Cyclone
Safe C-level Programming
CMSC 412, Fall 2004
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Credit where credit is due ...

• Cyclone is a research language, the product of the labors of many people:
  - Greg Morrisett (Harvard)
  - Dan Grossman (Washington)
  - Trevor Jim (AT&T)
  - Mike Hicks

1988? 2004?

• “In order to start copies of itself running on other machines, the worm took advantage of a buffer overrun...”

• “…it is estimated that it infected and crippled 5 to 10 percent of the machines on the Internet.”

• Fact: half of CERT advisories involve buffer overruns.

1998: Missile Cruisers

• “The controversy began when the USS Yorktown … suffered a widespread system failure … a crew member mistakenly entered a zero into the data field of an application … caused a buffer overflow … which turned into a memory leak … eventually brought down the ship’s propulsion system.

• The result: the Yorktown was dead in the water for more than two hours.”
Building Secure Software

- Today, our economy, government, and military depend upon the proper functioning of our computing and communications infrastructure.
- That infrastructure is coded in low-level, error-prone languages (i.e. C).
  - device drivers, kernels
  - file systems, web servers, email systems
  - switches, routers, firewalls

But C is a lousy language

- Must bypass the type system to do even simple things (e.g., allocate and initialize an object.)
- Libraries put the onus on the programmer to do the “right thing” (e.g., check return codes, pass in large enough buffer.)
- For efficiency, programmers stack-allocate arrays of size K (is K big enough? does the array escape downwards?)
- Programmers assume objects can be safely recycled when they cannot and fail to recycle memory when they should.
- It’s not “fail-stop” --- errors don’t manifest themselves until well after they happen (e.g., buffer overruns.)

But it’s also very useful:

- Almost every critical system is coded in C:
  - language run-times, operating systems, device drivers, servers, switches, etc.
- because it provides a lot of good things:
  - ported to lots of architectures
  - low-level control over data structures, memory management, instructions, etc.
  - good performance
- We need safety for these infrastructures.

What can we do?

- Rewrite the code in Java or some other type-safe language?
  - Not low-level enough.
  - no control over data representations.
  - no control over memory management.
  - performance isn’t there?
  - Just not realistic.
    - any more than telling all of those businesses to re-code their Cobol code to avoid Y2K.
    - need an incremental solution.
**Instead ...**

- We need a next-generation low-level language X with the following features:
  - The practical coding power of C.
  - Need to build device drivers, kernels, etc.
  - Transparent interoperability with legacy C.
  - Just can’t switch the whole world over at once.
  - The safety and scalability of Java.
  - Many errors caught at compile time
  - Fail-stop behavior at run time.
  - A relatively painless path from C to X.

**Cyclone: an experimental Safe-C**

- Start with ANSI-C.
- Throw out anything that can lead to a delayed core-dump:
  - E.g., arbitrary casts, unchecked pointer arithmetic.
- Add a combination of advanced typing mechanisms and dynamic checks to cover what’s missing.
  - Keep analyses intra-procedural.
  - Programmer will have to specify additional details at procedure boundaries.
- Minimize re-coding for safe idioms.
  - Best case: leave the code alone
  - Next best: add typing annotations
  - Worst case: re-write the code

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**What is a C buffer overflow?**

- `#include <stdio.h>`
- `int login() {`
  - `char user [100];`
  - `printf("login: ");`
  - `scanf("%s", &user);`
  - `... // get password etc.`
  - `}`

What happens if the user types in something that’s more than 100 characters?

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**Calling scanf()**

Stack grows downward.

32 bits

- `int login() {`
  - `char user [100];`
  - `printf("login: ");`
  - `scanf("%s", &user);`
  - `... // return here`
Calling `scanf()`

Stack grows downward

```
int login() {
    char user [100];
    printf("login: ");
    scanf("%s", &user);
    // return here
}
```

How to Prevent This?

- Don’t allow dereferencing a buffer unless compiler can prove it’s safe
  - Too conservative
- Have two separate stacks, one for data, one for return addresses
  - Violates standard calling convention
  - Could still work around this
- Prevent dereferencing with dynamic checks
I would like `scanf` to check each time it writes to its buffer to make sure that it’s not about to “go off the end.”

To do this, I must provide not only the buffer memory, but the bounds on it.

