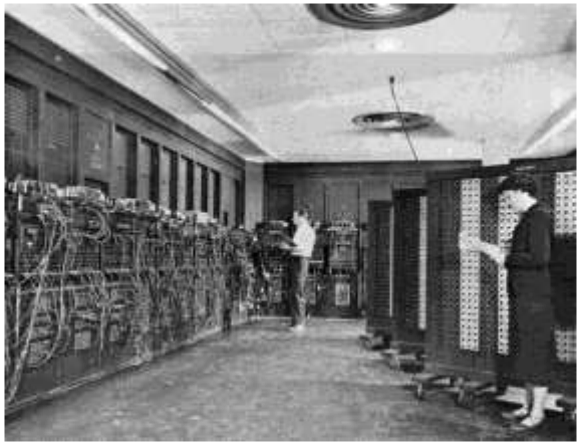
HIGH-LEVEL PROGRAMMING I

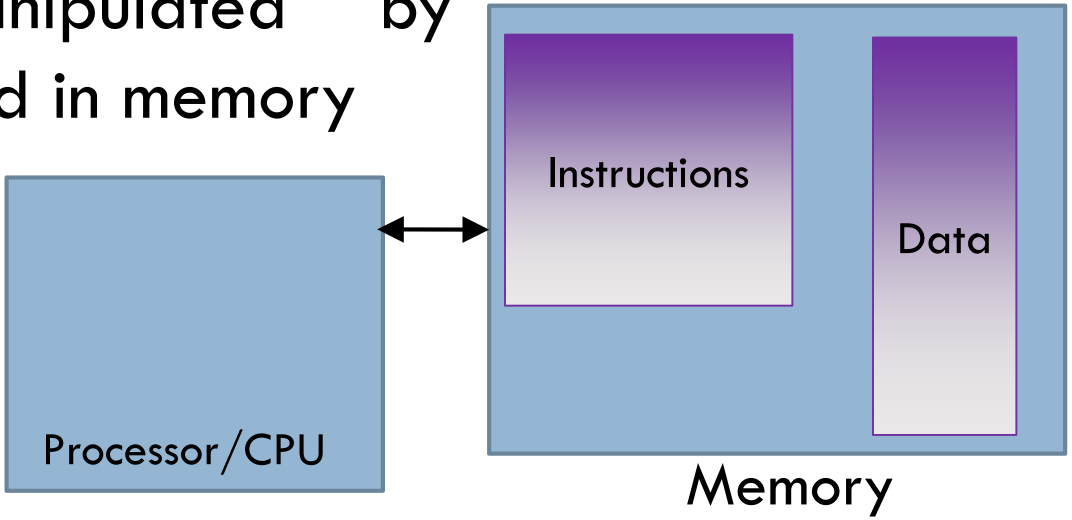
Program memory map and Heap by Prasanna Ghali

Stored-Program Computer

- Computers based on von Neumann architecture use *stored-program* concept:
  - Program that manipulates data is stored in memory
  - Data to be manipulated by program is also stored in memory



