Software Fault Tolerance for ~~Type-unsafe Languages~~ C/C++

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In collaboration with

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Vinod Grover, Darko Kirovski, Microsoft Research

Motivation

- Consider a shipped C program with a memory error (e.g., buffer overflow)
  - By language definition, “undefined”
  - In practice, assertions turned off – mostly works
    - I.e., data remains consistent
- What if you know it has executed an illegal operation?
  - Raise an exception?
  - Continue unsoundly (failure oblivious computing)
  - **Continue with well-defined semantics (Ndure)**

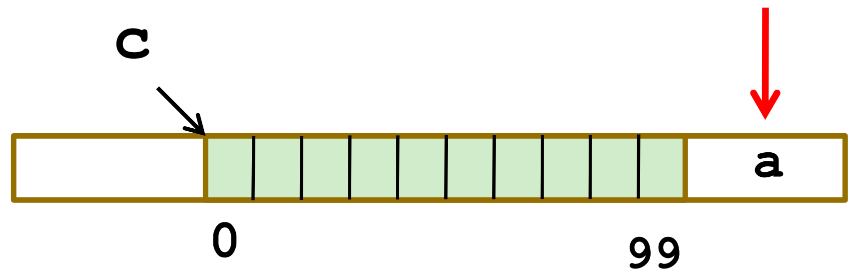
Ndure Project Vision

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

Focus on Heap Memory Errors

- Buffer overflow

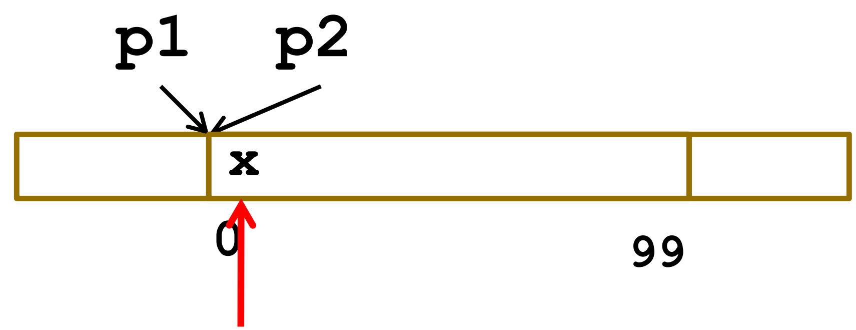
```
char *c = malloc(100);
c[101] = 'a';
```



- Dangling reference

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

free(p1);
p2[0] = 'x';
```



Ndure Project Themes

- Make existing programs more fault tolerant
  - Define semantics of programs with errors
  - Programs complete with correct result despite errors
- Go beyond all-or-nothing guarantees
  - Type checking, verification rarely a 100% solution
    - C#, Java both call to C/C++ libraries
  - Traditional engineering allows for errors by design
- Leverage flexibility in implementation semantics
  - Different runtime implementations are semantically equivalent

Approaches to Protecting Programs

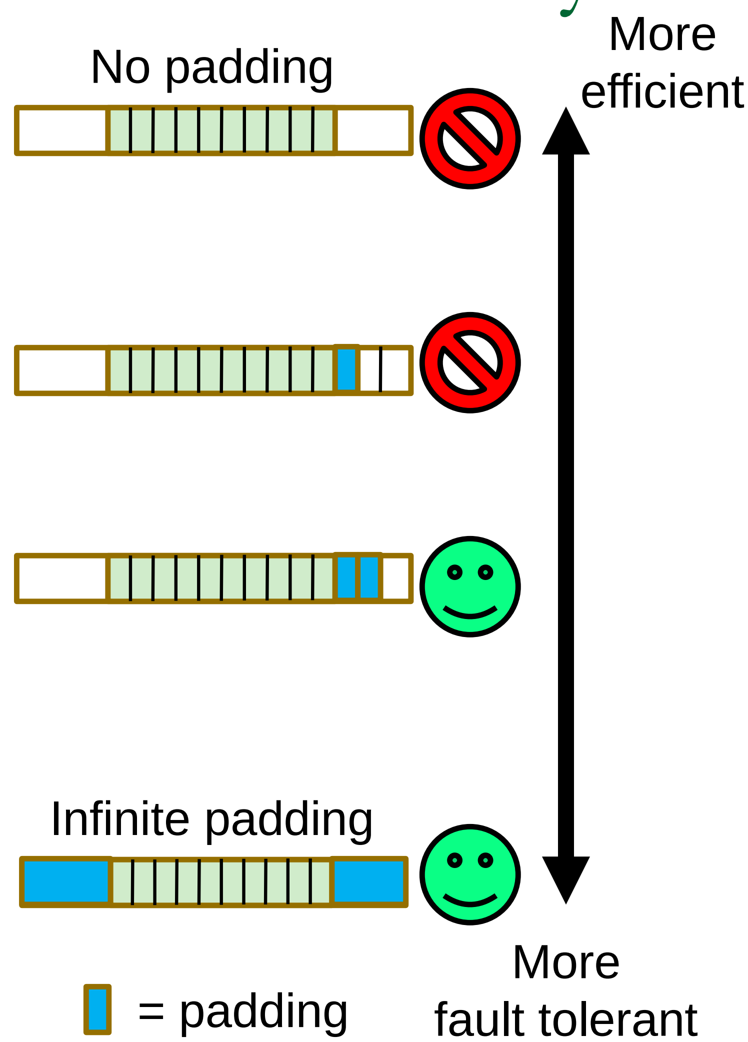
- Unsound, *may* work or abort
  - Windows, GNU libc, etc.
- Unsound, *might* continue
  - *Failure oblivious* (keep going) [Rinard]
    - Invalid read => manufacture value
    - Illegal write => ignore
- Sound, *definitely* aborts (fail-safe)
  - CCured [Necula], others
- Sound and continues
  - **DieHard, Samurai,** Rx, Boundless Memory Blocks

Exploiting Implementation Flexibility

- Runtimes are allowed to pad the allocation size request
- Consider a program with an off-by-2 buffer overflow:

```
char *c = (char*) malloc(100);
c[101] = 'a';
```

- Runtimes that pad by 2 or more will tolerate this error



Outline

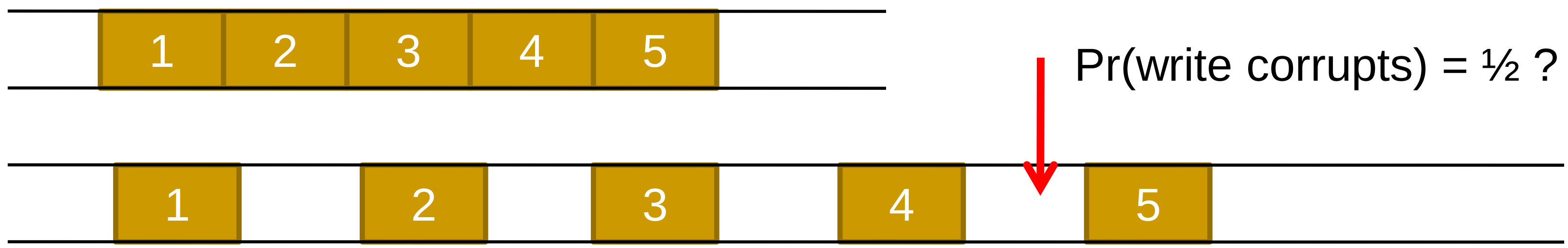
- Motivation
- DieHard
  - Collaboration with Emery Berger
  - Replacement for malloc/free heap allocation
  - No source changes, recompile, or patching, required
- Critical Memory / Samurai
  - Collaboration with Karthik Pattabiraman, Vinod Grover
  - New memory semantics
  - Source changes to explicitly identify and protect critical data
- Conclusion

DieHard: Probabilistic Memory Safety

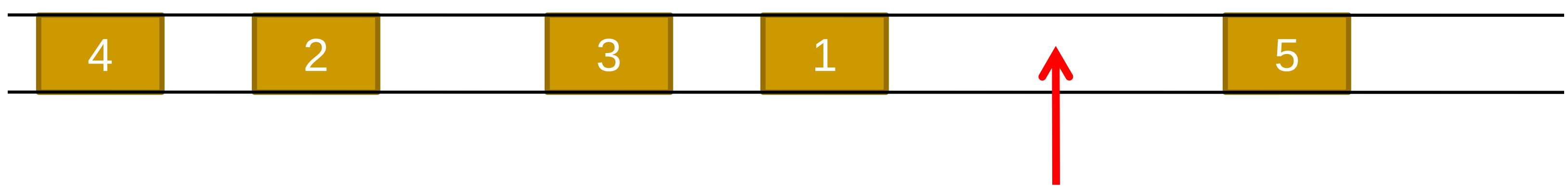
- Collaboration with Emery Berger
- Plug-compatible replacement for malloc/free in C lib
- We define “infinite heap semantics”
  - Programs execute as if each object allocated with unbounded memory
  - All frees ignored
- Approximating infinite heaps – 3 key ideas
  - Overprovisioning
  - Randomization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

Overprovisioning, Randomization

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



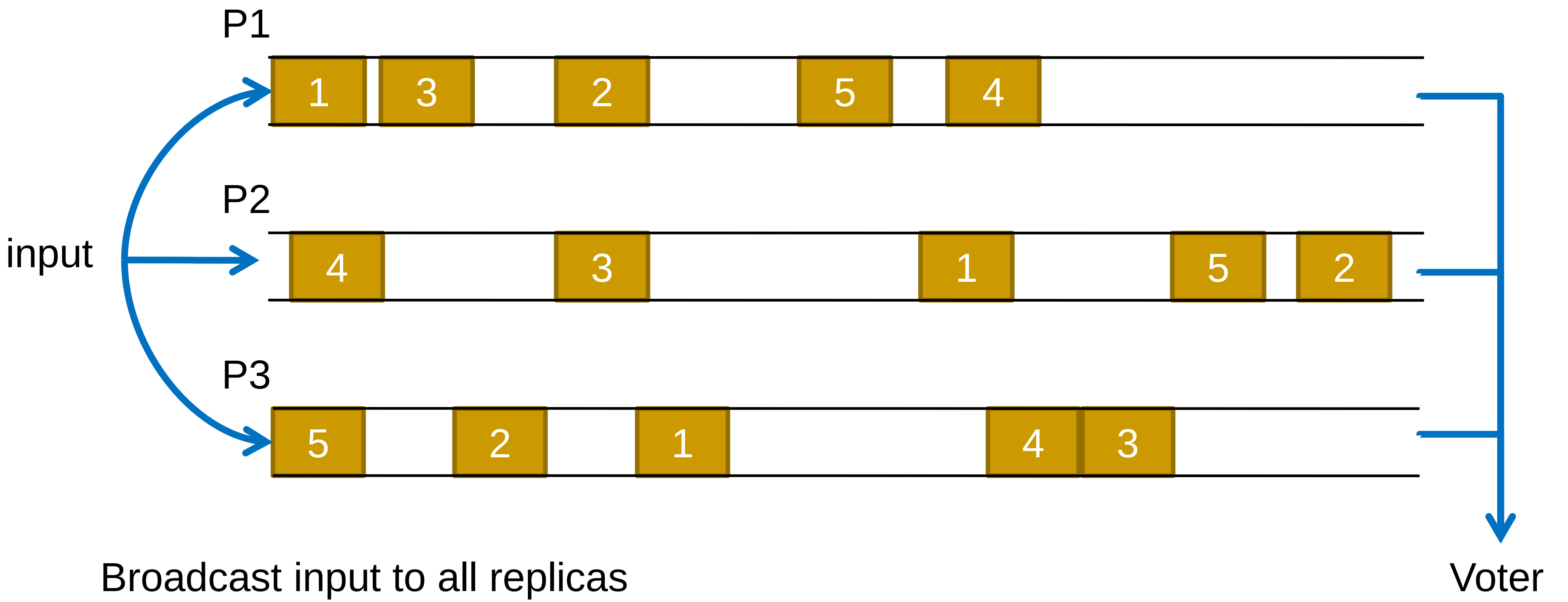
Randomize object placement



Pr(write corrupts) = ½ !

Replication

Replicate process with different randomization seeds



Broadcast input to all replicas

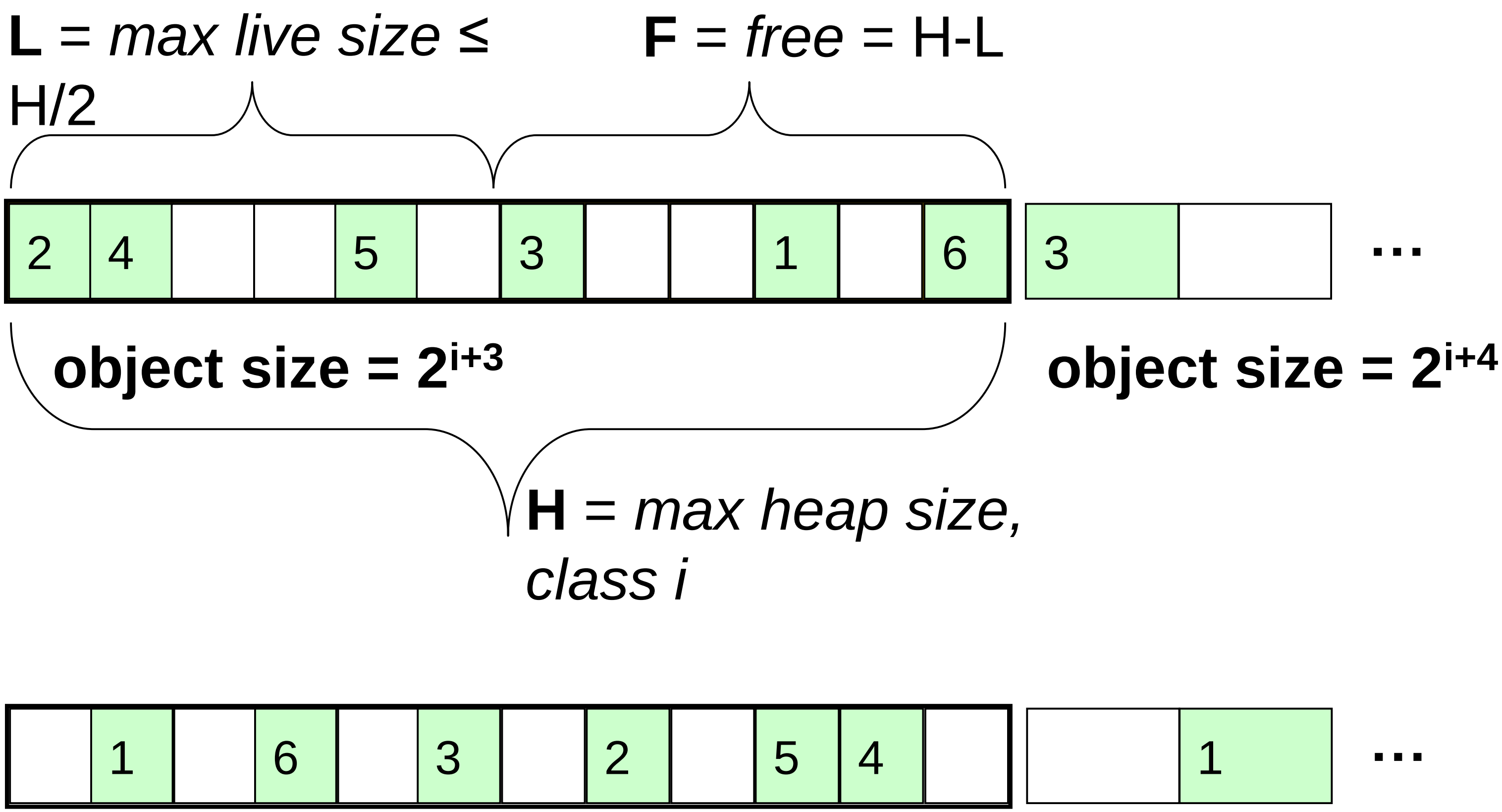
Compare outputs of replicas, kill when replica disagrees

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

- Segregated size classes

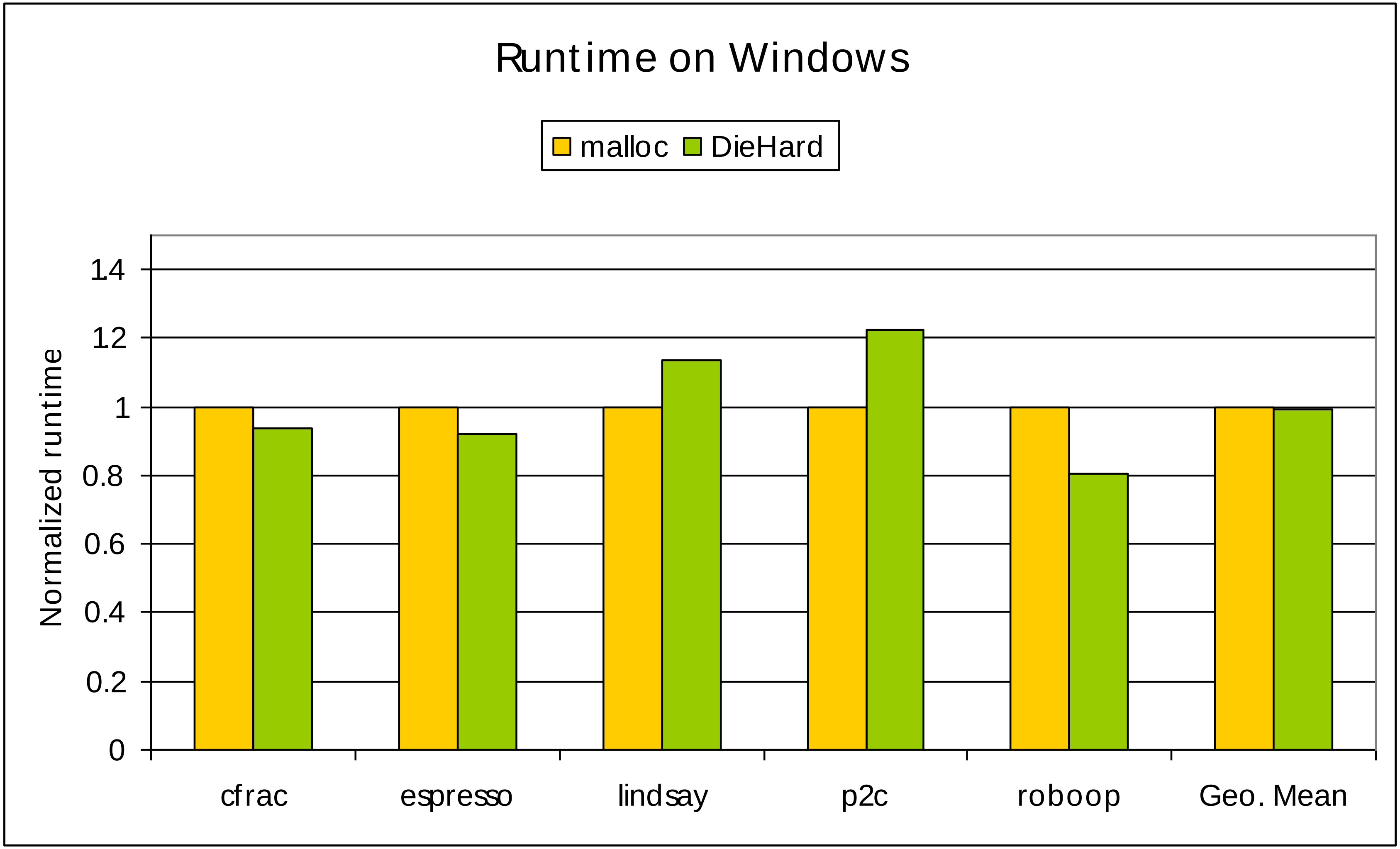


Randomness allows Analytic Reasoning Example: Buffer Overflows

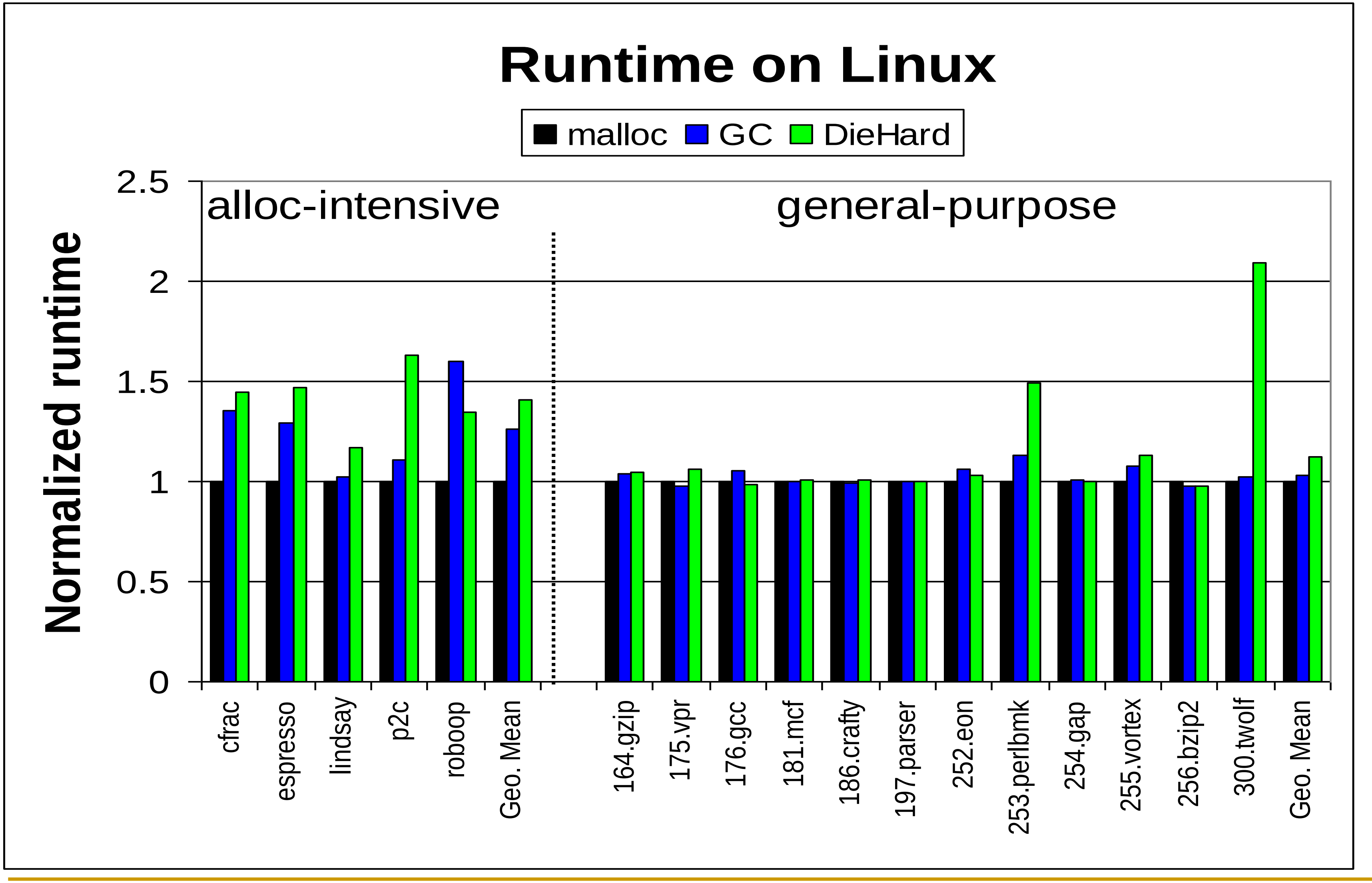
$$\text{Pr(Mask Buffer Overflow)} = 1 - \left[1 - \left(\frac{F}{H}\right)^{Obj}\right]^k$$

- *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)



Other Results

- Correctness
  - Tolerates high rate of synthetically injected errors in SPEC programs
  - Detected two previously unreported bugs (197.parser and espresso)
    - Uninitialized reads
  - Successfully hides buffer overflow error in Squid web cache server (v 2.3s5)
  - Tolerates crashing errors in FireFox browser
- Performance
  - With 16-way replication on Sun multiproc, execution takes 50% longer than single replica

