SafeDrive: Safe and Recoverable Extensions Using Language-Based Techniques

Feng Zhou, Jeremy Condit, Zachary Anderson,
Ilya Bagrak, Rob Ennals, Matthew Harren,
George Necula, Eric Brewer

CS Division, UC Berkeley
and Intel Research Berkeley

`http://ivy.cs.berkeley.edu/safedrive/`

The Problem

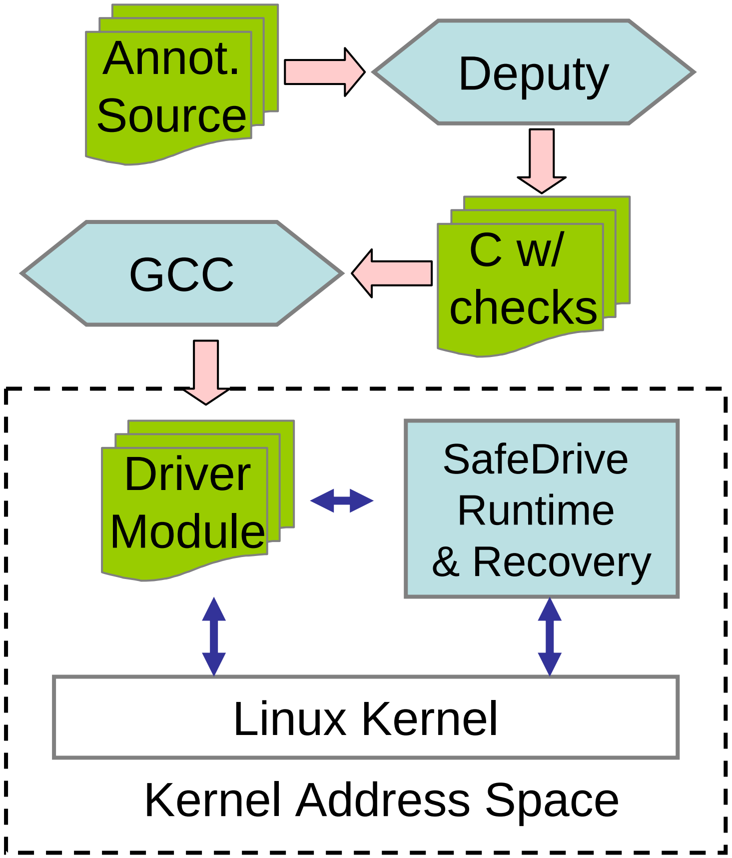
- OSes and applications often run loadable extensions
  - e.g. Linux kernel, Apache, Firefox
  - Run in the same protection domain
- Extensions are often buggier than hosts
  - Device drivers cause a large percentage of Windows crashes
  - Xbox hacked due to memory bugs in games
- SafeDrive detects and recovers from *type-safety and memory-safety* errors in Linux device drivers

Approaches

- Separate hardware protection domains: Nooks [Swift et al], L4 [LeVasseur et al], Xen [Fraser et al]
  - Relatively high overhead due to cross-domain calls, system specific
- Binary instrumentation: SFI [Wahbe et al, Small/Seltzer]
  - High overhead, coarse-grained
- Static analysis + software guards: XFI [Erlingsson et al]
  - Control flow safety
- What can be done at the C language level?
  - Add fined-grained type-safety, **to extensions only**
  - A way to recover from failures

A Language-Based Approach to Extension Safety

- Light annotations in extension code and host API
  - Buffer bounds, non-null pointers, nullterm strings, tagged unions
- Deputy src-to-src compiler emits safety checks when necessary
- Key: compatible extension-host **binary interface**
- Runtime tracks resource usage and restores system invariants at fail time



Deputy: Motivation

```
struct {
  unsigned int len;
  int * data;
} x;
for (i=0;i<x.len;i++) {
  … x.data[i] …
}
```

- Common C code
- How to check memory safety?
- C pointers do not express extent of buffers (unlike Java)

Previous Approach: Fat Pointers

```
struct {
  unsigned int len;
  int * data;
  int * data_b;
  int * data_e;
} x;
for (i = 0; i < x.len; i++) {
  if (x.data+i<x.data_b) abort();
  if (x.data+i>=x.data_e) abort();
  … x.data[i] …
}
```

- Used in CCured and Cyclone
- Compiler inserts extra bounds variables
- Changes memory layout
- Cannot be applied modularly

