CS 489 / 698: Software and Systems Security

Module 2: Program Security (Defenses)
entropy / moving-target defense

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Outline

Why entropy in security?

Nondeterminism is useful in software security when

- it has no impact on the intended finite state machine BUT
- limits attackers' abilities of programming the weird machine.

In this slide deck: we will examine some standard / deployed practices of safely introducing nondeterminism to boost system and software security.

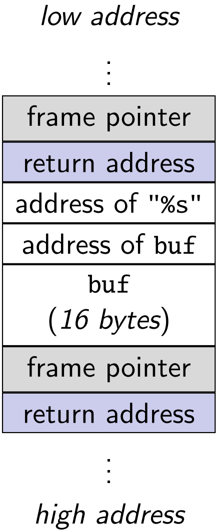
Choosing pills, a lot of pills

Figure: Red pill vs Blue pill. Credits / Trademark: The Matrix Movie

Outline

Recap: stack overflow

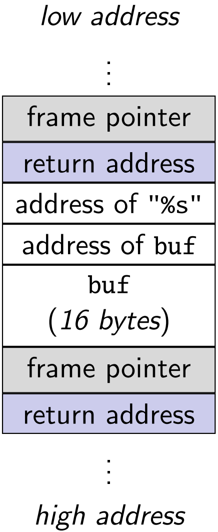
```c
int main() {
  char buf[16];
  scanf("%s", buf);
}
```



Solution 1: program analysis

```c
int main() {
  char buf[16];
  scanf("%s", buf);
}
```

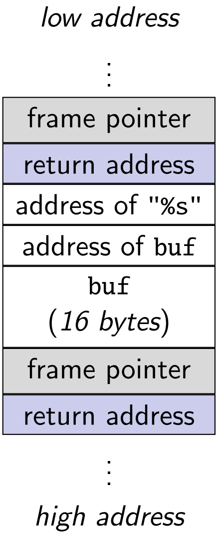
```diff
int main() {
  char buf[16];
- scanf("%s", buf);
+ scanf("%15s", buf);
}
```

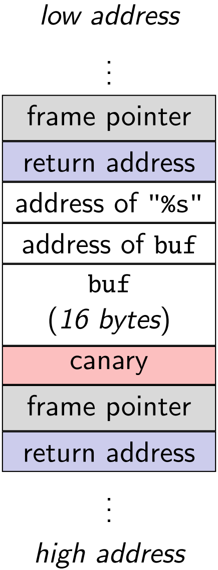


Solution 2: exploit mitigation

```c
int main() {
  char buf[16];
  scanf("%s", buf);
}
```

- On function entry, push canary value *X* onto stack.
- On function return, check canary value is still *X*.





Original use of canary

Figure: Canaries in coal-mining. Credits / Trademark: Alamy Stock Photo

The default implementation in GCC

```c
int main() {
  char buf[16];
  scanf("%s", buf);
}
```

```c
extern uintptr_t __stack_chk_guard;
noreturn void __stack_chk_fail(void);

int main() {
  uintptr_t canary = __stack_chk_guard;

  char buf[16];
  scanf("%s", buf);

  if ((canary = canary ^ __stack_chk_guard) != 0) {
    __stack_chk_fail();
  }
}
```

- The `__stack_chk_guard` and `__stack_chk_fail` symbols are normally supplied by a GCC library called `libssp`.
- You also have the option of specifying your own value for stack canaries.

Design choices of stack canaries

- Which value should we use as canary?
  - deterministic? secret? random?
- What is the granularity of the canary invocation?
  - per function? per execution?
- When to do the integrity check?
  - on function return? is that enough?
- How much randomness is needed?
  - 1 byte? 8 bytes? 64 bytes?

