabiraman, Vinod Grover
  - New memory semantics
  - Source changes to explicitly identify and protect critical data
- Conclusion

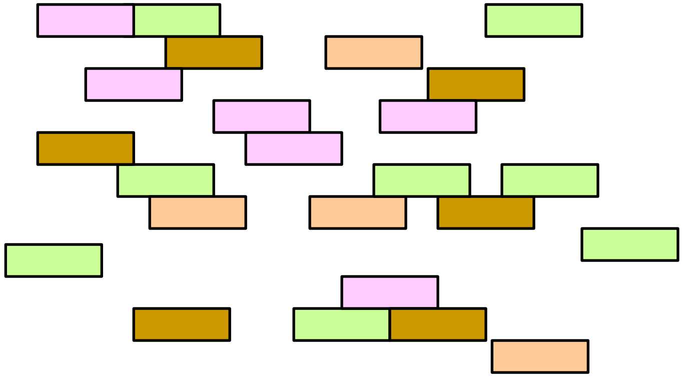
DieHard Allocator in a Nutshell

- With Emery Berger (PLDI'06)
- Existing heaps are packed tightly to minimize space
  - Tight packing increases likelihood of corruption
  - Predictable layout is easier for attacker to exploit
- <u>Randomize</u> and <u>overprovision</u> the heap
  - Expansion factor determines how much empty space
  - Does not change semantics
- Replication increases benefits
- Enables analytic reasoning

Normal Heap



DieHard Heap



DieHard in Practice

- DieHard (non-replicated)
  - Windows, Linux version implemented by Emery Berger
  - Try it right now! (http://www.diehard-software.org/)
  - Adaptive, automatically sizes heap
  - Mechanism automatically redirects malloc calls to DieHard DLL
- Application: Firefox & Mozilla
  - Known buffer in version 1.7.3 overflow crashes browser
- Experience
  - Usable in practice – no perceived slowdown
  - Roughly doubles memory consumption with 2x expansion
    - FireFox: 20.3 Mbytes vs. 44.3 Mbytes with DieHard

DieHard Caveats

- Primary focus is on protecting heap
  - Techniques applicable to stack data, but requires recompilation and format changes
- Trades space, processors for memory safety
  - Not applicable to applications with large footprint
  - Applicability to server apps likely to increase
- In replicated mode, DieHard requires determinism
  - Replicas see same input, shared state, etc.
- DieHard is a brute force approach
  - Improvements possible (efficiency, safety, coverage, etc.)

Exterminator Motivation

- DieHard limitations
  - Tolerates errors probabilistically, doesn’t fix them
  - Memory and CPU overhead
  - Provides no information about source of errors
- “Ideal” solution addresses the limitations
  - Program automatically detects and fixes memory errors
  - Corrected program has no memory, CPU overhead
  - Sources of errors are pinpointed, easier for human to fix
- Exterminator = correcting allocator
  - Joint work with Emery Berger, Gene Novark
  - **Plan: isolate / patch bugs while tolerating them**

Exterminator Components

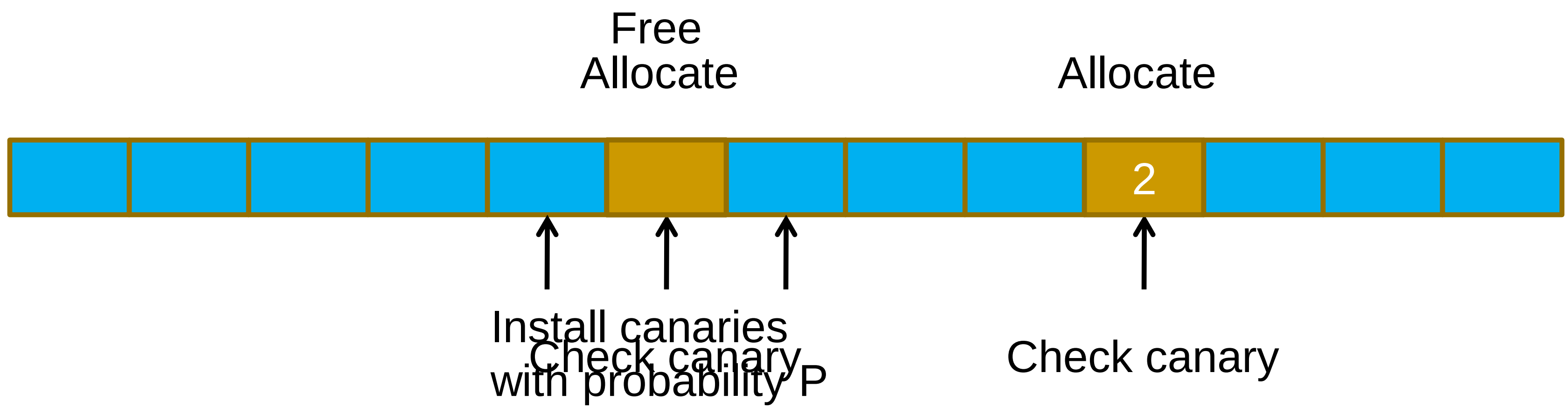
- Architecture of Exterminator dictated by solving specific problems
- How to detect heap corruptions effectively?
  - DieFast allocator
- How to isolate the cause of a heap corruption precisely?
  - Heap differencing algorithms
- How to automatically fix buggy C code without breaking it?
  - Correcting allocator + hot allocator patches

DieFast Allocator

- Randomized, over-provisioned heap
  - Canary = random bit pattern fixed at startup 100101011110
  - Leverage extra free space by inserting canaries
- Inserting canaries
  - Initialization – all cells have canaries
  - On allocation – no new canaries
  - On free – put canary in the freed object with prob. P
- Checking canaries
  - On allocation – check cell returned
  - On free – check adjacent cells

