# CS 489 / 698: Software and Systems Security

**Module: Defenses against Common Vulnerabilities**
Lecture: 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 to program the weird machine.

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

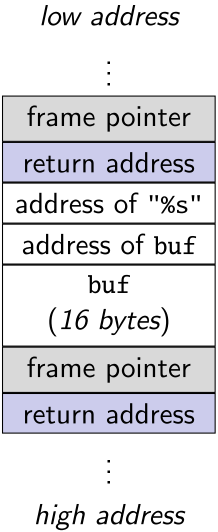
# Choosing pills, a lot of pills

**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

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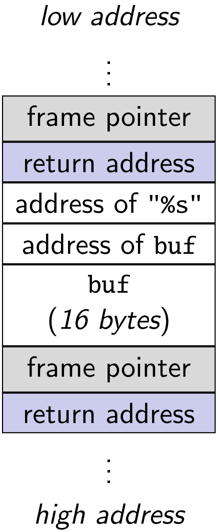

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int main() {
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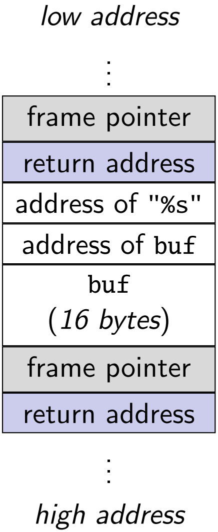
```c
int main() {
  char buf[16];
- scanf("%s", buf);
+ scanf("%15s", buf);
}
```



# Solution 2: exploit mitigation

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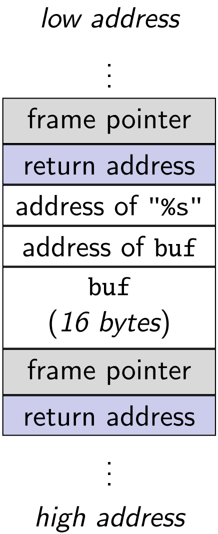

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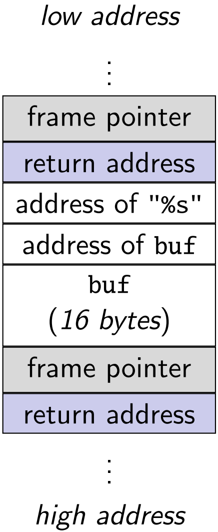


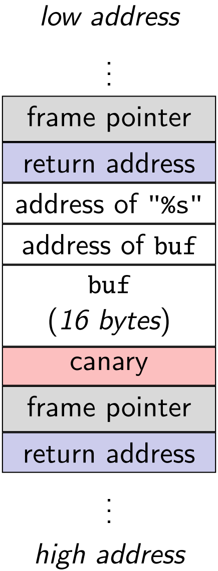

# Solution 2: exploit mitigation

```c
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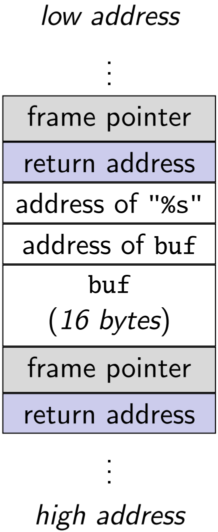
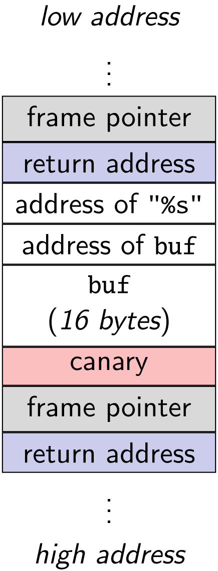
---

- 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();
  }
}
```

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  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.

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- How much randomness is needed?
  - 1 byte? 8 bytes? 64 bytes?