Limitations of stack canary

- Vulnerable to information leak
  - e.g., using a buffer over read to retrieve the canary value
- Limited protection for frame pointer and return address only
  - other stack variables are not protected
- Unable to defend against arbitrary writes
  - i.e., non-continuous overrides

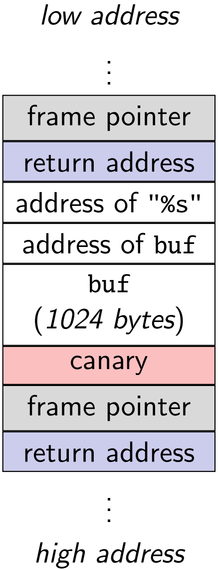
Outline

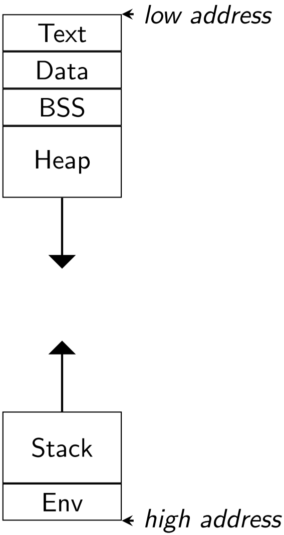
Back to the example

```c
int main() {
  char buf[1024];
  scanf("%s", buf);
}
```

Meaningful values for return address:

- Shellcode (stack)
- `system()` in `libc`



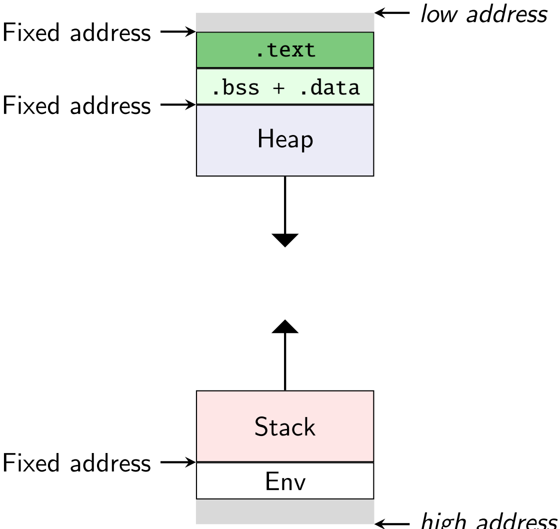


Randomize the addresses

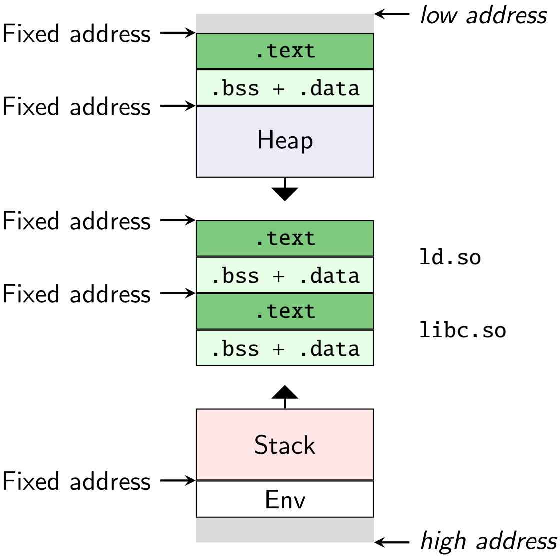
ASLR — Address Space Layout Randomization, is a system-level protection that randomly arranges the address space positions of key data areas of a process, including the base of the executable and the positions of the stack, heap and libraries.

PIE — Position Independent Executable, is a body of machine code that executes properly regardless of its absolute address. This is also known as position-independent code (PIC).