Installing and Checking Canaries

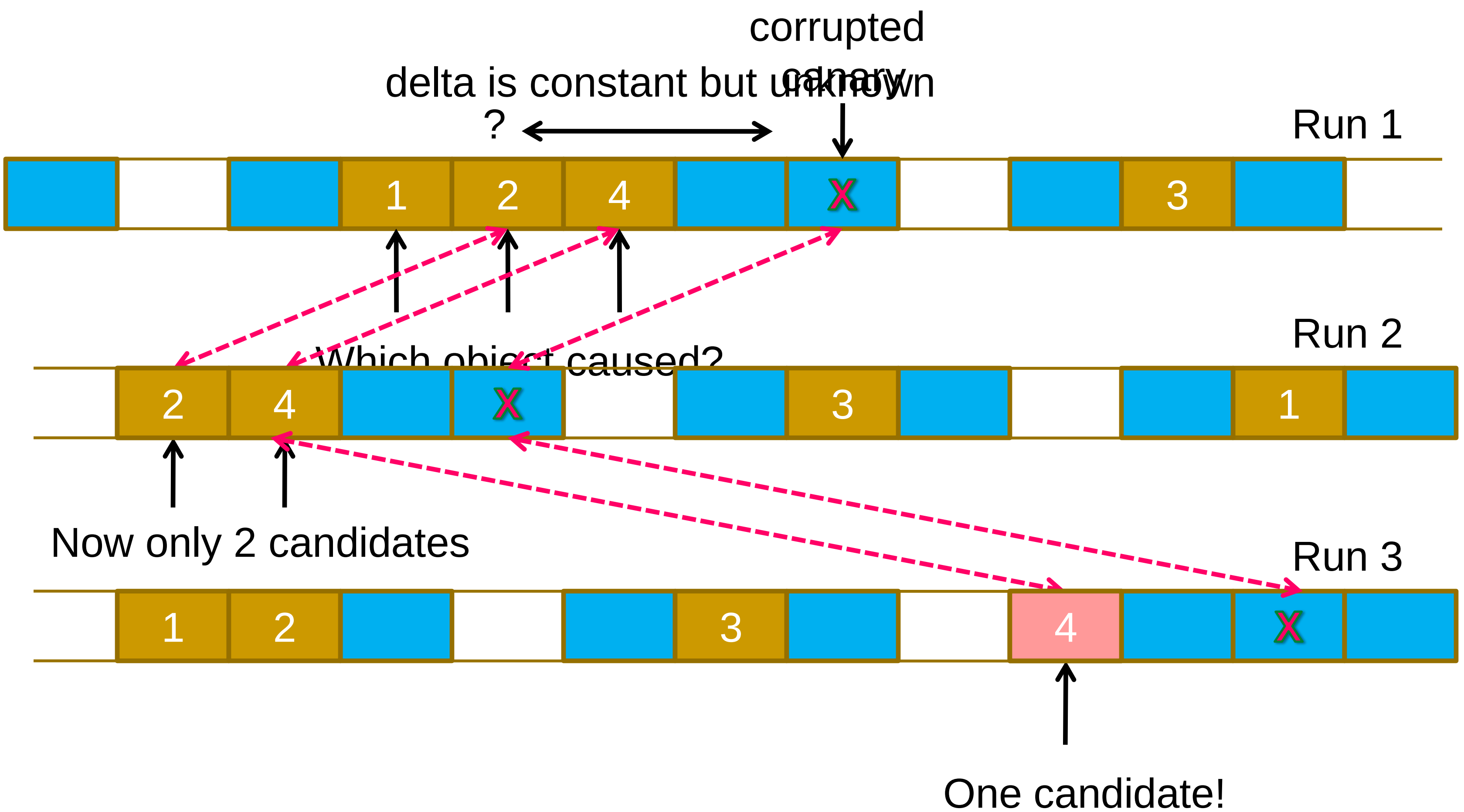
Initially, heap full of canaries



Heap Differencing

- Strategy
  - Run program multiple times with different randomized heaps
  - If detect canary corruption, dump contents of heap
  - Identify objects across runs using allocation order
- Insight: Relation between corruption and object causing corruption is invariant across heaps
  - Detect invariant across random heaps
  - More heaps => higher confidence of invariant

Attributing Buffer Overflows



Precision increases exponentially with number of runs

Detecting Dangling Pointers (2 cases)

- Dangling pointer read/written (easy)
  - Invariant = canary in freed object X has same corruption in <u>all</u> runs
- Dangling pointer only read (harder)
  - Sketch of approach (paper explains details)
    - Only fill freed object X with canary with probability P
    - Requires multiple trials: ≈ $\log_2$(number of callsites)
    - Look for correlations, i.e., X filled with canary => crash
    - Establish conditional probabilities
      - Have: P(callsite X filled with canary | program crashes)
      - Need: P(crash | filled with canary), guess "prior" to compute

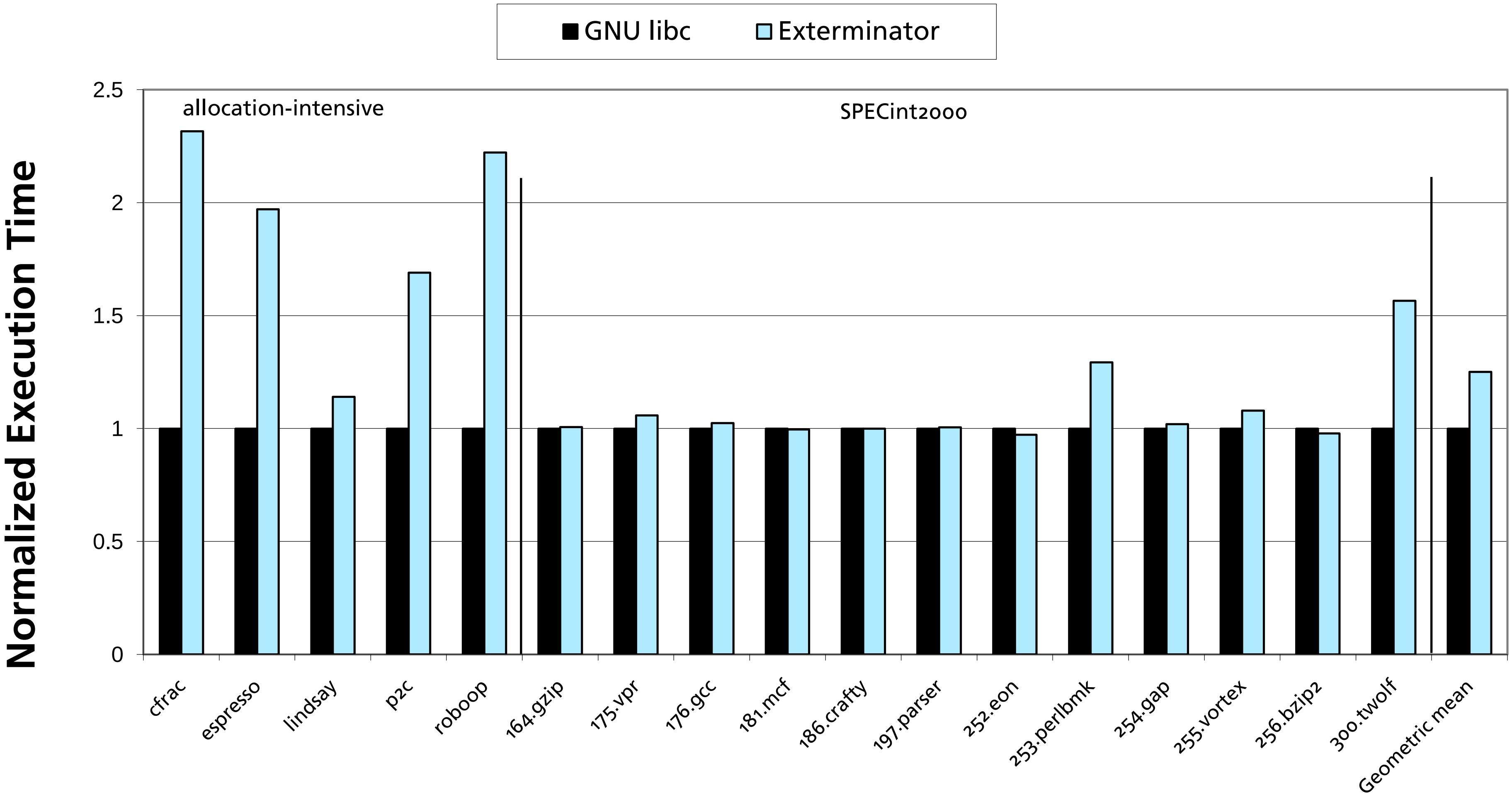
Correcting Allocator

- Group objects by allocation site
- Patch object groups at allocate/free time
- Associate patches with group
  - Buffer overrun => add padding to size request
    - malloc(32) becomes malloc(32 + delta)
  - Dangling pointer => defer free
    - free(p) becomes defer_free(p, delta_allocations)
  - Fixes preserve semantics, no new bugs created
- Correcting allocation may != DieFast or DieHard
  - Correction allocator can be space, CPU efficient
  - “Patches” created separately, installed on-the-fly