Deputy Bounds Annotations

```
struct {
  unsigned int len;
  int * count(len) data;
} x;
for(i = 0; i < x.len; i++) {
  if (i<0||i>=x.len) abort();
  … x.data[i] …
}
```

- Annotations use existing bounds info in programs, or constants
- Compiler emits runtime checks
- No memory layout change → Can be applied to one extension a time
- Many checks can be optimized away

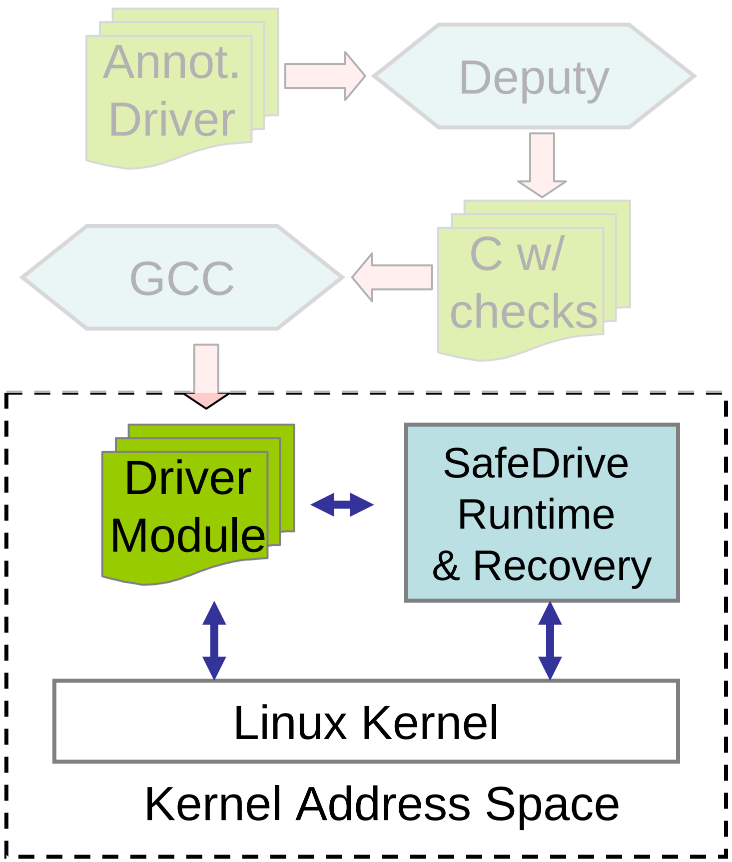
Deputy Features

- Bounds: **`safe,count(n)`**, **`bound(lo,hi)`**
  - Default: **`safe`**
- Other annotations
  - Null terminated string/buffer
  - Tagged unions
  - Open arrays
  - Checks for **`printf()`** arguments
- Automatic bounds variables for local variables
  → reduced annotation burden

Deputy Guarantees

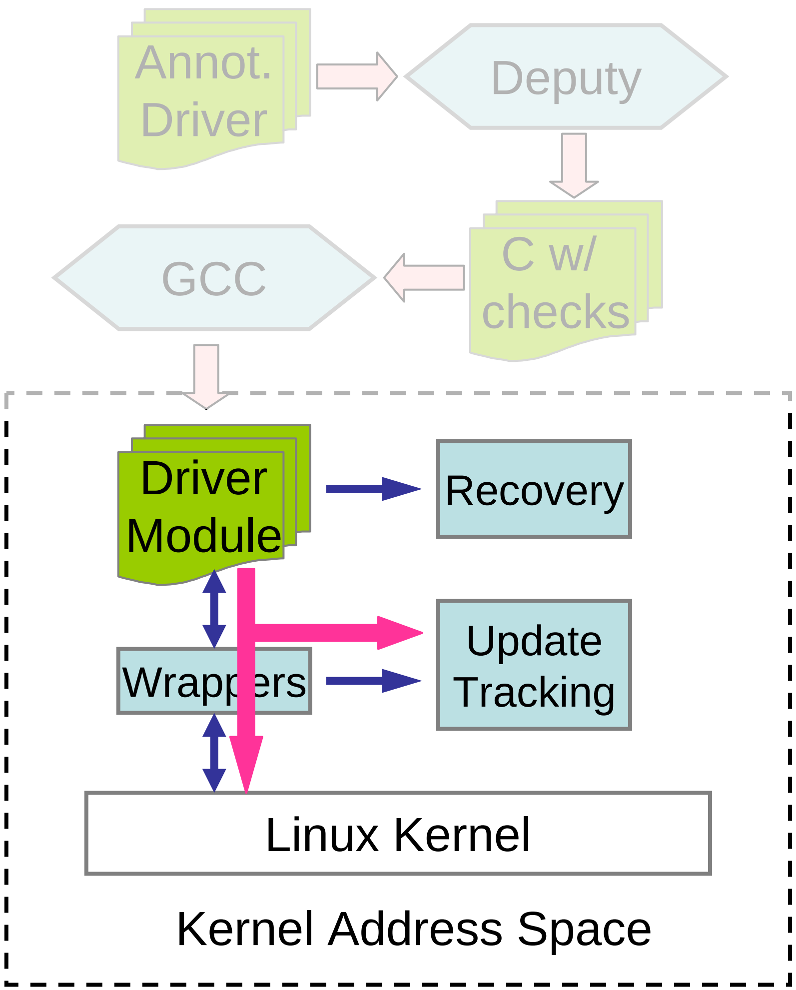
- Deputy guarantees **type-safety** if,
  - Programmer correctly annotates globals and function parameters used by the extension
  - Deallocation does not create dangling pointers
  - Trusted casts are correct
  - External modules / trusted code establish and preserve Deputy annotations