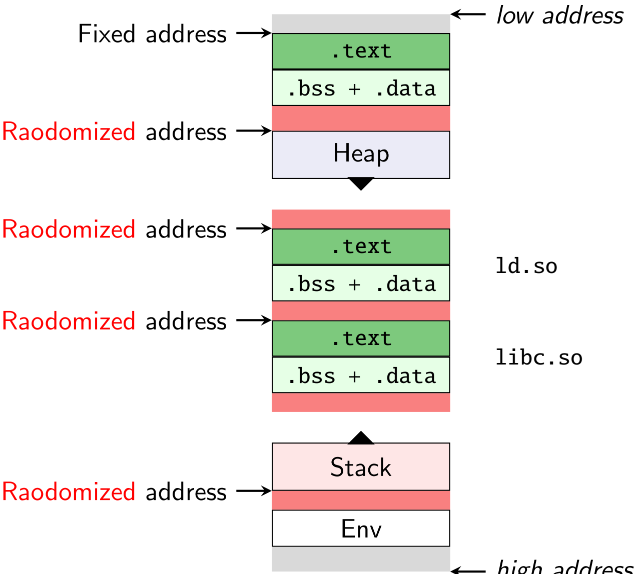
Base case: static program



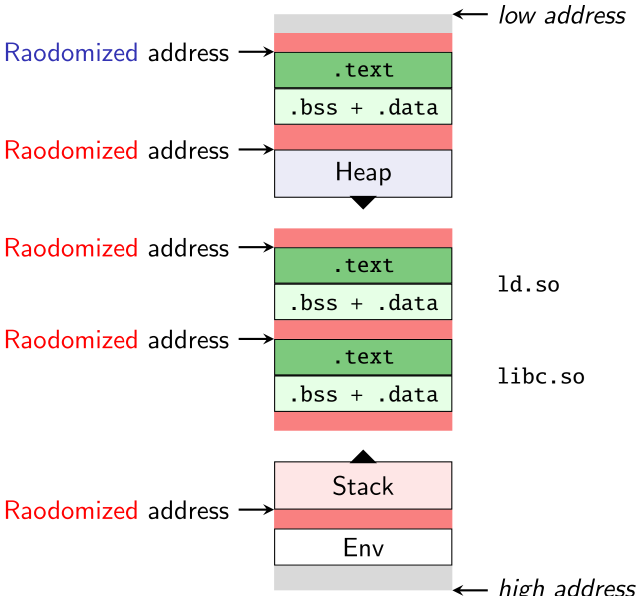
Static program + shared libraries



Static program + shared libraries + ASLR



Static program + shared libraries + ASLR + PIE



Paranoid randomization

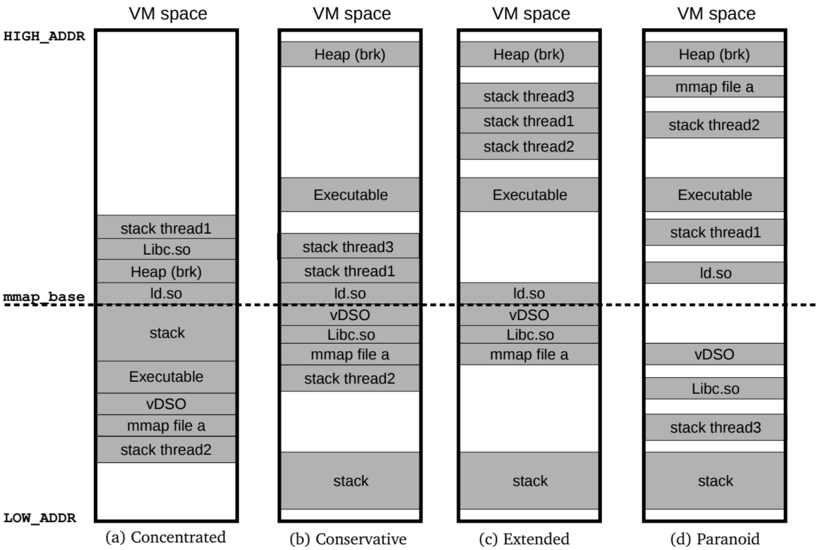


Figure: Different level of randomization proposed by the ASLR-NG project

Limitations of ASLR + PIE

- Limited entropy
  - visualized by the ASLR-NG project
- Memory layout inheritance
  - Child processes inherit/share the memory layout of the parent.