Deploying Exterminator

- Exterminator can be deployed in different modes
- Iterative – suitable for test environment
  - Different random heaps, identical inputs
  - Complements automatic methods that cause crashes
- Replicated mode
  - Suitable in a multi/many core environment
  - Like DieHard replication, except auto-corrects, hot patches
- Cumulative mode – partial or complete deployment
  - Aggregates results across different inputs
  - Enables automatic root cause analysis from Watson dumps
  - Suitable for wide deployment, perfect for beta release
  - Likely to catch many bugs not seen in testing lab

DieFast Overhead



Exterminator Effectiveness

- Squid web cache buffer overflow
  - Crashes glibc 2.8.0 malloc
  - 3 runs sufficient to isolate 6-byte overflow
- Mozilla 1.7.3 buffer overflow (recall demo)
  - Testing scenario - repeated load of buggy page
    - 23 runs to isolate overflow
  - Deployed scenario – bug happens in middle of different browsing sessions
    - 34 runs to isolate overflow

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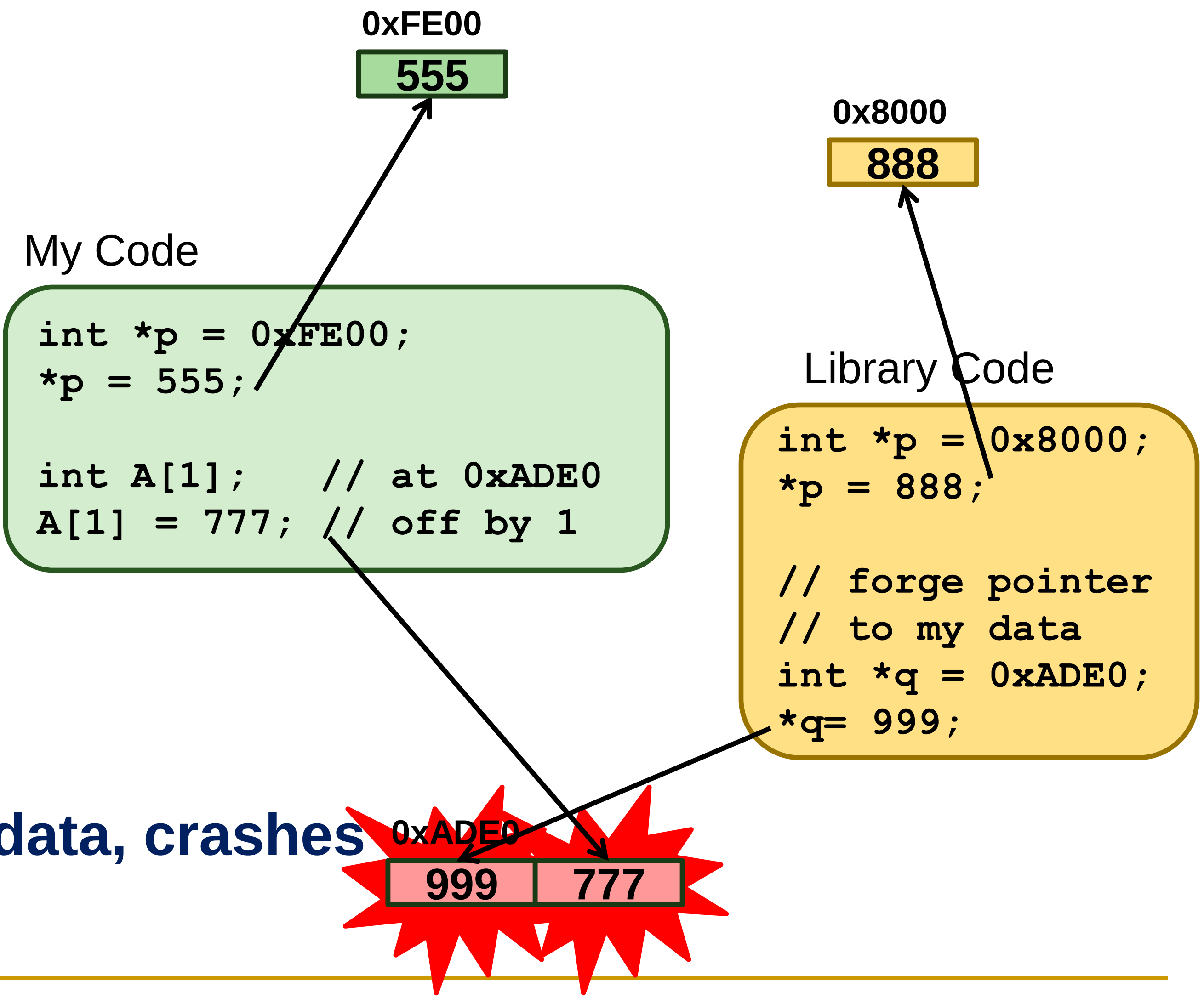
The Problem: A Dangerous Mix

Danger 1:
Flat, uniform address space

Danger 2:
Unsafe programming languages

Danger 3:
Unrestricted 3rd party code



Result: corrupt data, crashes security risks

Critical Memory

- Approach
  - Identify **critical program data**
  - Protect it with **isolation & replication**
- Goals:
  - **Harden** programs from both SW and HW errors
    - Unify existing ad hoc solutions
  - Enable **local reasoning** about memory state
    - Leverage powerful static analysis tools
  - Allow **selective, incremental hardening** of apps
  - Provide **compatibility** with existing libraries, apps

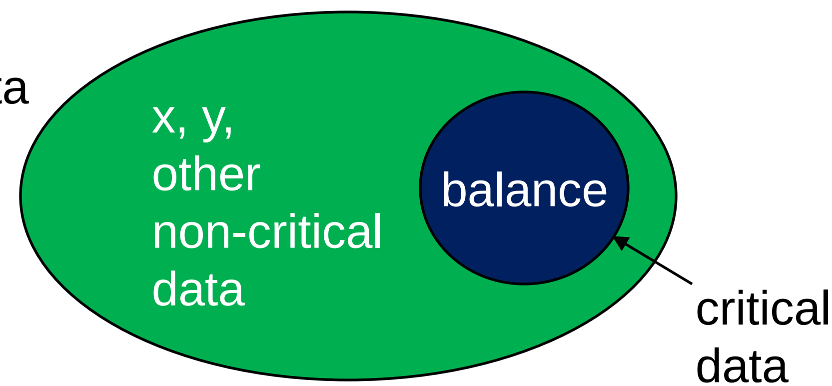
Critical Memory: Idea

Code

```
critical int balance;

balance += 100;
if (balance < 0) {
    chargeCredit();
} else {
    // use x, y, etc.
}
```

Data



- Identify and mark some data as “critical
  - Type specifier like **const**
- Shadow critical data in parallel address space (critical memory)
- New operations on critical data
  - cload – read
  - cstore - write

Critical Memory: Example

buffer overflow into balance

```
int buffer[10];
critical int balance ;

balance = 100;

buffer[10] += 200;
…..

if (balance < 0) {
    …
```

```
map_critical(&balance);

temp1 = 100;
cstore(&balance, temp1);
temp = load ( (buffer+40));
store( (buffer+40), temp+200);
temp2  = cload(&balance);
if (temp2 > 0) { … }
```

	balance				
Normal Mem	0	100	100	300	100
Critical Mem	0	100	100	100	100

Third-party Libraries/Untrusted Code

- Library code does not need to be critical memory aware
  - If library does not update critical data, no changes required
- If library needs to modify critical data
  - Allow normal stores to critical memory in library
  - Explicitly "promote" on return
- Copy-in, copy-out semantics

```
critical int balance = 100;
…
library_foo(&balance);
promote balance;
…
______________________

// arg is not critical int *
void library_foo(int *arg)
{
    *arg = 10000;
    return;
}
```