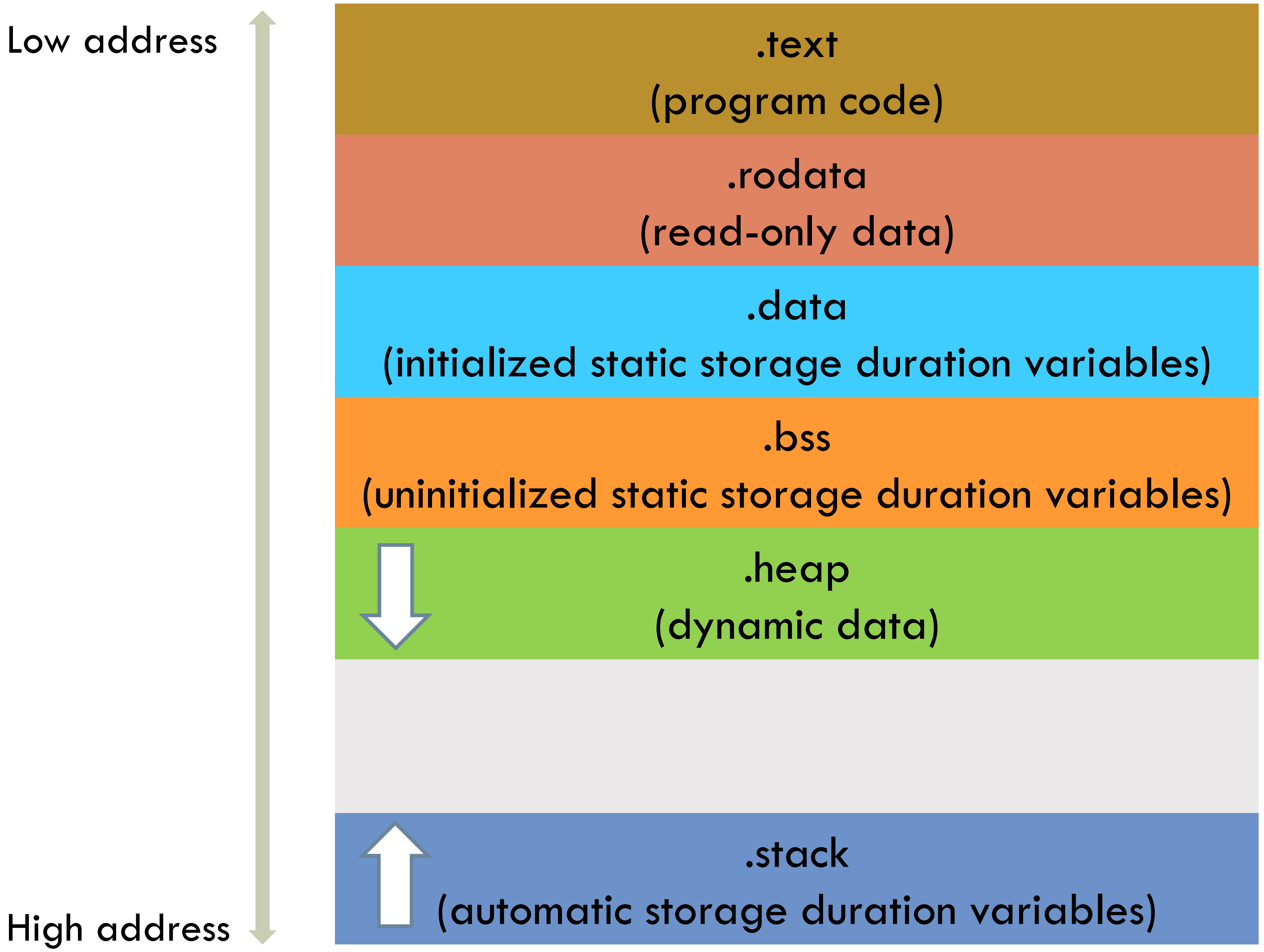
Reference



Program memory map (1/2)

- C program is single binary file containing all the information necessary to load program into memory and run it
  - Machine code of program
  - Read-only data such as format strings in `printf` statements
  - Initialized and uninitialized variables with static storage duration
- When program is executed, OS program called *loader* copies code and data from executable file in disk to memory

Program memory map (2/2)