Outline

1. Introduction
2. Stack canary
3. Randomizing memory addresses
4. Entropies in heap allocators
5. Security through diversity

Motivation for secure heap allocators

Memory errors are equally (if not more) likely to happen on heap objects which can cause all sorts of unexpected behaviors.

A heap buffer overflow case

```
struct dispatcher {
    uint64_t counter;
    int (*action)(uint64_t counter, char *data);
}

int main() {
  char *p1 = malloc(16);
  char *p2 = malloc(sizeof(struct dispatcher));
  p2->counter = 0;
  p2->action = /* some valid function */;

  scanf("%s", p1);
  int result = p2->action(p2->counter, p1);

  free(p1);
  free(p2);
  return result;
}
```

A heap use-after-free case

```c
struct dispatcher {
  uint64_t counter;
  int (*action)(uint64_t counter, char *data);
}

char *p1;

void main() {
  p1 = malloc(16);
  pthread_create(/* ... */, thread_1);
  pthread_create(/* ... */, thread_2);
  /* wait for thread termination */
}
```

```c
void thread_1() {
  scanf("%15s", p1);
  /* ... compromised here ... */
  /* use-after-free */
  free(p1);
  ((struct dispatcher *)p1)
    ->action = /* bad function */;
}
```

```c
void thread_2() {
  char *p2 = malloc(
    sizeof(struct dispatcher));
  p2->counter = 0;
  p2->action = /* good function */;
  p2->action(p2->counter, p1);
  free(p2);
}
```

Secure heap allocators

These exploits have implicit assumptions on the layout of the heap, which can be invalidated by a secure heap allocator.

Basic allocator example

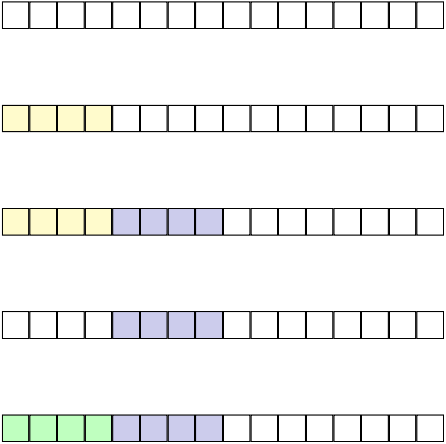
Initial state:

`p1 = malloc(16);`

`p2 = malloc(sizeof(..));`

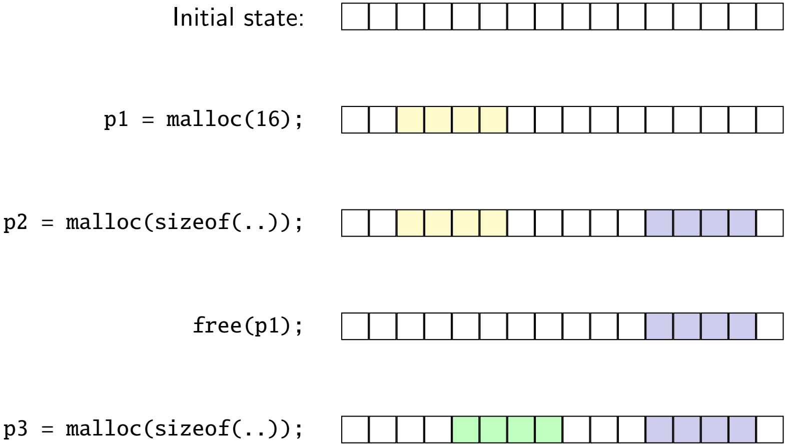
`free(p1);`

`p3 = malloc(sizeof(..));`



[0] Each square is a 4-byte box

Allocator + random placement



[0] Each square is a 4-byte box

Allocator + random placement + canary

Initial state:

```
p1 = malloc(16);
```

```
p2 = malloc(sizeof(..));
```

```
free(p1);
```

```
p3 = malloc(sizeof(..));
```