Failure Handling



- Everything runs inside the same protection domain
- After Deputy check failure: could just halt
- More useful: clean-up extension and let host continue
- Assumption: restarts should fix most transient failures

Update Tracking and Restarts

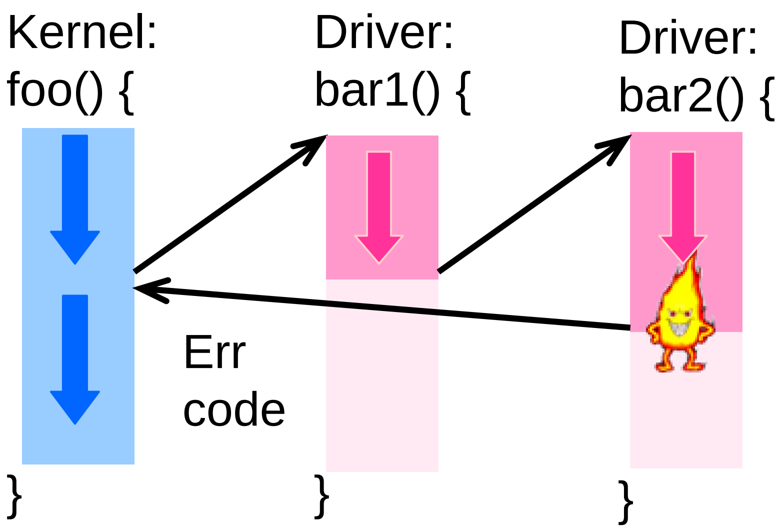


- Free resources and undo state changes done by driver
- Kernel API functions "wrapped" to do **update tracking**
  - Compensations: **`spin_lock(l)`** vs. **`spin_unlock(l)`**
- After failure, undo updates in LIFO order
- Then restart driver

Return Gracefully from Failure

Invariants:

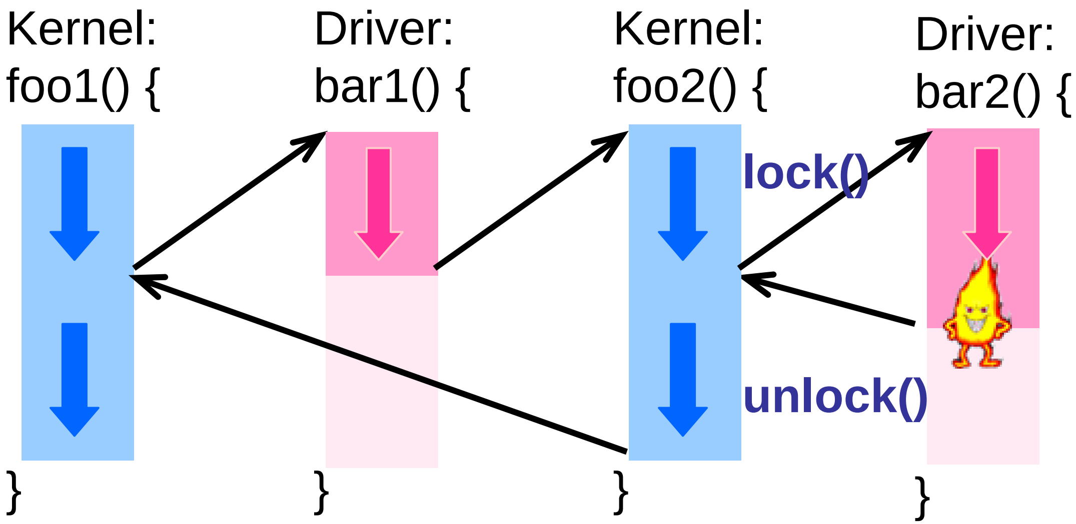
- No driver code is executed after failure