Caveats

- Primary focus is on protecting heap
  - Techniques applicable to stack data, but requires recompilation and format changes
- DieHard trades space, extra processors for memory safety
  - Not applicable to applications with large footprint
  - Applicability to server apps likely to increase
- DieHard requires non-deterministic behavior to be made deterministic (on input, gettimeofday(), etc.)
- DieHard is a brute force approach
  - Improvements possible (efficiency, safety, coverage, etc.)

DieHard Summary

- DieHard exists, is available for download
  - Implemented by Emery Berger, UMass.
  - http://www.cs.umass.edu/~emery/diehard/
- You can try DieHard right now
  - Possible to replace Windows / Linux allocators
    - Requires no changes to original program
    - Non-replicated version
  - Applied to FireFox browser
    - Video on the web site
    - Hardens against heap-based exploits
- Biggest perf impact is memory usage

Outline

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  - No source changes, recompile, or patching, required
- Critical Memory / Samurai
  - Collaboration with Karthik Pattabiraman, Vinod Grover
  - New memory semantics
  - Source changes to explicitly identify and protect critical data
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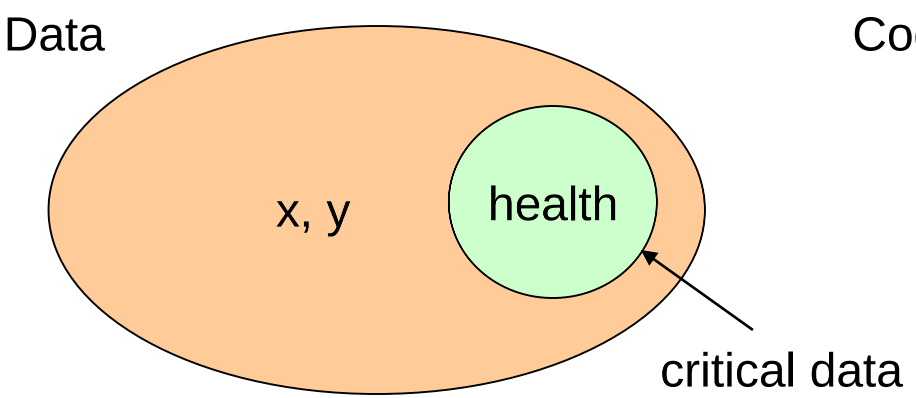
Critical Memory Motivation

- C/C++ programs vulnerable to memory errors
  - Software errors: buffer overflows, etc.
  - Hardware transient errors: bit flips, etc.
    - Increasingly a problem due to process shrinking, power
- Critical memory goals:
  - Harden programs from both SW and HW errors
  - Allow local reasoning about memory state
  - Allow selective, incremental hardening of apps
  - Provide compatibility with existing libraries, applications

Main Idea: Data-centric Robustness

- Critical memory
  - Some data is more important than other data
  - Selectively protect that data from corruption
- Examples
  - Account data, document contents are critical // UI data is not
  - Game score information, player stats, critical // rendering data structures are not



Code

code that references critical data