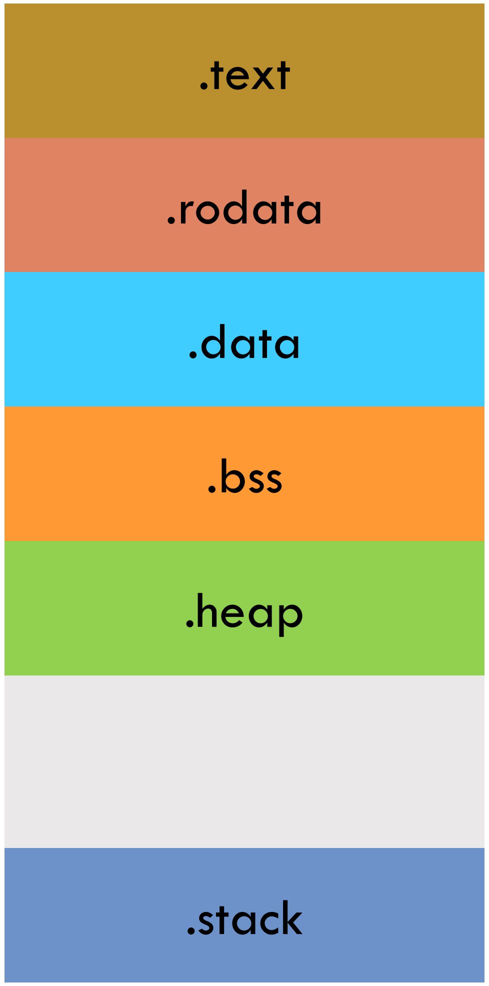

Low address
High address
.text
(program code)
.rodata
(read-only data)
.data
(initialized static storage duration variables)
.bss
(uninitialized static storage duration variables)
.heap
(dynamic data)
.stack
(automatic storage duration variables)

.text segment

- Machine code of compiled program plus external library code added by linker

.rodata segment

```
char const ival = 40;
char const *pc  = "Singapore";
printf( "Hello World" );
```

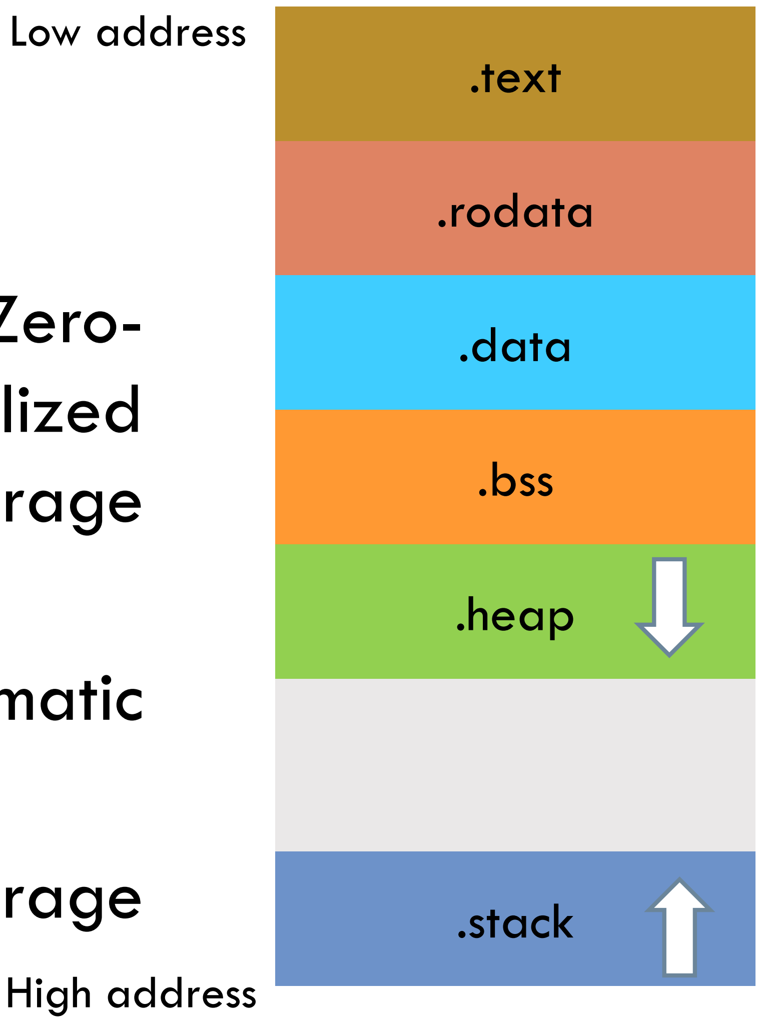


External `const` variables `ival` and `pc` and string literals `"Singapore"`, and `"Hello World"` are stored in .rodata

Internal `const` variables stored in stack or values represented in machine language instructions

Data segment (1/2)