Then I can check that every dereference is within bounds.

This is what Java does, too.

What kind of bounds do I need?
- Just the length of the array
  - This is what Java does
  - But, what happens with pointer arithmetic?
    - A pointer to the current location, and a pointer to the end of the array
      - Allows forward arithmetic. (x++)
      - But what about backward arithmetic? (x--)
      - Answer: pointers to the beginning and end of the buffer, and a pointer to the current location.

“Fat” pointer implementation

A “thin” pointer (one word).
Pointer arithmetic unsafe

A “fat” pointer (three words).
Pointer arithmetic OK.
A “thin” pointer (one word). Pointer arithmetic unsafe

A “fat” pointer (three words). Pointer arithmetic OK.

A “thin” pointer (one word). Pointer arithmetic unsafe

A “fat” pointer (three words). Pointer arithmetic OK.

#include <stdio>

int foo() {
    char buf[100] = {'h','e','l',...};
    int i;
    for (i = 0; i<100; i++) {
        putc(buf[i]);
    }
}

Do I really need bounds checks here?

No. Compiler can easily prove that all dereferences will be in bounds, so no need for extra information.
What about NULL?

```c
#include <stdio>

int foo(char *filename, char *buf) {
    FILE *fp;
    fp = fopen(filename, "r");
    fwrite(fp, buf);
}
```

What happens if `fopen` failed, returning NULL?

Can result in a crash. C library assumes the user will check for NULL. In Cyclone we enforce this.

Not-null Pointers

- Two pointer types
  - int *
    - A possibly-null pointer to an int
  - int * @nonnull
    - A definitely-not-null pointer to an int
    - Abbreviated int @
  - Library functions can specify the latter, thus forcing the user to do a null check.

Not-null Pointer Usage

```c
int *p = NULL;
int @q = NULL; // not allowed
int @r = p; // not allowed; type(p) != type(r)
int @r = (int @)p; // ok, does a null check
extern int fwrite(FILE @fp, char *buf);
// requires that fp be not-null
```

Pointer Summary

- Three kinds of pointers make intention clear:
  - fat pointers: int ?
    - represented as a triple: {base, upper, curr}
    - supports all operations that C does on int*
    - any dereference is checked against bounds
    - ? makes representation change clear
  - thin, definite pointers: int @, int @[const-exp]
    - thin, possibly null pointers: int *, int*[const-exp]
      - bounds tracked statically -- same rep. as C
      - limited pointer arithmetic
      - * requires a null check.
Cyclone Hello World

```c
#include <stdio.h>

int main(int argc, char **argv) {
    if (argc > 1) {
        printf("Hello %s,\n",*(argv+1));
        return 0;
    }
    fprintf(stderr,"Usage: %s <name>\n",argv[0]);
    return -1;
}
```

Libraries are wrapped to prevent bad inputs

Another Example:

```c
typedef struct Point { int x,y; } pt;

void addTo(pt p, pt q) {
    p->x += q->x;
    p->y += q->y;
}

void foo() {
    pt a = {1,2};
    pt b = {3,4};
    pt *aptr = &a;
    pt *bptr = &b;
    addTo(aptr,bptr);
}
```

Many times, C code such as this compiles directly with no changes needed by programmer. However, there may be additional run-time checks.

A Better Port

```c
typedef struct Point { int x,y; } pt;

void addTo(pt @p, pt @q) {
    p->x += q->x;
    p->y += q->y;
}

void foo() {
    pt a = {1,2};
    pt b = {3,4};
    pt @aptr = &a;
    pt @bptr = &b;
    addTo(aptr,bptr);
}
```

By refining the types of variables, programmers can often get rid of the overheads.

Making Libraries Robust

```c
struct FILE;
extern FILE *fopen(char *name, char *mode);
extern int putc(char, FILE *);

void foo() {
    FILE *f = fopen("/tmp/bar.txt","wb");
    char s[] = "hello";
    int i;
    for (i = 0; i < 5; i++) { putc(s[i],f); }
}
```

most implementations core dump when given NULL.

Type error here because f has type FILE* but putc demands FILE/@.
One way to fix:

```c
struct FILE;
extern FILE *fopen(char *name, char *mode);
extern int putc(char, FILE*);

void foo() {
    FILE *f = fopen("/tmp/bar.txt", "wb");
    char s[] = "hello"
    int i;
    for (i = 0; i < 5; i++) { putc(s[i], (FILE *)f); }
}
```
dynamically checks that f is an actual file.