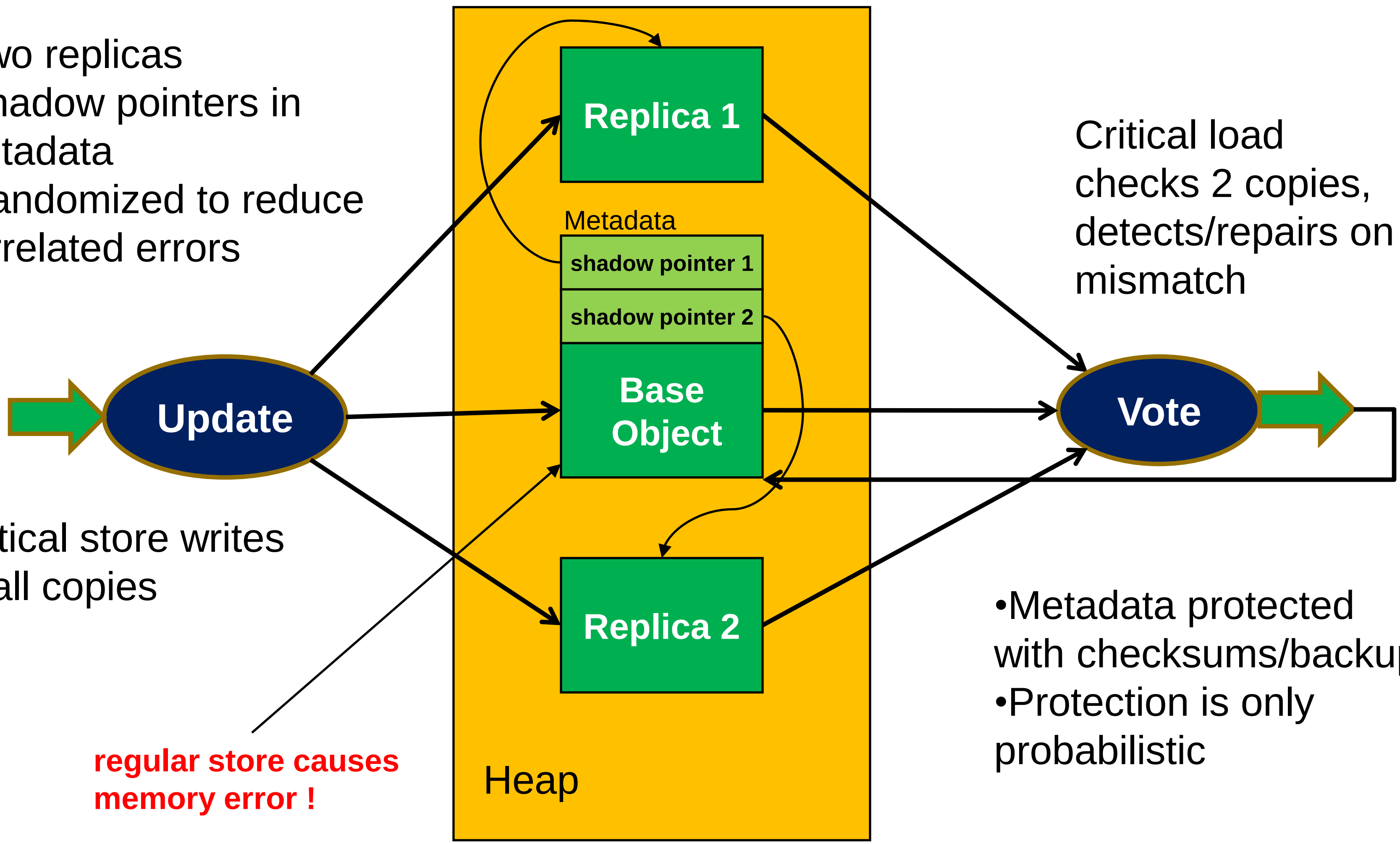
Samurai: Heap-based Critical Memory

- Software critical memory for heap objects
  - Critical objects allocated with crit_malloc, crit_free
- Approach
  - Replication – base copy + 2 shadow copies
  - Redundant metadata
    - Stored with base copy, copy in hash table
    - Checksum, size data for overflow detection
  - Robust allocator as foundation
    - DieHard, unreplicated
    - Randomizes locations of shadow copies

Samurai Implementation

- Two replicas
- Shadow pointers in metadata
- Randomized to reduce correlated errors