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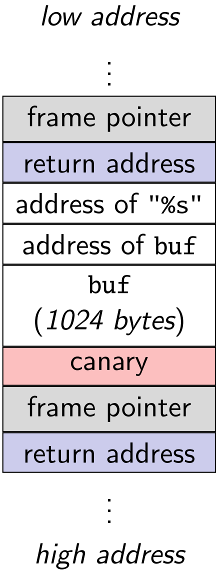
- Limited protection for frame pointer and return address only
  - other stack variables are not protected
- Unable to defend against arbitrary writes
  - i.e., non-continuous overrides

# Outline

# Back to the example

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



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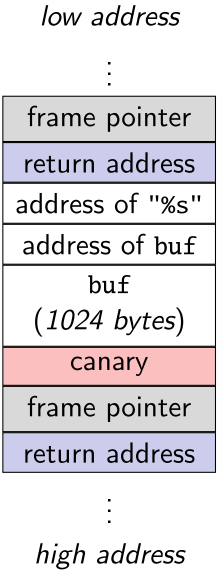
Meaningful values for return address:

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



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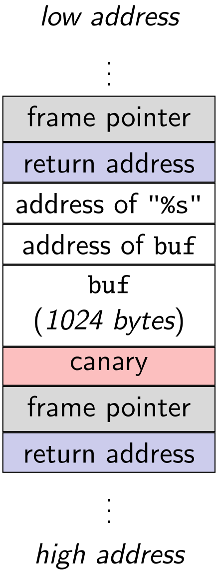
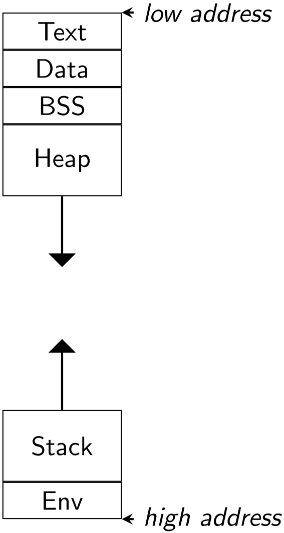


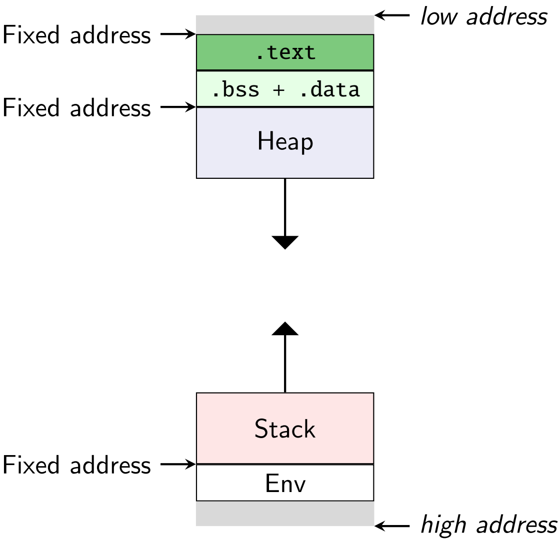



# Randomize the addresses

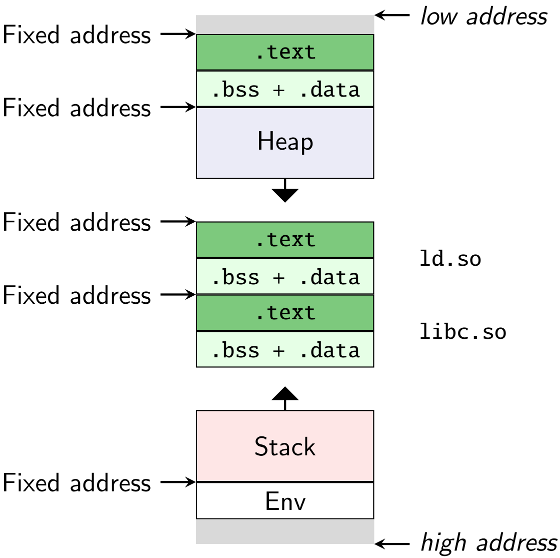
ASLR — Address Space Layout Randomization, is a system-level protection that randomly arranges the address space positions of key data areas of a process, including the base of the executable and the positions of the stack, heap and libraries.

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).