```
health += 100;
if (health < 0) {
    die();
} else {
    x += 10;
    y += 10;
}
```

Critical Memory Semantics

- Conceptually, critical memory is parallel and independent of normal memory
- Critical memory requires special allocate/deallocate and read/write operations
  - critical_store (cstore) – only way to consistently update critical memory
  - critical_load (cload) – only way to consistently read critical memory
- Critical load/store have priority over normal load/store
- Normal loads still see the value of critical memory

Critical Memory Benefits

- Associate critical property with types:
  - Easy to use, minimal source mods
- Allows local reasoning
  - External libraries, code cannot modify critical data
- Tolerates memory errors
  - Non-critical overflows cannot corrupt critical values
- Alllows static analysis of program subset
  - Critical subset of program can be statically checked independently
- Additional checking on critical data possible

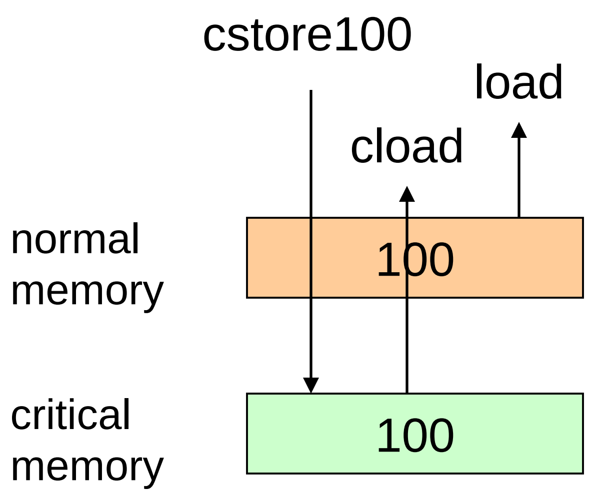
```
int x, y, buffer[10];
critical int health = 100;