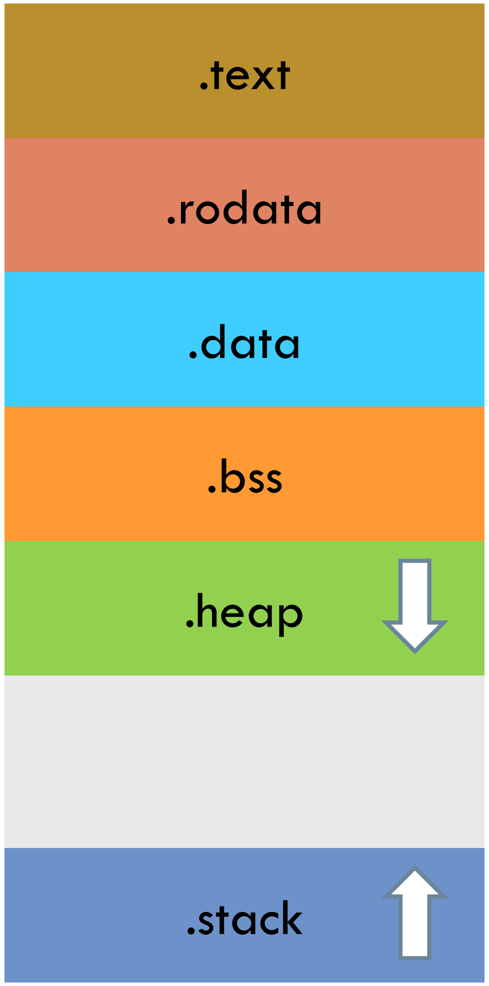
- .data: Non-zero initialized variables with static storage duration
- .bss (Block Storage Start): Zero-initialized and uninitialized variables with static storage duration
- .stack: Variables with automatic storage duration
- .heap: Values with dynamic storage duration



Data segment (2/2)

```c
int varA_bss;
double varB_bss = 0;
int varC_data = 1;
int const varD_rodata = 2;
// string literal also stored in rodata
char const *ptrE_rodata = "String";

void foo(int paramF_stack) {
  int varG_stack;
  float varH_stack;
  static int varI_bss;
  static double varJ_bss = 0.0;
  static int varK_data = 10;
  char * ptrL_TO_HEAP_MEM_stack = malloc(81);
  // more code here
  free(ptrL_TO_HEAP_MEM_stack);
}
```



.stack segment

- stack is memory region where local variables and function parameters live
- Portion of stack allocated for that function called *stack frame*
- When function is called, stack frame allocated for that function
- When function returns, function's stack frame goes away