[0] Each square is a 4-byte box

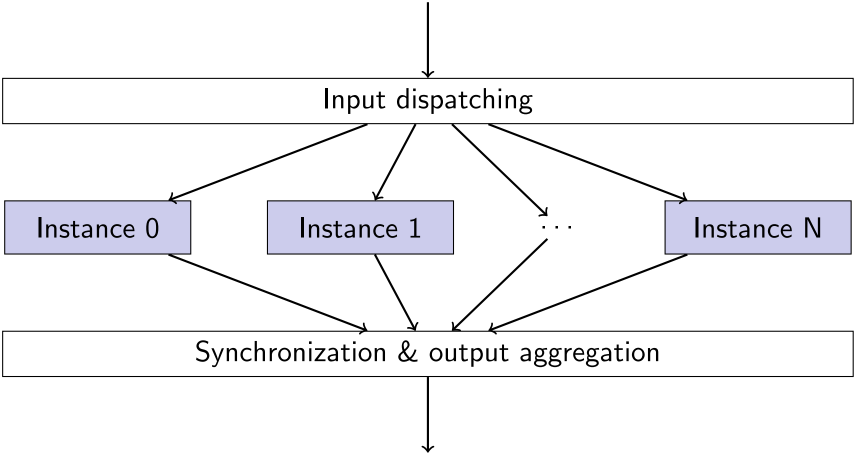
Outline

Intuition: gene/DNA diversity

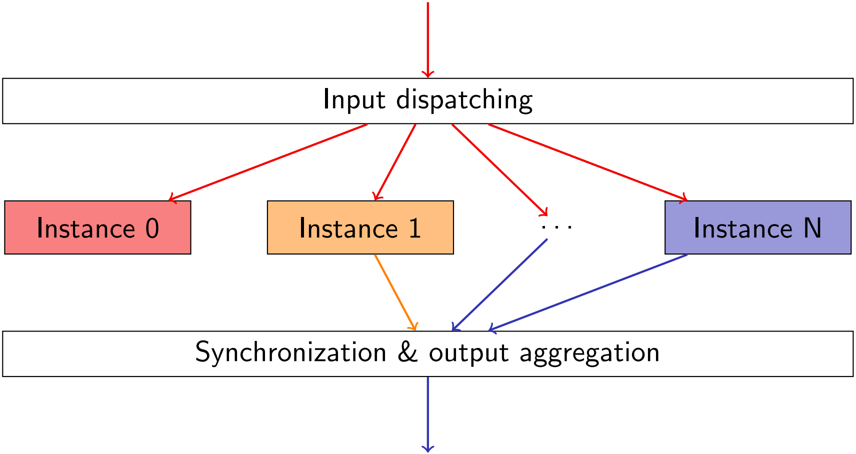
In biology, maintaining high genetic diversity allows species to adapt to future environmental changes, survive from deadly diseases, and avoid inbreeding.

Similarly, we expect software diversity to protect software systems (especially critical systems) from deadly viruses and attacks while also serving as an early signal of being attacked.

Core architecture



Core architecture (under attack)



Challenges of applying diversity-based defenses

- Source of diversity
- Synchronization of diversified instances

Source of diversity

- Compiler/loader-assisted diversity
  - e.g., direction of stack growth
  - e.g., different canary values
  - e.g., different sanitizer instrumentation
- N-version programming
  - e.g., different language VM (V8 vs SpiderMonkey)
  - e.g., different applications (nginx vs apache web server)
  - e.g., similar applications from independent vendors/teams
- Platform diversity
  - e.g., different `libc` implementations (glibc vs musl libc)
  - e.g., Adobe Reader on MacOS and Windows
  - e.g., Server programs on Intel and ARM CPUs

Mode of synchronization

- Online mode (via rendezvous points)
- Offline mode (via record-and-replay)

The key is to synchronize all sources of nondeterminism.

⟨ End ⟩