Return Gracefully from Failure

Invariants:

- No driver code is executed after failure
- No kernel function is forced to return early



Discussion

- Compared to Nooks
  - Significantly less interception → Much simpler overall
  - Deputy does fine-grained per-allocation checks → No separate heap/stack
  - No help from virtual memory hardware
  - Works for user-level applications and safe languages
- Compared to C++/Java exceptions
  - Compensation does not contain any code from driver
  - Only restores host state, not extension state

Implementation

- Deputy compiler: 20K lines of OCaml
- Kernel patch to 2.6.15.5: 1K lines
- Kernel headers patch: 1.9K lines
- Patch for 6 drivers in 4 categories
  - Network: **e1000, tg3**
  - USB: **usb-storage**
  - Sound: **intel8x0**, emu10k1
  - Video: nvidia

Evaluation: Recovery Rate

- Inject random errors with compile-time injection: 5 errors from one of 7 categories each time
  - Faults chosen following empirical studies
    [Sullivan & Chillarege 91], [Christmansson & Chillarege 96]
  - Scan overrun, loop fault, corrupt parameter, off-by-one, flipped condition, missing call, missing assignment
- Load buggy **`e1000`** driver w/ and w/o SafeDrive
- Exercise by downloading a 89MB file, verifying it and unloading the driver
- Then rerun with original driver