The Stack

```c
#include <stdio.h>

void boo(int x) {
  int y = x * 2;
  printf("y: %d\n", y);
}

void foo(int c) {
  int d = c + 1;
  boo(d);
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int main(void) {
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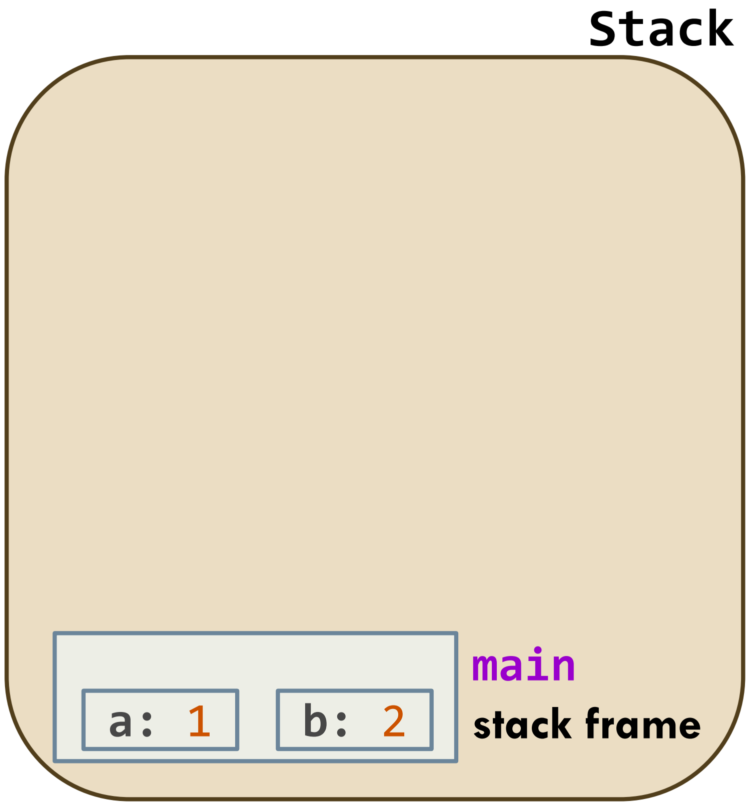