third_party_lib(&x, &y);
buffer[10] = 10000;

// health still == 100

if (health < 0) {
    die();
} else {
    x += 10;
    y += 10;
}
```

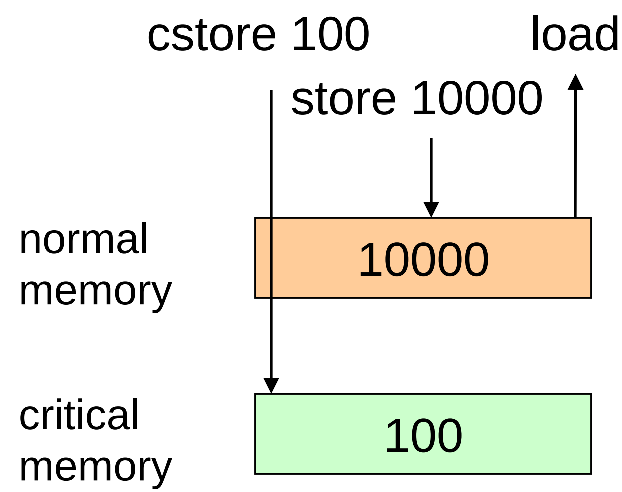
Examples

cstore health, 100
…
cload health returns 100
load health returns 100

cstore health, 100
store health, 10000
(applications should not do this)
…
load health returns 10000
(depends on semantics)

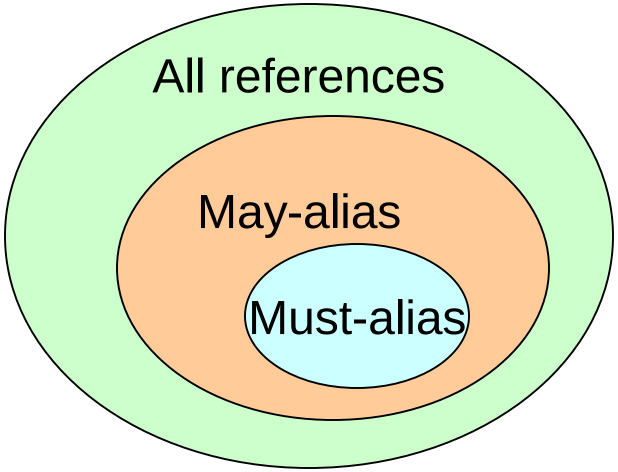
cload health returns 100
(possibly triggers exception)

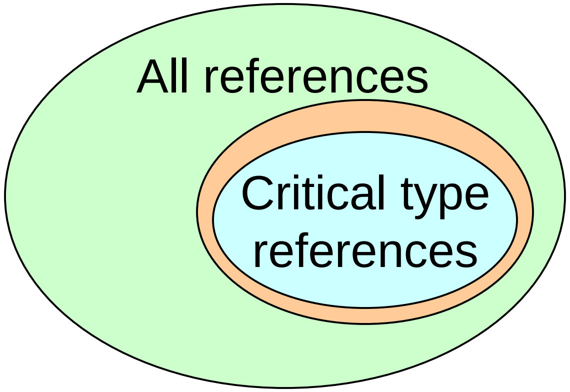




Which Loads/Stores are Critical?

- All references that can read/write critical data
  - Needs to be “may-alias” for correctness
  - Must be close to the set of “must-alias” for coverage
- One approach – critical types
  - Marks an entire type as critical
  - Type-safety of subset of program that manipulates critical data
  - Rest of program can be type-unsafe





Third-party Libraries/Untrusted Code

- Library code does not need to be critical memory aware
  - If library does not mod critical data, no changes required
- If library modifies critical data
  - Allow normal stores to critical memory in library
  - Follow by a “promote”
    - Makes normal memory value critical

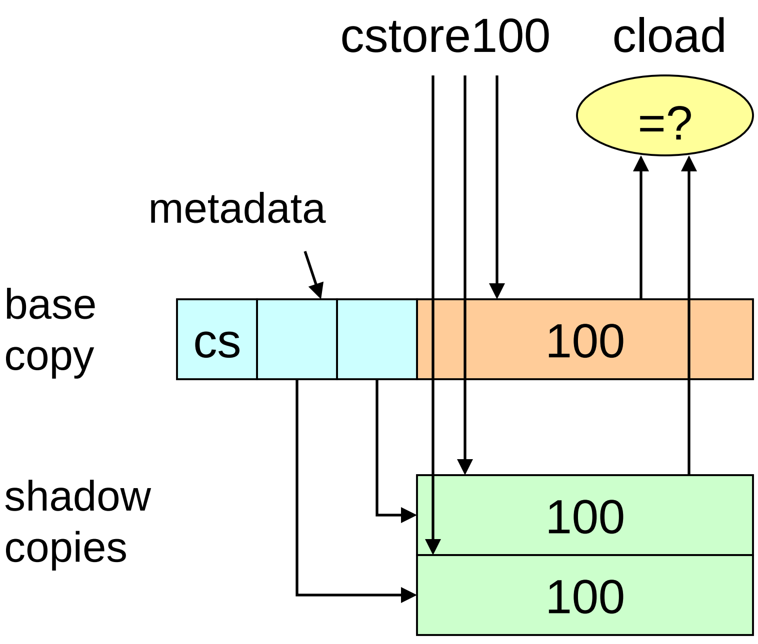
```
critical int health = 100;
…
library_foo(&health);
promote health;
…
________________________

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

Samurai: SCM Implementation

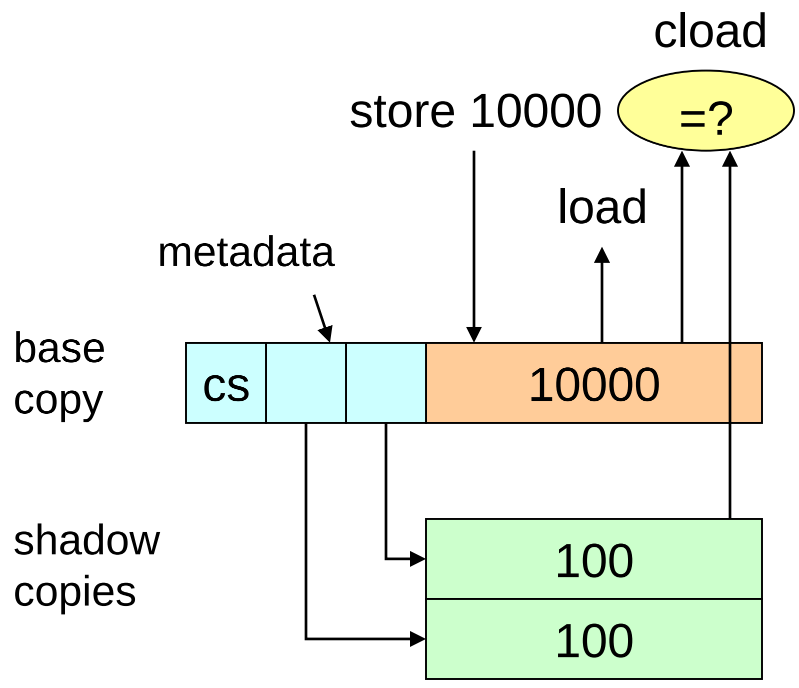
- Software critical memory for heap objects
  - Critical objects allocated with crit_malloc, crit_free
- Approach
  - Replication – base copy + 2 shadow copies
  - Redundant metadata
    - Stored with base copy, copy in hash table
    - Checksum, size data for overflow detection
  - Robust allocator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

Implementation

cstore health, 100
…
cload health returns 100
load health returns 100



cstore health, 100
store health, 10000…
load health returns 10000
cload health returns 100