Critical load checks 2 copies, detects/repairs on mismatch



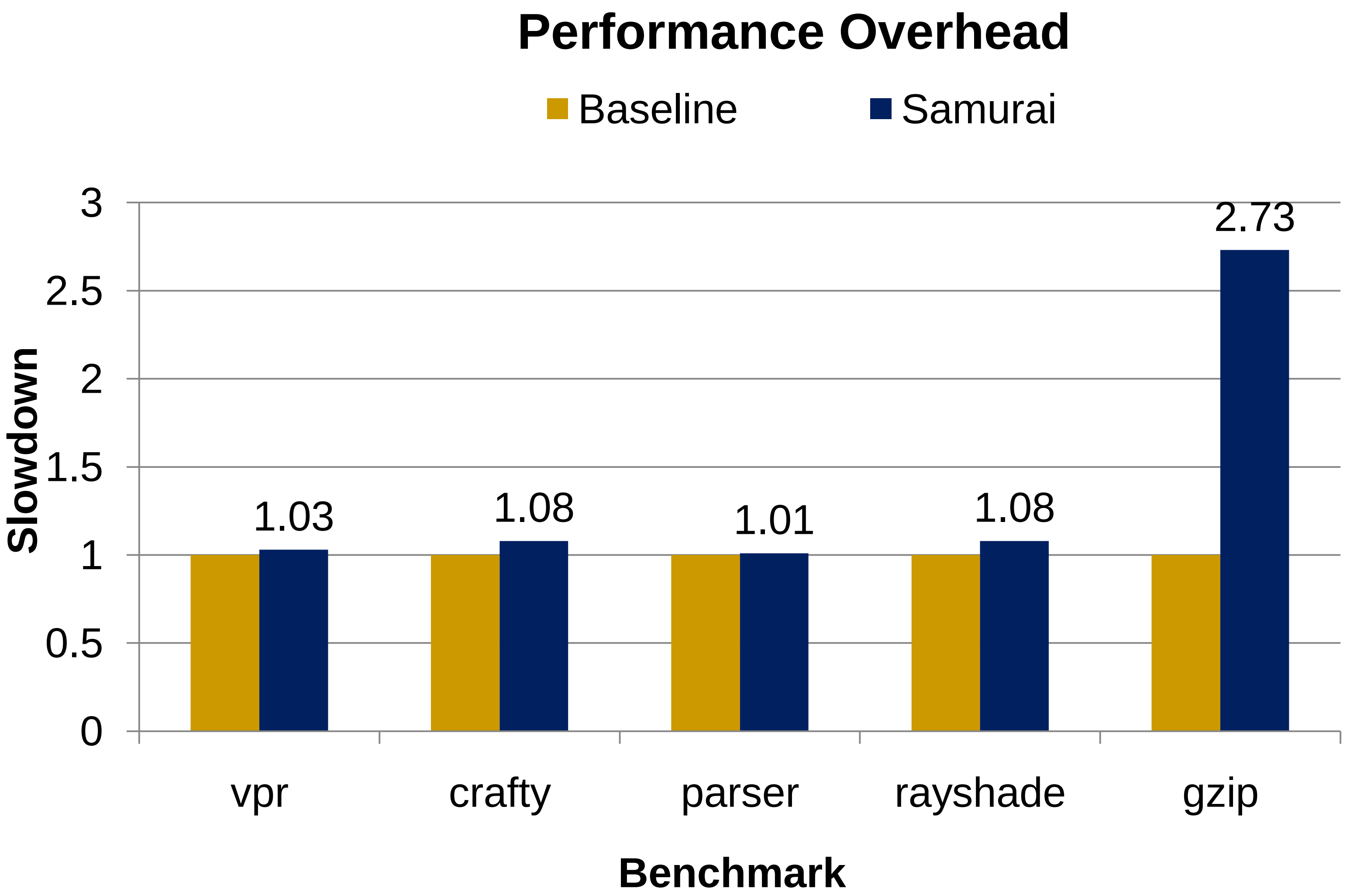
Critical store writes to all copies

- Metadata protected with checksums/backup
- Protection is only probabilistic

Samurai Experimental Results

- Implementation
  - Automated Phoenix pass to instrument loads and stores
  - Runtime library for critical data allocation/de-allocation (C++)
- Protected critical data in 5 applications (mostly SPEC)
  - Chose data that is crucial for end-to-end correctness of program
  - Evaluation of performance overhead by instrumentation
  - Fault-injections into critical and non-critical data (for propagation)
- Protected critical data in libraries
  - **STL List Class**: Backbone of list structure (link pointers)
  - **Memory allocator**: Heap meta-data (object size + free list)

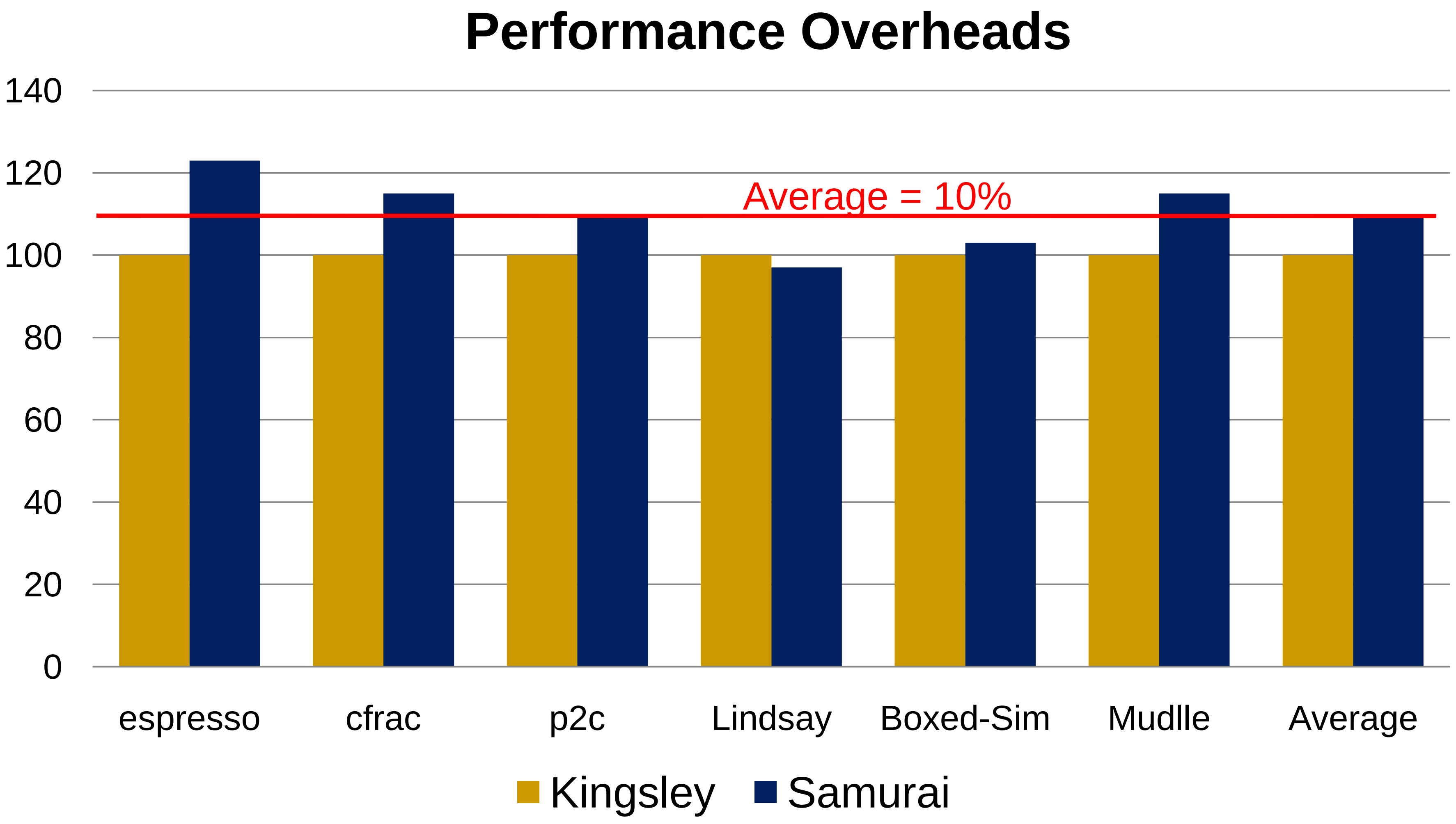
Samurai Performance Overheads



Samurai: STL Class + WebServer

- **STL List Class**
  - Modified memory allocator for class
  - Modified member functions *insert, erase*
  - Modified custom iterators for list objects
  - Added a new call-back function for direct modifications to list data
- **Webserver**
  - Used STL list class for maintaining client connection information
  - Made list critical – one thread/connection
  - Evaluated across multiple threads and connections
  - Max performance overhead = **9%**

Samurai: Protecting Allocator Metadata



Conclusion

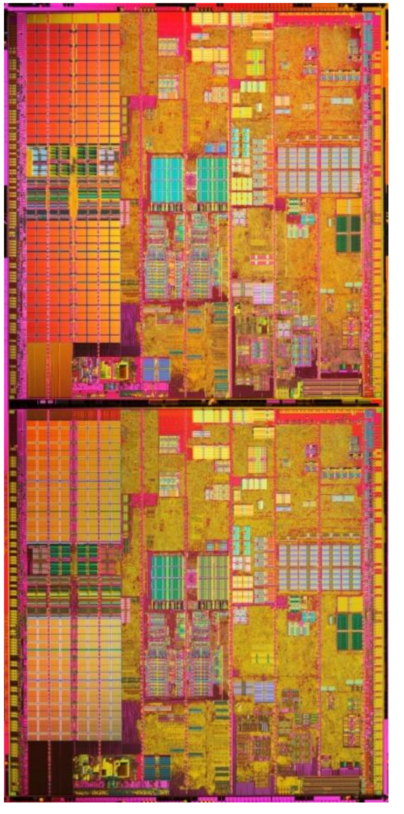
- Programs written in C / C++ can execute safely and correctly despite memory errors
- Research vision
  - Improve existing code without source modifications
  - Reduce human generated patches required
  - Increase reliability, security by order of magnitude
- Current projects
  - **DieHard / Exterminator**: automatically detect and correct memory errors (with high probability)
  - **Critical Memory / Samurai**: enable local reasoning, allow selective hardening, compatibility
  - **ToleRace**: replication to hide data races