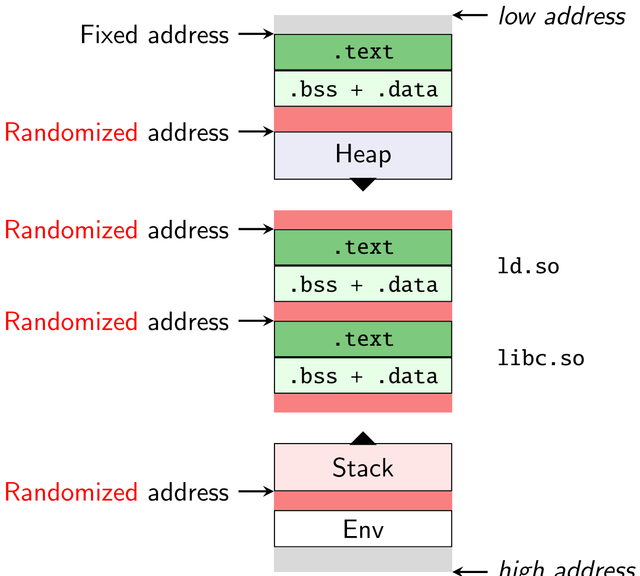
# Base case: static program



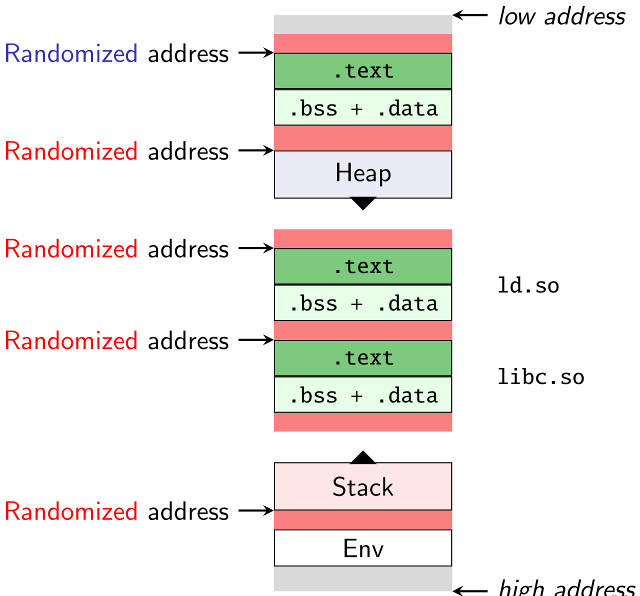
# Static program + shared libraries



# Static program + shared libraries + ASLR



# Static program + shared libraries + ASLR + PIE



# Paranoid randomization

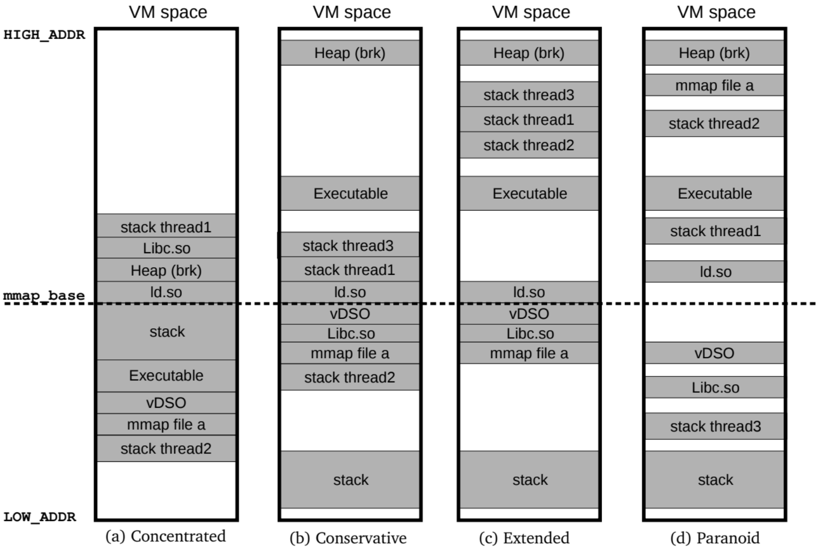



**Figure:** Different level of randomization proposed by the ASLR-NG project

# Limitations of ASLR + PIE

- Limited entropy
  - visualized by the ASLR-NG project

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- Limited entropy
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- Memory layout inheritance
  - Child processes inherit/share the memory layout of the parent.