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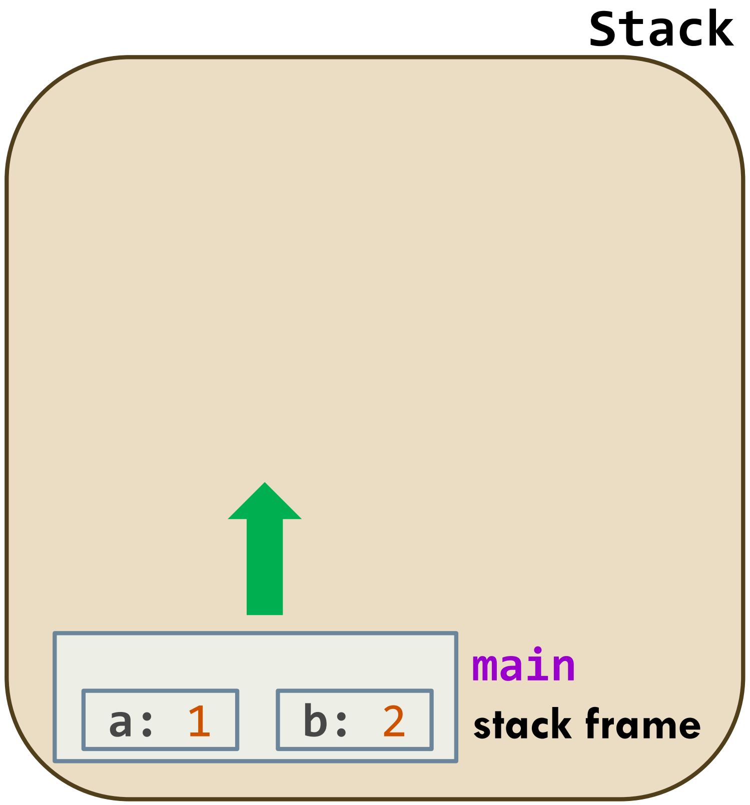

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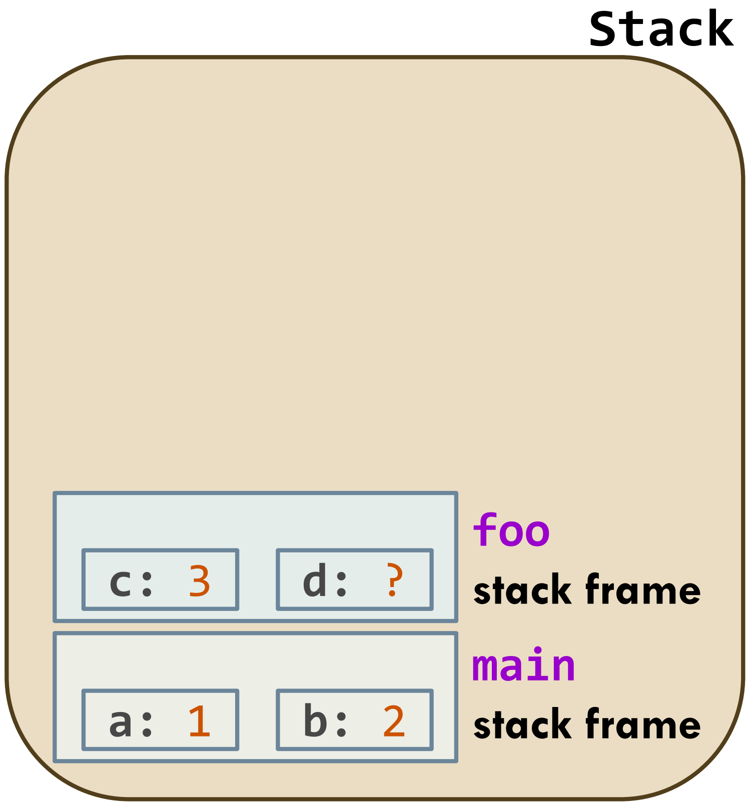

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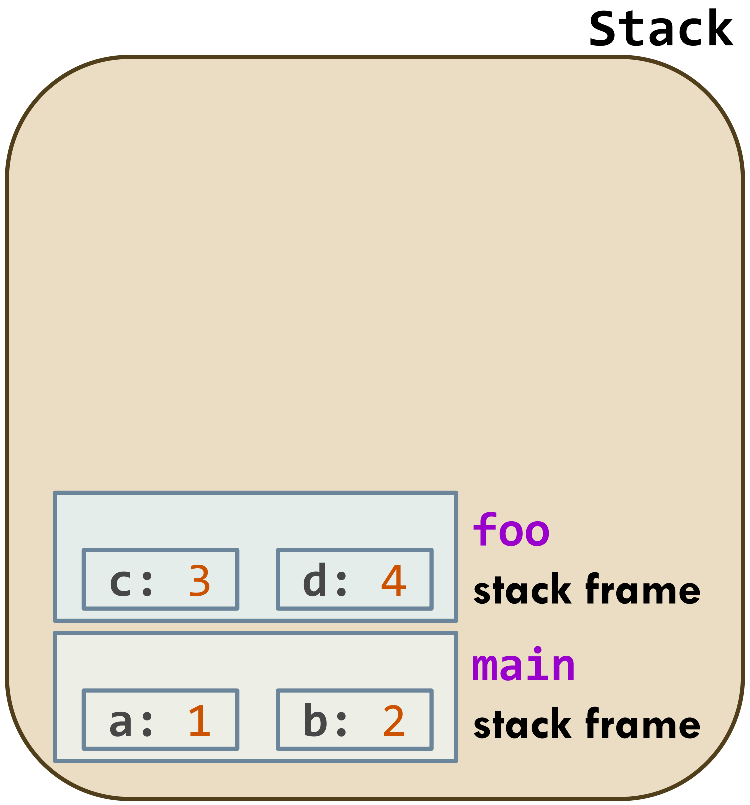