Hardware Trends (1) Reliability

- Hardware transient faults are increasing
  - Even type-safe programs can be subverted in presence of HW errors
    - Academic demonstrations in Java, OCaml
  - Soft error workshop (SELSE) conclusions
    - Intel, AMD now more carefully measuring
    - “Not practical to protect everything”
    - Faults need to be handled at all levels from HW up the software stack
  - Measurement is difficult
    - How to determine soft HW error vs. software error?
    - Early measurement papers appearing

Hardware Trends (2) Multicore

- DRAM prices dropping
  - 2Gb, Dual Channel PC 6400 DDR2 800 MHz $85
- Multicore CPUs
  - **Quad-core** Intel Core 2 Quad, AMD Quad-core Opteron
  - **Eight core** Intel by 2008?
- *Challenge:*
  How should we use all this hardware?



Additional Information

- Web sites:
  - Ben Zorn: http://research.microsoft.com/~zorn
  - DieHard: http://www.diehard-software.org/
  - Exterminator: http://www.cs.umass.edu/~gnovark/
- Publications
  - Emery D. Berger and Benjamin G. Zorn, "**DieHard: Probabilistic Memory Safety for Unsafe Languages**", *PLDI'06.*
  - Karthik Pattabiraman, Vinod Grover, and Benjamin G. Zorn, "**Samurai: Protecting Critical Data in Unsafe Languages**", *Eurosys 2008*.
  - Gene Novark, Emery D. Berger and Benjamin G. Zorn, **"Exterminator: Correcting Memory Errors with High Probability**", *PLDI'07.*
  - Lvin, Novark, Berger, and Zorn, "**Archipelago: Trading Address Space for Reliability and Security**", *ASPLOS 2008*.

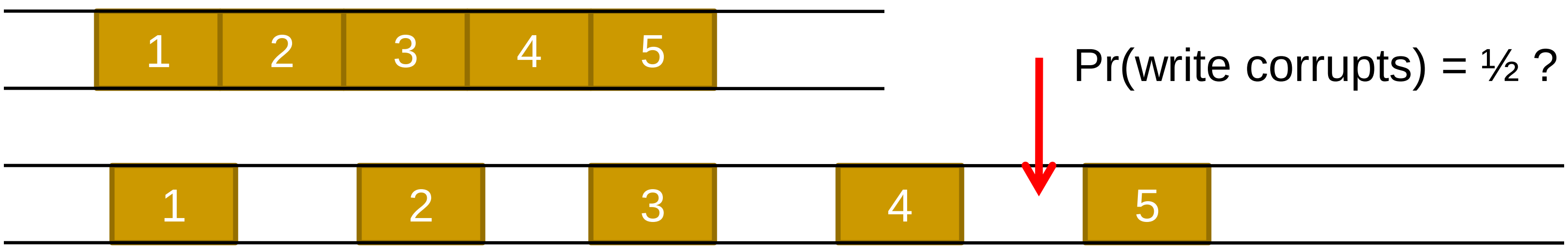
Backup Slides

DieHard: Probabilistic Memory Safety

- Collaboration with Emery Berger
- Plug-compatible replacement for malloc/free in C lib
- We define "infinite heap semantics"
  - Programs execute as if each object allocated with unbounded memory
  - All frees ignored
- Approximating infinite heaps – 3 key ideas
  - Overprovisioning
  - Randomization
  - Replication
- Allows analytic reasoning about safety

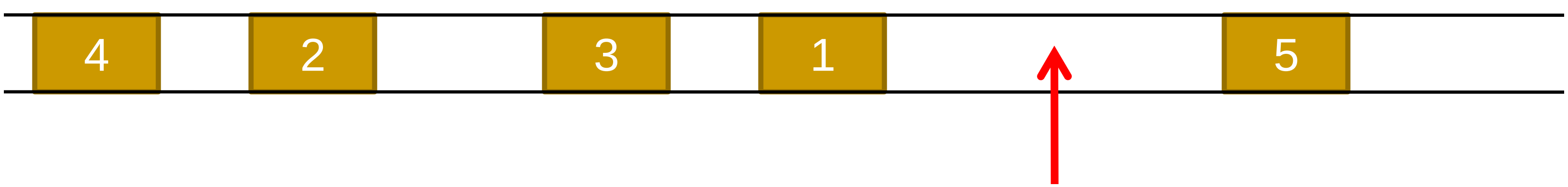
Overprovisioning, Randomization

Expand size requests by a factor of M (e.g., M=2)



Pr(write corrupts) = ½ ?

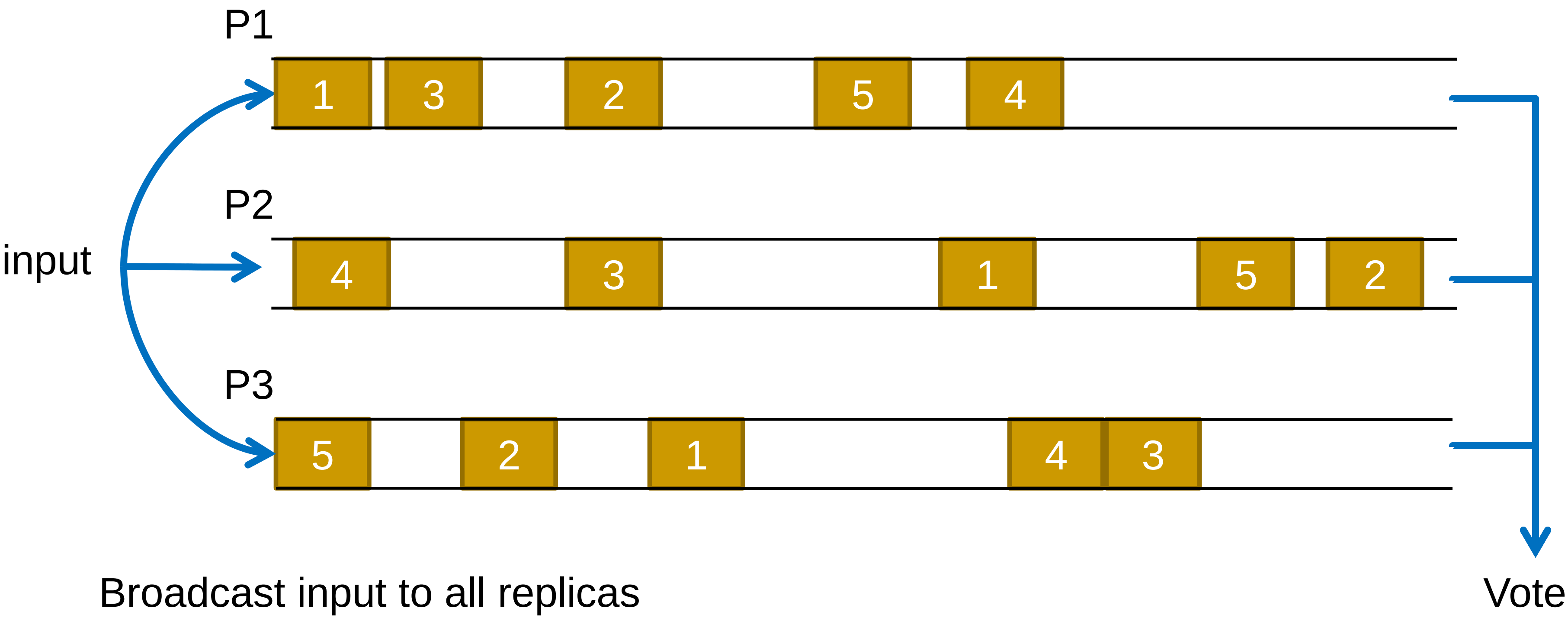
Randomize object placement



Pr(write corrupts) = ½ !