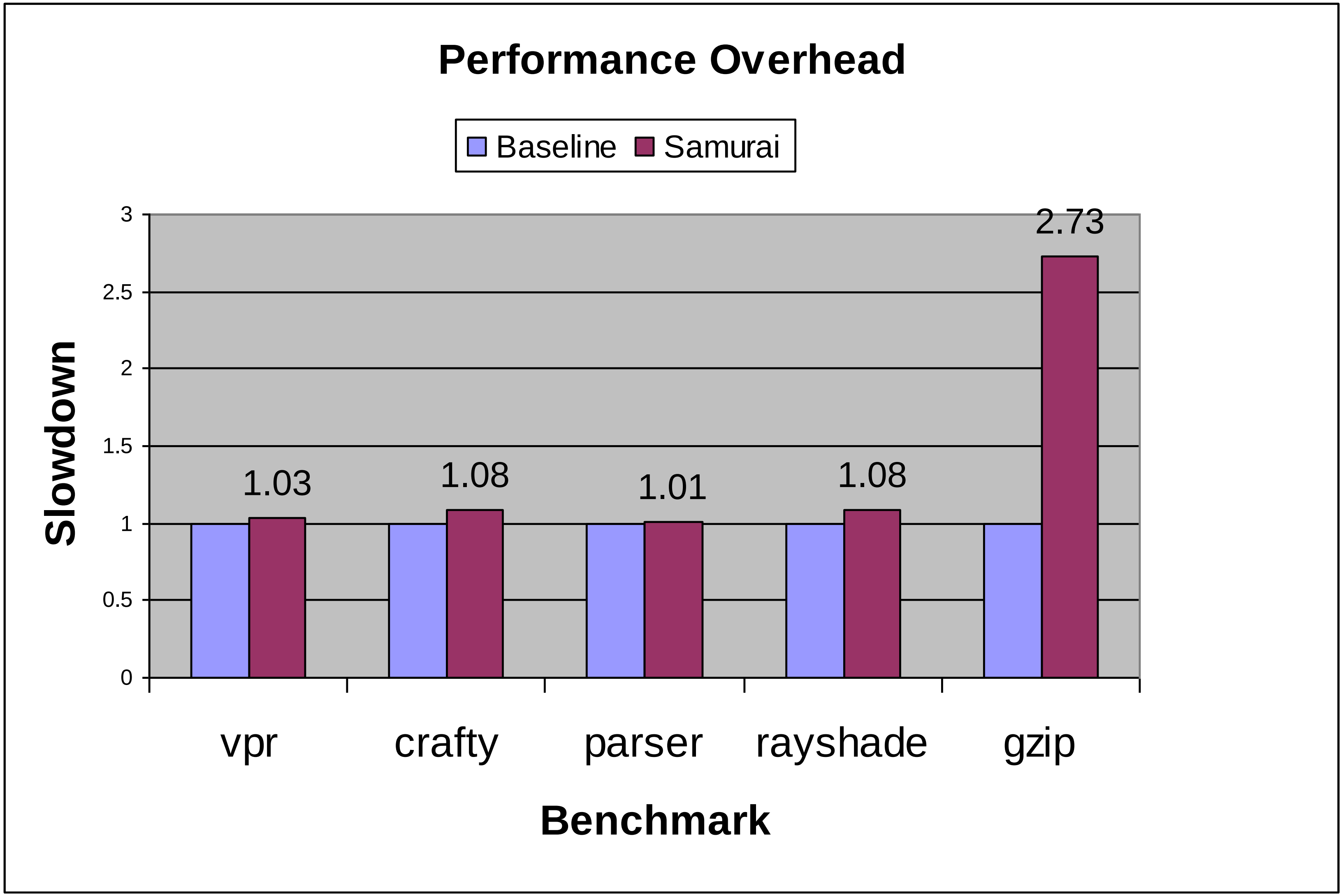
Samurai Experimental Results

- Prototype implementation of critical memory
  - Fault-tolerant runtime system for C/C++
  - Applied to heap objects
  - Automated Phoenix compiler pass
- Identified critical data for five SPECint applications
  - Low overheads for most applications (less than 10%)
- Conducted fault-injection experiments
  - Fault tolerance significantly improved over based code
  - Low probability of fault-propagation from non-critical data to critical data for most applications
  - No new assertions or consistency checks added

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

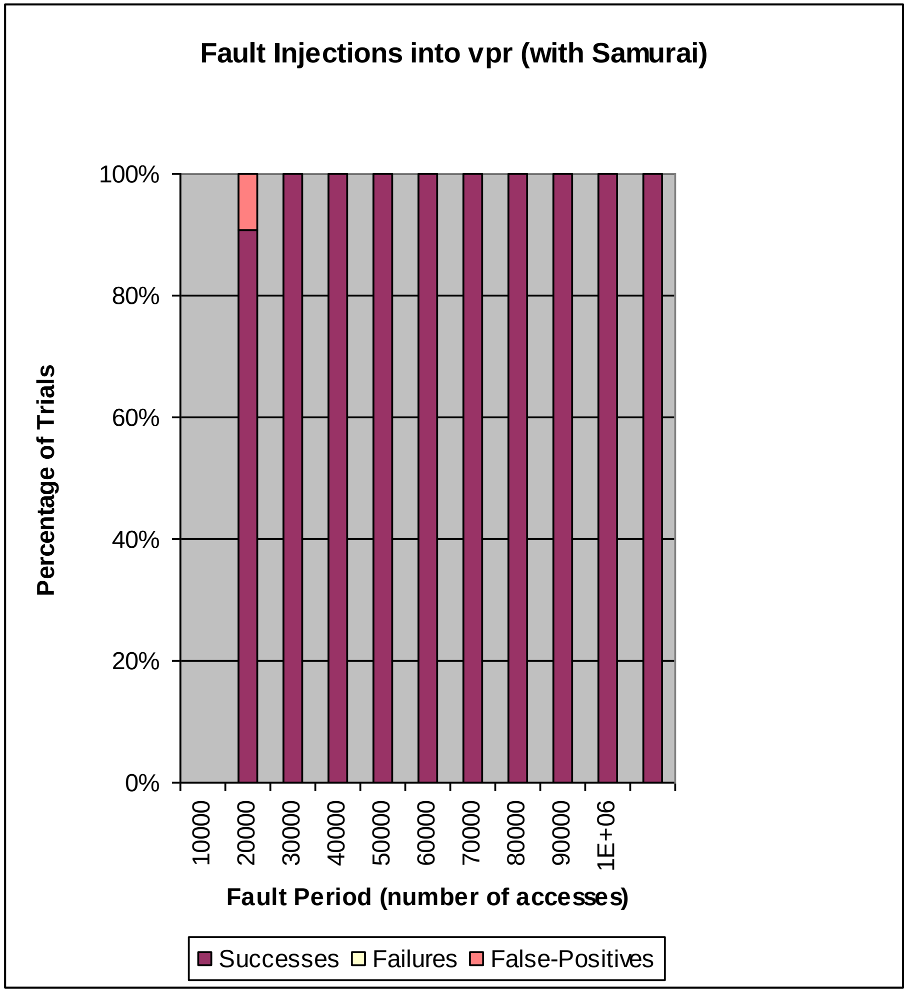
Results (Performance)

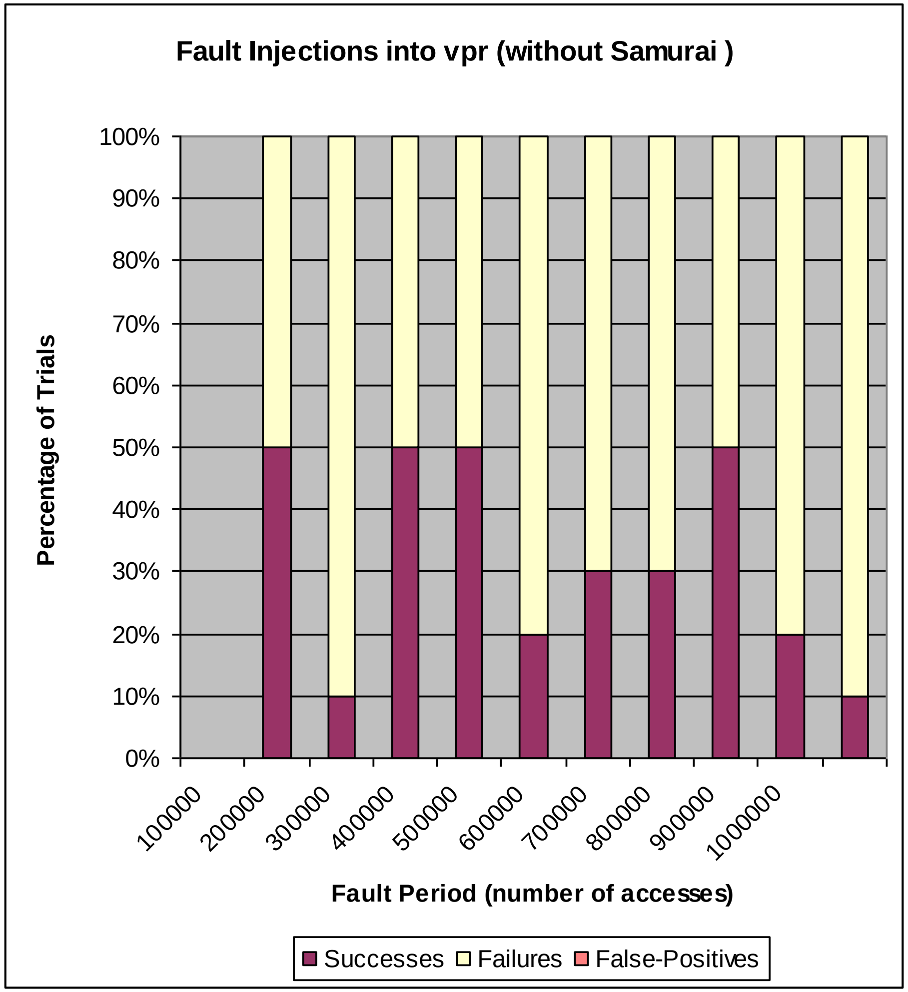


Fault Injection Methodology

- Injections into critical data
  - Corrupted objects on DieHard heap, one at a time
  - Injected more faults into more populated heap regions (Weighted fault-injection policy)
  - Outcome: success, failure, false-positive
- Injections into non-critical data
  - Measure propagation to critical data
  - Corrupted results of random store instructions
  - Compared memory traces of verified stores
  - Outcomes: control error, data error, pointer error