A better fix:

```c
struct FILE;
extern FILE *fopen(char *name, char *mode);
extern int putc(char, FILE*);

void foo() {
    FILE *fn = fopen("/tmp/bar.txt", "wb");
    char s[] = "hello"
    int i;
    if (*fn != NULL) {
        FILE *f = (FILE *)fn;
        for (i = 0; i < 5; i++) { putc(s[i], f); }
    } else {
        throw new FileError("can't open /tmp/bar.txt!");
    }
}
```

Object Lifetimes: Spot the Bug

```c
pt *add(pt *p, pt *q) {
    pt r;
    r->x = p->x + q->x;
    r->y = p->y + q->y;
    return &r;
}
```

```c
void foo() {
    pt a = {1,2};
    pt b = {3,4};
    pt *c = add(&a, &b);
    c->x = 10;
}
```
s'x lifetime ends here!

Tracking Object Lifetimes

- Cyclone uses a region-based type system:
  - Each lexical block is treated as a distinct region.
  - Each pointer type has an associated region: int* x
  - The heap is treated as a special region ("H") with a global lifetime (more on this later).
  - A pointer can only be dereferenced while the region is still live.
Simple Region Example

\[ \text{pt } a = \{1,2\}; \]

\begin{verbatim}
void foo() {
  pt b = \{3,4\};
  pt @H aptr = &a;
  pt @ foo bptr = &b;
  addTo(&a, &b);
}
\end{verbatim}

- `a` lives in the heap region, so `&a` has type `pt @H`.
- `b` lives in the activation record of `foo` so `&b` has type `pt @foo`.

Region inference can figure out the regions, so the programmer doesn't have to write them.

Definite Initialization

\begin{verbatim}
void foo() {
  pt a;
  pt * aptr = &a;
  if (rand()){
    a.x = 1;
    a.y = 2;
  }
  aptr->x++;  
}
\end{verbatim}

Flow analysis determines that this may not be initialized.

Dangling Pointers

\begin{verbatim}
void foo() {
  int *x = malloc(sizeof(int));
  int *y;
  *x = 1;
  // do some stuff
  y = x;
  free(x);
  *y = 5; // freed storage!
}
\end{verbatim}

Eliminating Dangling Pointers

- Garbage collection (simplest)
  - `free()` is removed
  - Memory is freed when it could not possibly be used by the program (reachability)
- Scoped memory management
- Safe `malloc/free`
- Cyclone supports all of these
Other things to be nervous about

- Unsafe casts
  ```
  int *p = (int *)1;
  ```
- Unsafe uses of union
  ```
  union u { int x; int *p;}
  union u v;
  v.x = 1;
  *v.p = 5;
  ```
- varargs (as implemented in C)
- Cyclone prevents these bad usages

Performance

- Typically 1.5x C; up to 4-5x
- Bottlenecks
  - Array-bounds checks
  - Unoptimized libraries (e.g. string, file I/O libraries)

Cyclone: where we stand

- Cyclone compiler
  - ~100KLoC of Cyclone code
  - Bulk is the type-checker and dataflow analyses
  - Straightforward translation to C
  - Available for many architectures (Linux, BSD, Irix, Cygwin, Sparc, etc.)
- Ports
  - Libc and other libs (sockets, XML, lists, and more)
  - bison, flex, web server, cfarc, grobner, NT device driver ... (~40KL total)
  - Typically differ from original C by 5-15%

Tools and Applications

- Lex, Bison, Memory profiler
- Semi-automated porting tools
  - Guess whether to convert a C * to Cyclone *, @, or ?
- In-kernel transport protocols (SOSP 03)
- Streaming data overlay networks (OPENARCH 03)
- In-kernel extensions (OPENARCH 02)
- Hardware description languages
Summary

• Research in safe, low-level languages is crucial.
• Programmer-controlled data representations and memory management are critical issues.
• We have good typing technologies at this point, but adapting them to practical settings is a lot of work.
• Cyclone isn’t a full solution but it’s moving in the right direction.

Obligatory URL

http://www.cs.umd.edu/projects/cyclone

• Includes code, papers, documentation, and more!