Replication (optional)

Replicate process with different randomization seeds



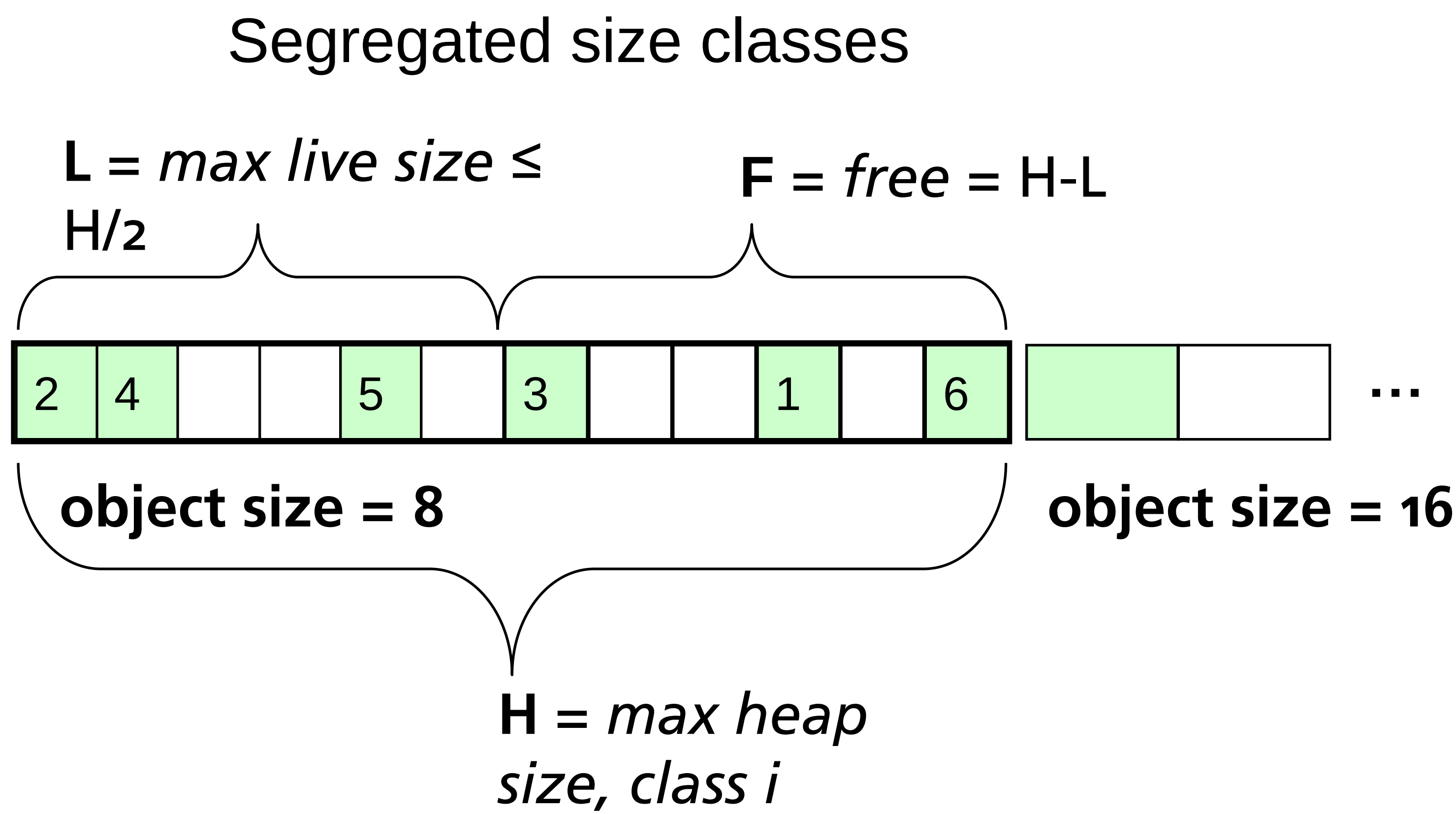
Broadcast input to all replicas

Compare outputs of replicas, kill when replica disagrees

DieHard Implementation Details

- Multiply allocated memory by factor of M
- Allocation
  - Segregate objects by size (log2), bitmap allocator
  - Within size class, place objects randomly in address space
    - Randomly re-probe if conflicts (expansion limits probing)
  - Separate metadata from user data
  - Fill objects with random values – for detecting uninit reads
- Deallocation
  - Expansion factor => frees deferred
  - Extra checks for illegal free

Over-provisioned, Randomized Heap



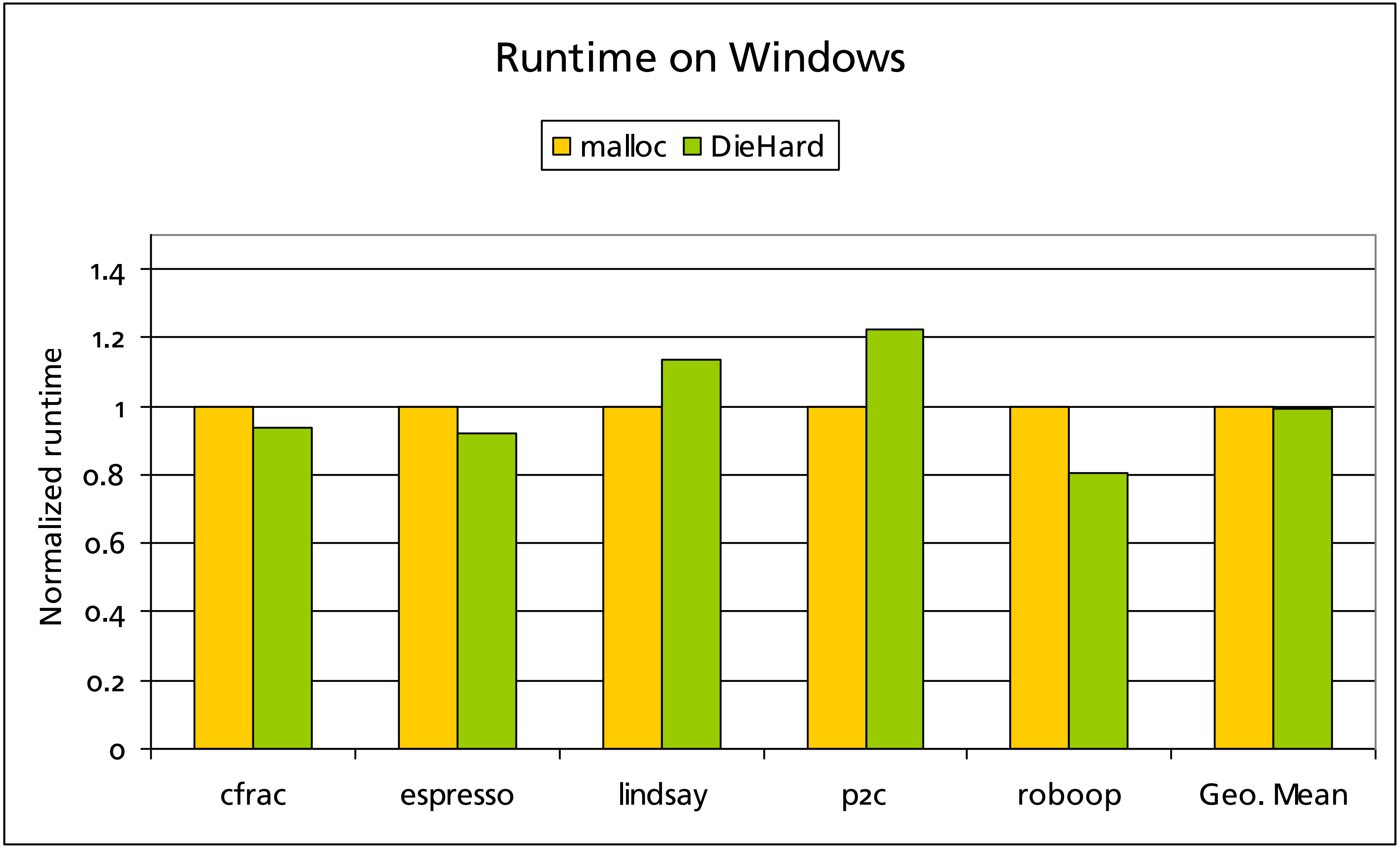
- Static strategy pre-allocates size classes
- Adaptive strategy grows each size class incrementally