Fault Injection into Critical Data (vpr)





Fault Injection into Non-Critical Data

App	Number of Trials	Control Errors	Data Errors	Pointer Errors	Assertion Violations	Total Errors
vpr	550 (199)	0	203 (0)	1 (0)	2 (2)	203 (0)
crafty	55 (18)	12 (7)	9 (3)	4 (3)	0	25 (13)
parser	500 (380)	0	3 (1)	0	0	3 (1)
rayshade	500 (68)	0	5 (1)	0	1 (1)	5 (1)
gzip	500 (239)	0	1 (1)	2 (2)	157 (157)	3 (3)

Samurai Summary

- Critical memory
  - Local reasoning about data consistency
  - Selective protection of application data
  - Compatible with existing libraries
- Samurai runtime
  - CM for heap-allocated data
  - Fault tolerance for C/C++ programs
- Future work
  - Uses for concurrency (integration with STM)
  - Applications to security, performance optimizations, static analysis, etc.
  - Better language integration

Conclusion

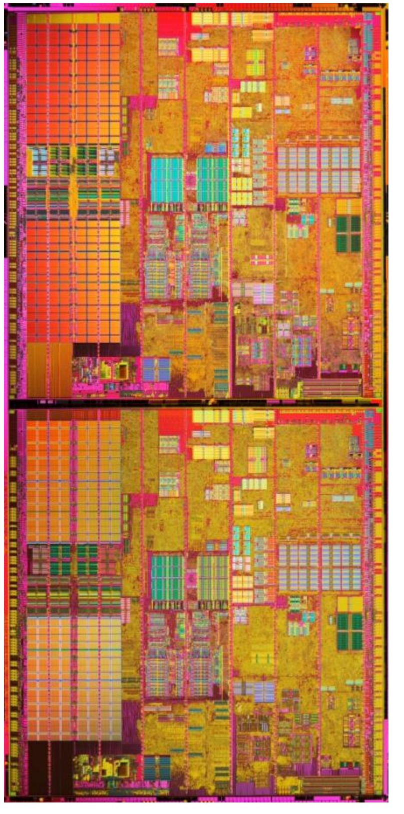
- Programs written in C can execute safely, despite memory errors with little or no source changes
- Vision
  - Improve existing code with little or no change
  - Reduce number of patches required
  - More memory => more reliable
- Ndure project investigates possible approaches
  - DieHard: overprovisioning + randomization + replicas = **probabilistic memory safety**
  - Critical Memory / Samurai: protect important data
- Hardware trends
  - More processors, more memory, more transient errors

Hardware Trends

- 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

Power to Spare

- DRAM prices dropping
  - 1GB < $160
- SMT & **multi-core CPUs**
  - **Dual-core** – Intel Pentium D & Xeons, Sun UltraSparc IV, IBM PowerPC 970MP (G5)
  - **Quad-core** Sparcs (2006), Intels and AMD Opterons (2007); **more** coming
- *Challenge:*
  How should we use all this hardware?



Additional Information

- Publications
  - Karthik Pattabiraman, Vinod Grover, and Benjamin G. Zorn, "**Samurai - Protecting Critical Heap Data in Unsafe Languages**", Microsoft Research, Tech Report MSR-TR-2006-127, September 2006.
  - Karthik Pattabiraman, Vinod Grover, and Benjamin G. Zorn, "**Software Critical Memory - All Memory is Not Created Equal**", Microsoft Research, Tech Report MSR-TR-2006-128, September 2006.
  - Emery D. Berger and Benjamin G. Zorn, "**DieHard: Probabilistic Memory Safety for Unsafe Languages**", to appear, *ACM SIGPLAN 2006 Conference on Programming Language Design and Implementation (PLDI'06)*, Ottawa, Canada, June 2006.
- Acknowledgements
  - Emery Berger, Mike Hicks, Pramod Joisha, and Shaz Quadeer

Backup Slides

DieHard 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
- Failure-oblivious computing [Rinard]
  - Hope that program will continue after memory error with no untoward effects

Samurai Related Work

- Address-Space Protection
  - Virtual memory, Mondrian Memory Protection
  - Kernel extensions [SPIN, Vino], Software Fault Isolation
- STM [Herlihy, Harris, Adl-Tabatabi]
  - Strong atomicity for Java programs [Hindman, Grossman]
- Memory Safety
  - C-Cured, Cyclone, Jones-Kelley, CRED, Dhurjati-Adve
  - Singularity approach, Pittsfield
- Error-Tolerance
  - Rx, Failure-oblivious computing, Diehard
  - N-version programming, Recovery Blocks
  - Rio File Cache, Application-specific recovery

How to Decide What is Critical?

- Data that is important for correct execution of application or data that is required to restart the application after a crash
  - Banking application: Account data critical; GUI, networking data not critical
  - Web-server: Table of connections critical; connection state data may not be critical
  - Word-processor/Spreadsheet: Document contents critical; internal data structures not critical
  - E-Commerce application: Credit card data/shopping cart contents more critical than user-preferences
  - Game: User state such as score, level critical; state of game world not critical

Critical Memory Advantages

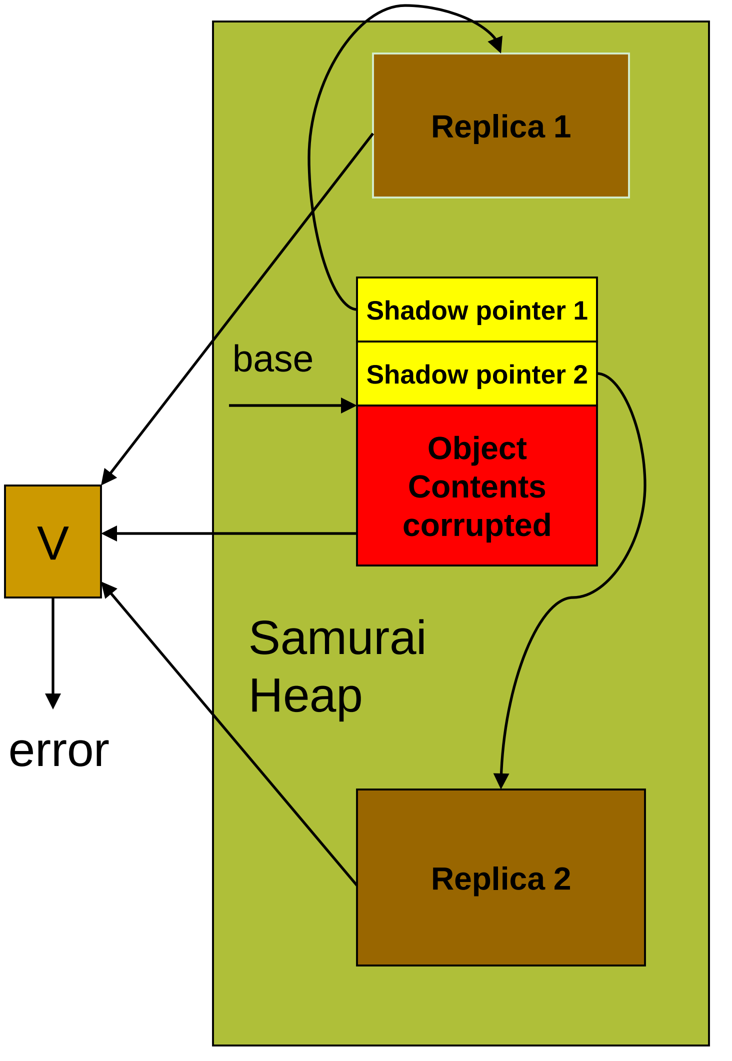
- Requires only accesses to critical-data to be type-safe/annotated
  - No runtime checks on non-critical accesses
- Can be deployed in an incremental fashion
  - Versus all-or-nothing approach of systems such as CCured
- Protection even in presence of unsafe/third-party library code, without requiring changes to library function or aborting upon an error
  - SFI requires modifications to library source/binary
- Amenable to possible hardware implementation