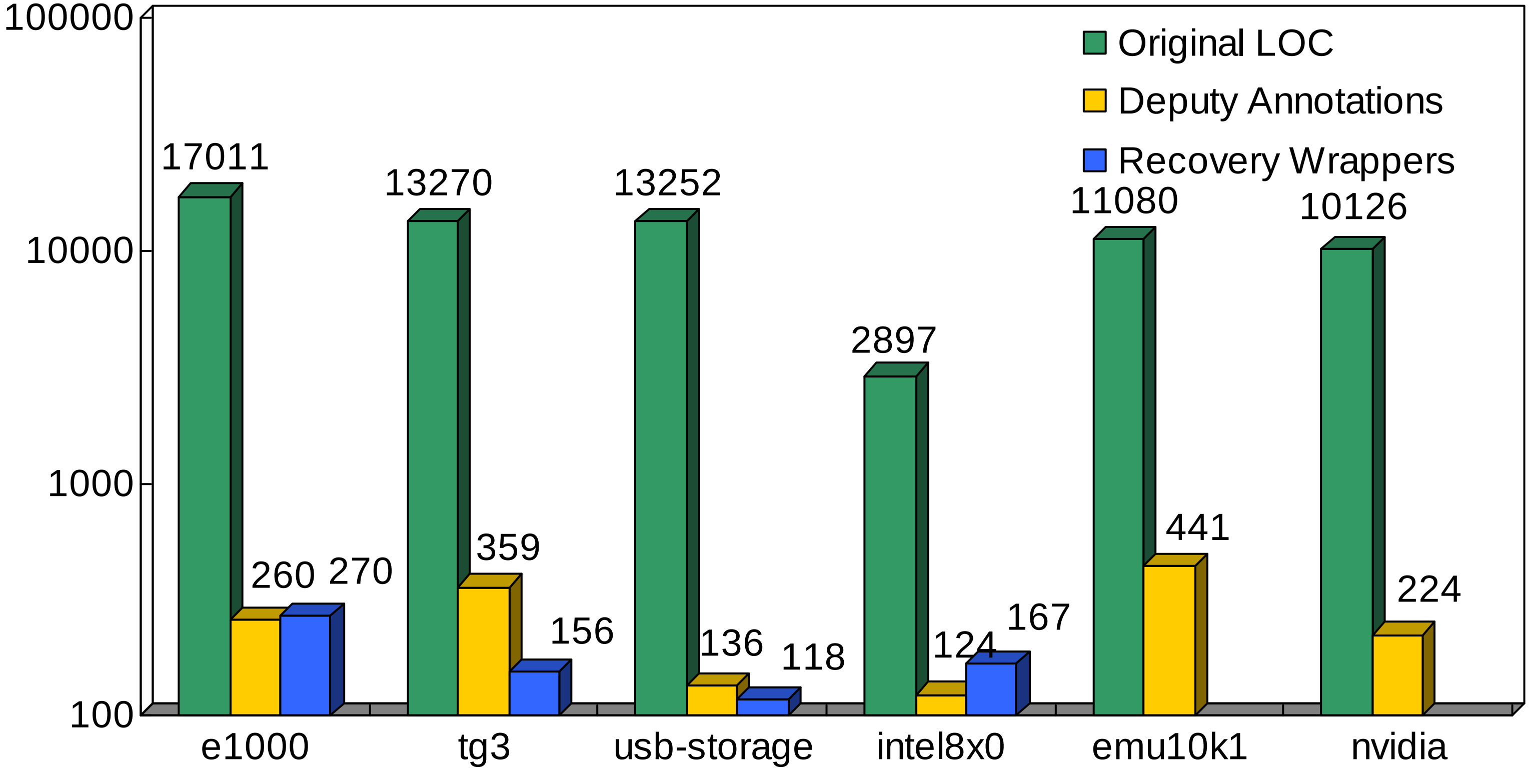
Recovery Rate Results

- 140 runs, 20 per fault category

SafeDrive off		44 crashes	21 failures	75 passes
SafeDrive on	Static error	**10**	0	3
	Runtime error	**34**	2	5
	No problem detected	0	19	67
Recovery successes		44 (100%)	2 (100%)	8 (100%)

- SafeDrive is effective at detecting and recovering from crashing problems, and can detect some statically.

Annotation Burden



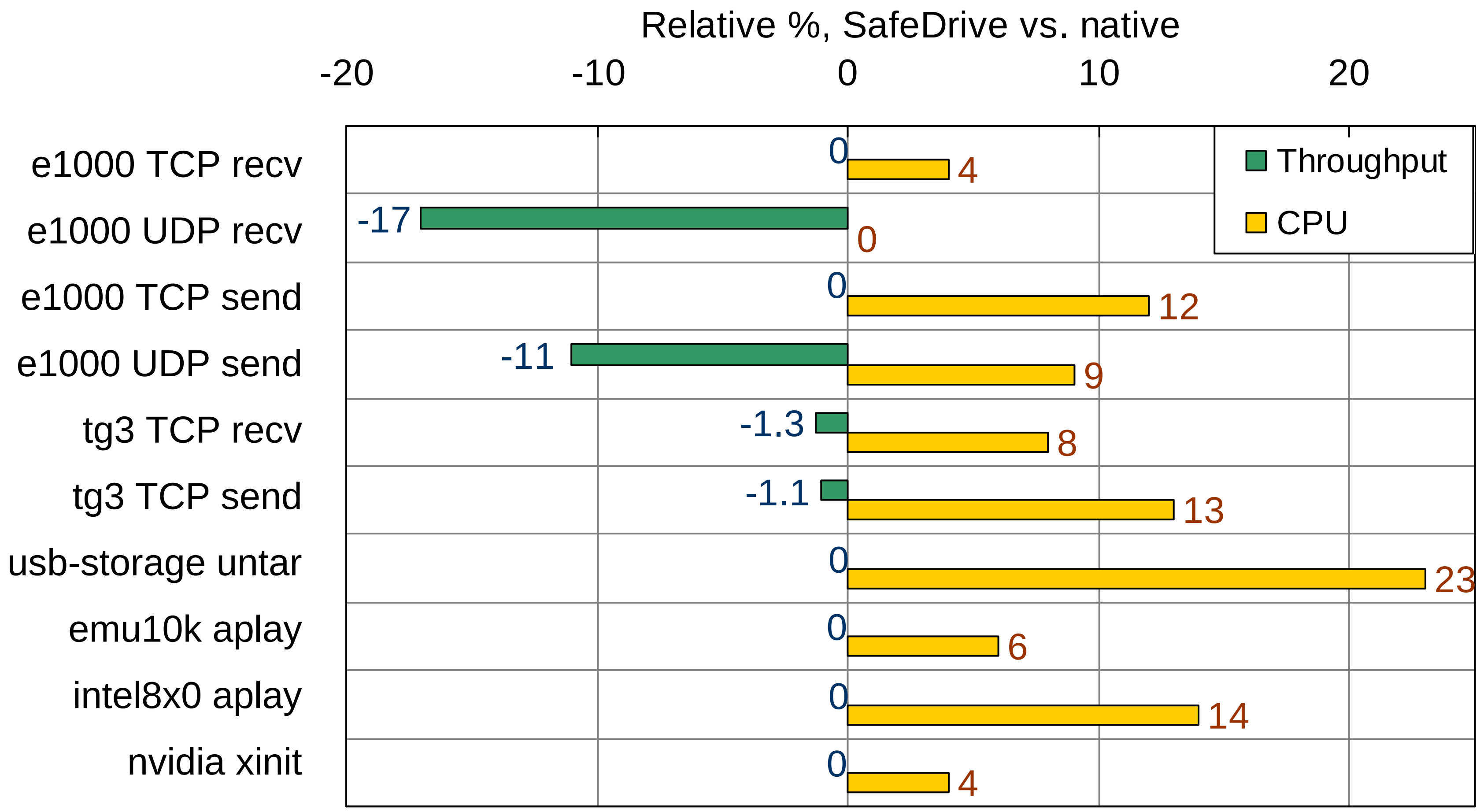
- 1%-4% of lines with Deputy annotations
- Recovery wrappers can be automatically generated