Randomness enables Analytic Reasoning Example: Buffer Overflows

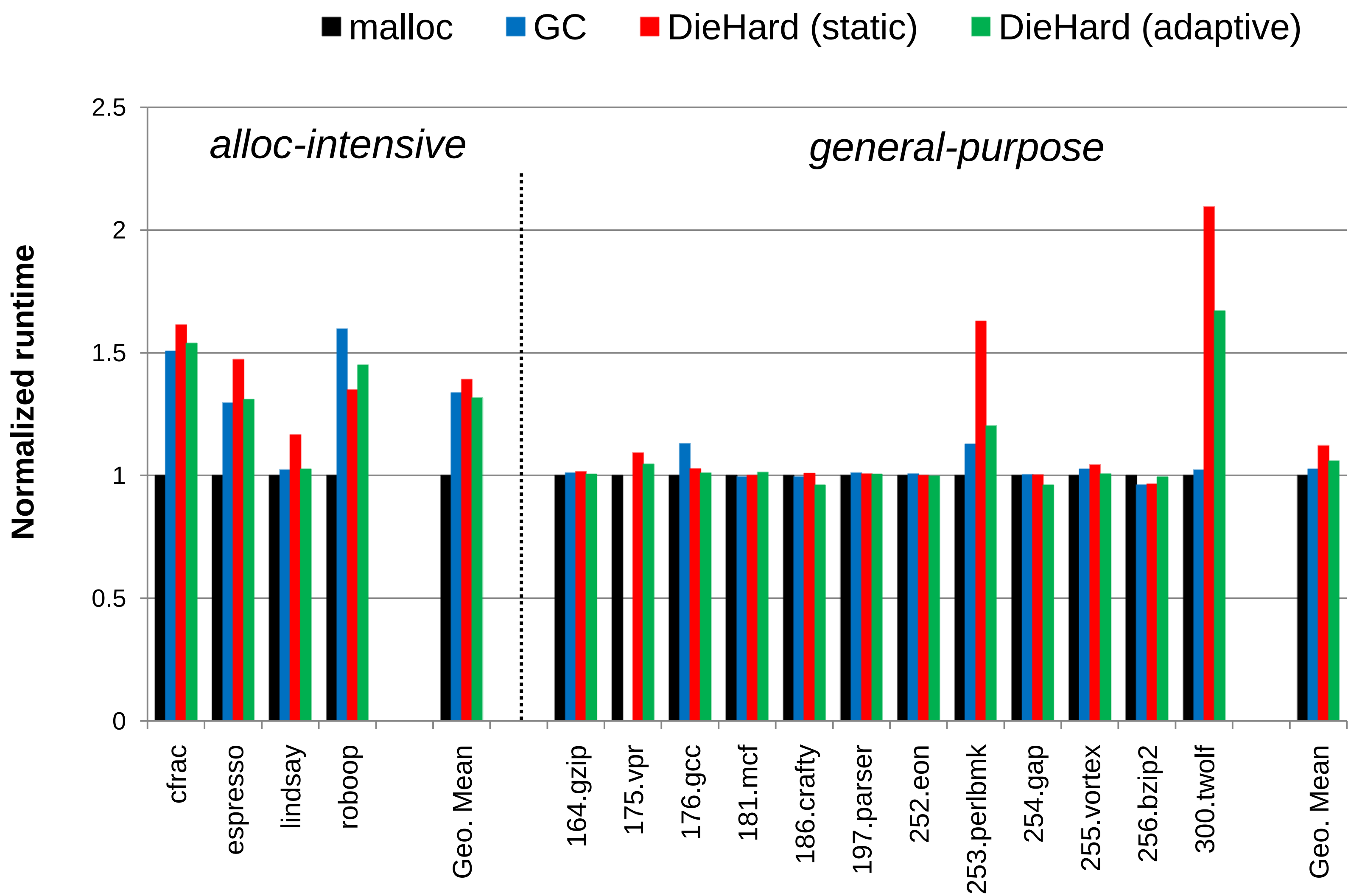
$$\Pr(\text{Mask Buffer Overflow}) = 1 - \left[1 - \left(\frac{F}{H}\right)^{Obj}\right]^k$$

- *k* = # of replicas, *Obj* = size of overflow
- With no replication, Obj = 1, heap no more than 1/8 full:
  Pr(Mask buffer overflow), = 87.5%
- 3 replicas: Pr(*ibid*) = 99.8%

DieHard CPU Performance (no replication)



DieHard CPU Performance (Linux)



Correctness Results

- Tolerates high rate of synthetically injected errors in SPEC programs
- Detected two previously unreported benign bugs (197.parser and espresso)
- Successfully hides buffer overflow error in Squid web cache server (v 2.3s5)
- But don’t take my word for it…

Experiments / Benchmarks

- vpr: Does place and route on FPGAs from netlist
  - Made routing-resource graph critical
- crafty: Plays a game of chess with the user
  - Made cache of previously-seen board positions critical
- gzip: Compress/Decompresses a file
  - Made Huffman decoding table critical
- parser: Checks syntactic correctness of English sentences based on a dictionary
  - Made the dictionary data structures critical
- rayshade: Renders a scene file
  - Made the list of objects to be rendered critical

Related Work

- Conservative GC (Boehm / Demers / Weiser)
  - Time-space tradeoff (typically >3X)
  - Provably avoids certain errors
- Safe-C compilers
  - Jones & Kelley, Necula, Lam, Rinard, Adve, …
  - Often built on BDW GC
  - Up to 10X performance hit
- N-version programming
  - Replicas truly statistically independent
- Address space randomization (as in Vista)
- Failure-oblivious computing [Rinard]
  - Hope that program will continue after memory error with no untoward effects