Critical Memory Limitations

- Errors in non-critical data can propagate to critical data
  - Control-flow errors (does not replace control-flow checking)
  - Data-consistency errors (assumes existence of executable assertions and consistency checks)
  - Occurred rarely in random fault-injection experiments
- Malicious attackers
  - No attempt made to hide location of shadow copies
    - Protection from adversary requires more mechanisms
  - Can exploit memory errors in non-critical data

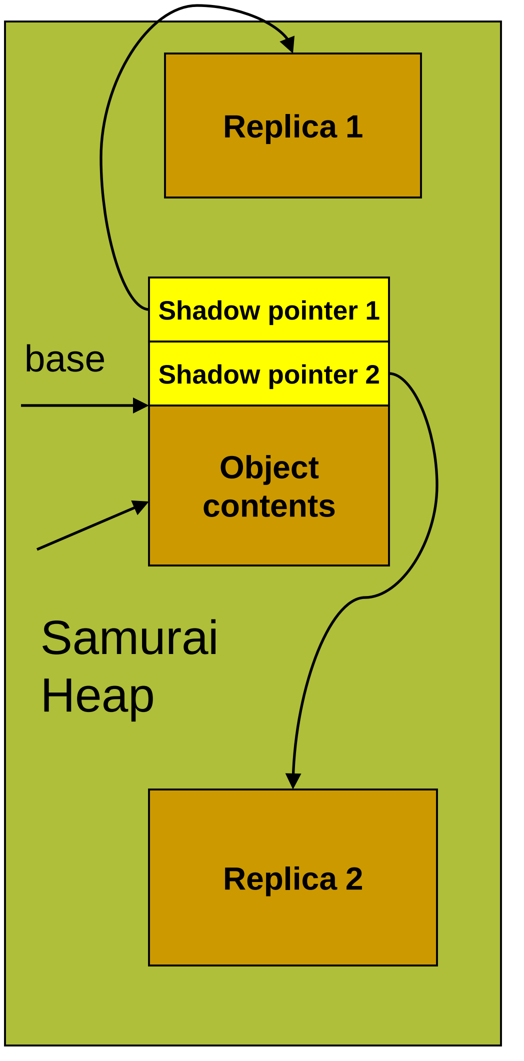
Samurai Operations

- **Critical store**
  - Compute base address of object
  - Check if object is valid
  - Follow shadow pointers in metadata
  - Update replicas with stored contents
- **Critical load**
  - Compute base address of object
  - Check if object is valid
  - Follow shadow pointers in metadata
  - Check object with replicas
  - Fix any errors found by voting on a per-byte basis



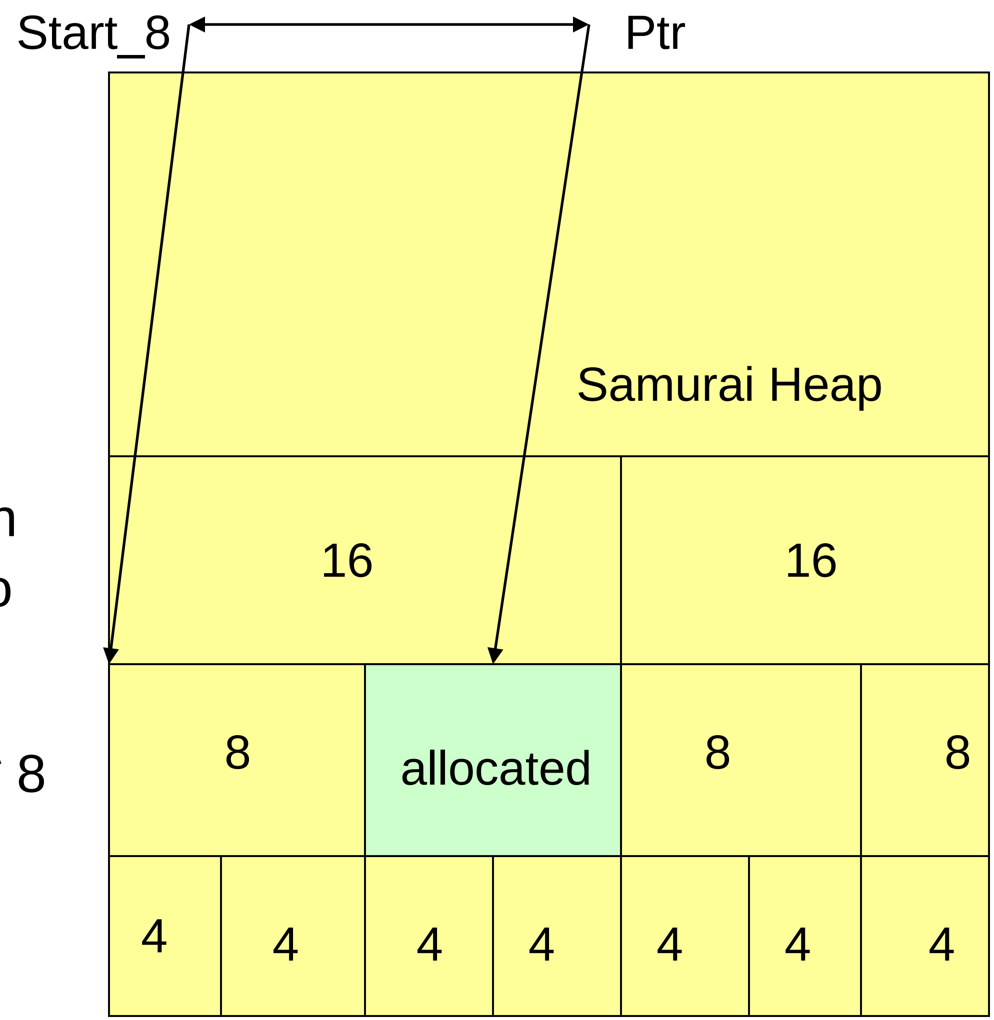
Samurai Operations (continued)

- Critical malloc
  - Allocates 3 objects with diehard
  - Initializes metadata of parent object with shadow pointers
  - Set valid bits of object
  - Return base pointer to user
- Critical free
  - Free all 3 copies on diehard heap
  - Reset metadata of object
  - Reset valid bits of object



Heap Organization (BiBOP)

- Used in DieHard, PHKmalloc
- Allows maping internal pointer to base object
  - Heap partitioned into pages of fixed size
  - Size classes of size 2^n
  - Address computation to recover base pointer



Base = ((Ptr – Start_8) / 8) * 8

  - Useful for checking overflow as well

Considerations and Optimizations

- Considerations
  - Metadata itself protected from memory errors using checksums (backup copy in protected hash table)
  - Consistency checks in implementation
    - Bounds checking critical accesses
- Optimizations
  - Cache frequent metadata lookups for speed
  - Compare with only one shadow on critical loads
    - Periodically switch pointers to prevent error accumulation
  - Adaptive voting strategy for repairing errors
    - Exponential back-off based on object size
    - Mainly used for errors in large objects