Annotations Break-down

	Lines Changed	Bounds	Strings	Tagged Unions	Trusted Code
All 6 drivers	1544	379	83	2	390
Kernel headers	1866	187	260	8	140

- Common reasons for trusted casts and trusted code
  - **Polymorphic private data**, e.g. **`netdev->priv`**
  - Small number of cases where buffer bounds are not available
  - Code manipulating pointer values directly, e.g. **`PTR_ERR(x)`**

Performance



- Nooks (Linux 2.4): e1000 TCP recv: **46% (vs. 4%)**,
  e1000 TCP send: **111% (vs. 12%)**

Conclusion

- SafeDrive does fine-grained memory safety checking for extensions with low overhead and few code changes
- A recovery scheme for in-process extensions via restarts
- It is feasible to get much of the safety guarantee in type-safe languages in extensions without abandoning existing systems in C
- Language technology makes extension isolation easier

`http://ivy.cs.berkeley.edu/safedrive`

`http://deputy.cs.berkeley.edu`

How do you change bounds/tags

```
struct {
  unsigned int len;
  int * count(len) data;
} x;

1  x.data = NULL;
   if (x.data!=NULL && (A<0||A>len)) abort
2  x.len = A;
   if (B<sizeof(int)*x.len) abort
3  x.data = malloc(B);
```

Related Work

- Improving memory safety of C
  - Safe C-like language: Cyclone [Morrisett et al]
  - Hybrid checking (non-modular): CCured [Necula et al]
  - Type qualifiers for static checking: CQual [Foster et al, Johnson/Wagner], Sparse [Torvalds]
- Improving OS/extension reliability
  - Hardware protection: Nooks [Swift et al], L4 [LeVasseur et al], Xen [Fraser et al]
  - Binary instrumentation: SFI [Wahbe et al, Small/Seltzer], XFI [Erlingsson]
  - Using Cyclone: OKE [Bos/Samwel]
  - Static validation of API usage: SLAM [Ball et al]
  - Writing OS with safe language: Singularity [Patel et al]

More Deputy Features

- Checking types of arguments in **`printf`**-like functions
- Bounds for open arrays
- Special support for **`memset(), memcpy()`**
- Trusted casts for programmer to override the type system

Recovery Rate Results

SafeDrive	Crashes	Mal-functions	Innocuous Errors	Works
Off	44	21	n/a	75
On	0	19	8	113

- 140 runs, 20 per fault category
- SafeDrive prevented all 44 crashes with 100% recovery rate
  - 5 of 7 categories caused crashes
  - All caused by memory-safety errors

Recovery Rate Results (2)

Detection	Crashes	Mal-function	Innocuous	Total
Static	10	0	3	13 (**24%**)
Dynamic	34	2	5	47 (76%)
Total	44	2	8	54

- 24% problems are detected statically, including 10 crashes
  - e.g. wrong constant size for **`memcpy()`**, deref of uninitialized ptr

- Wrappers are currently hand-written
- No session restoration for failed drivers