# Outline

# 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

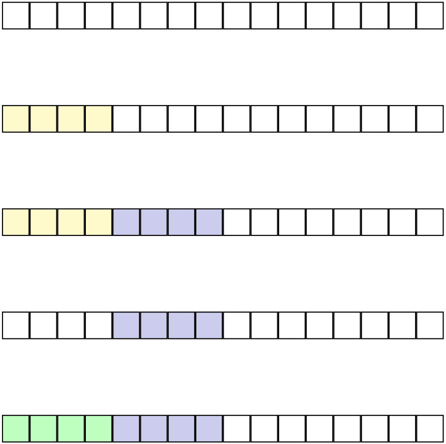
Initial state:

`p1 = malloc(16);`

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

`free(p1);`

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



[0] Each square is a 4-byte box

# Allocator + random placement

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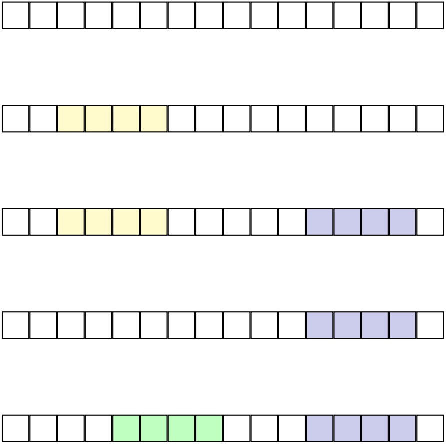

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# Allocator + random placement + canary

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

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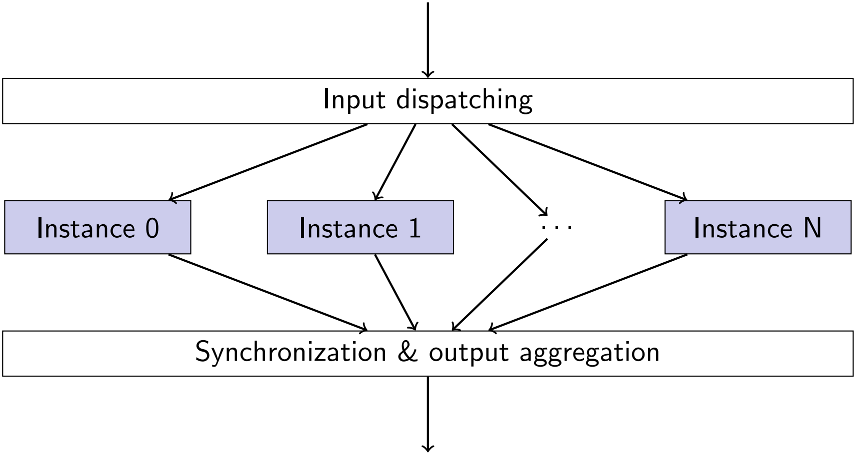
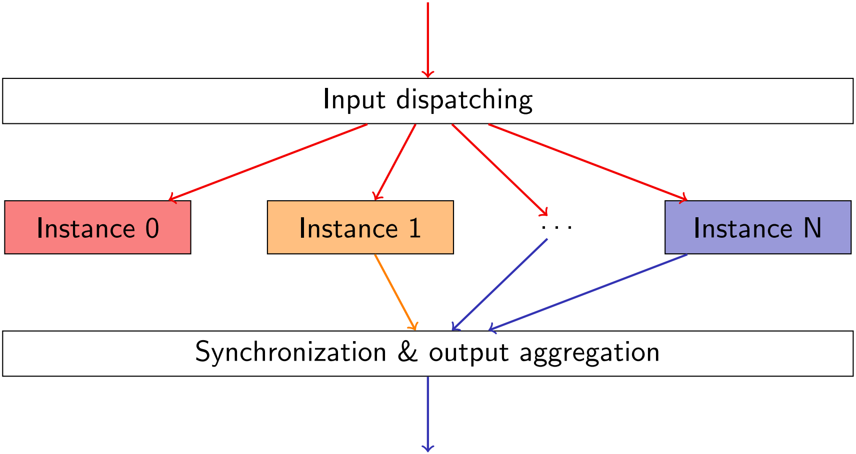
Similarly, we expect software diversity to protect software systems (especially critical systems) from deadly viruses and attacks while also serving as an early signal of being attacked.

# Core architecture



# Core architecture (under attack)



# Challenges of applying diversity-based defenses

- Source of diversity
- Synchronization of diversified instances

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  - e.g., different canary values
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- 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.

$\langle$ **End** $\rangle$