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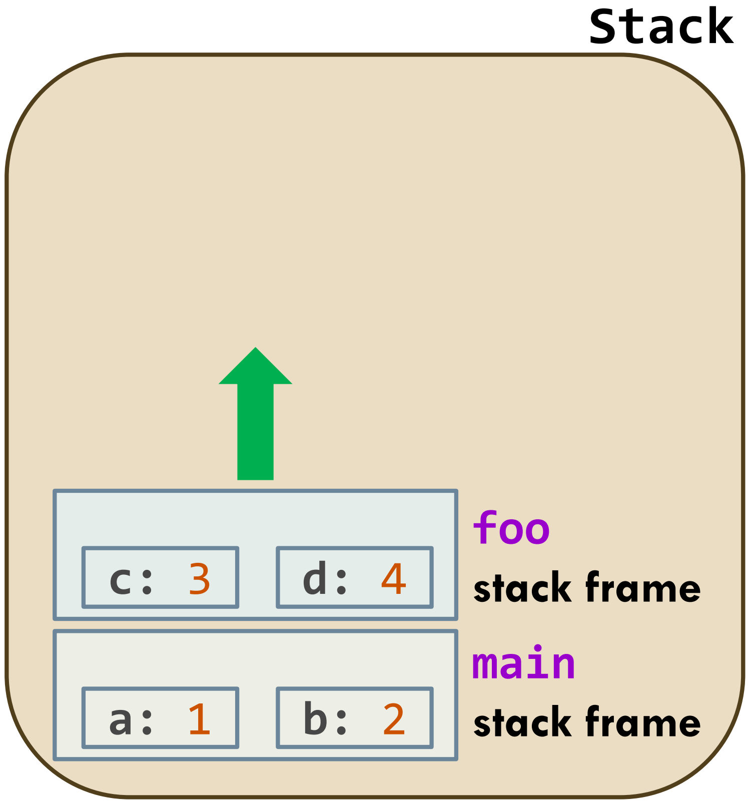

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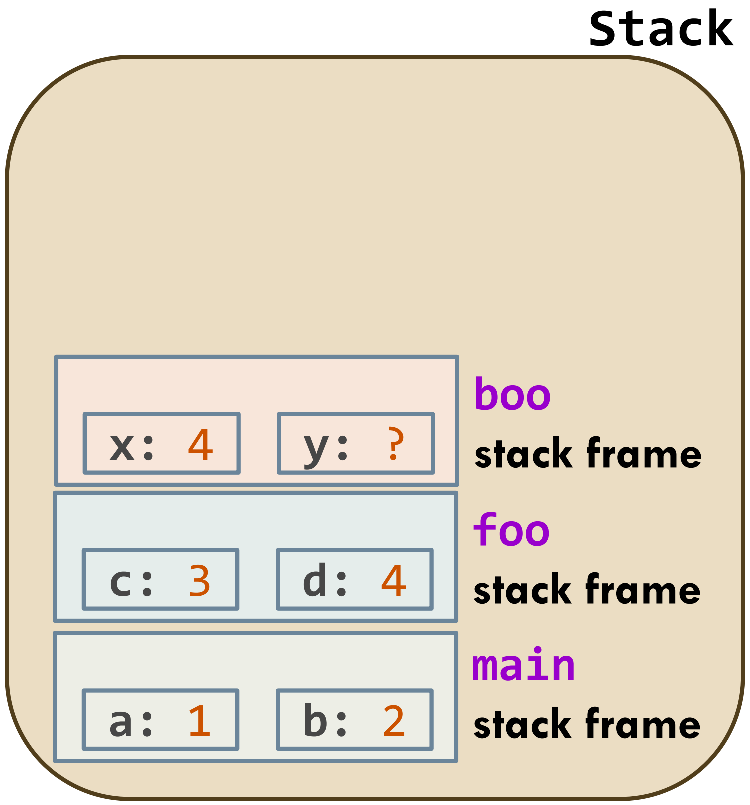

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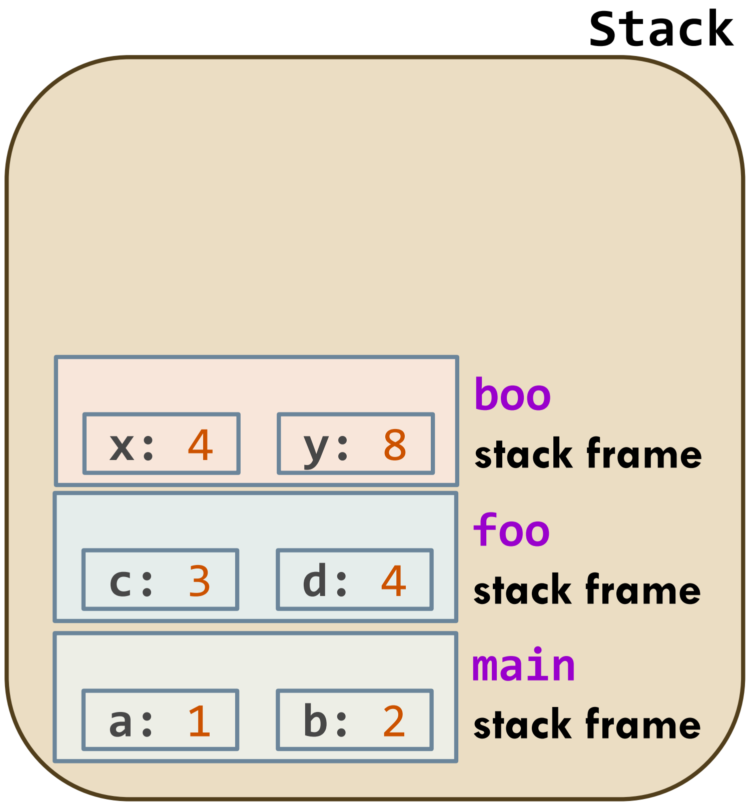

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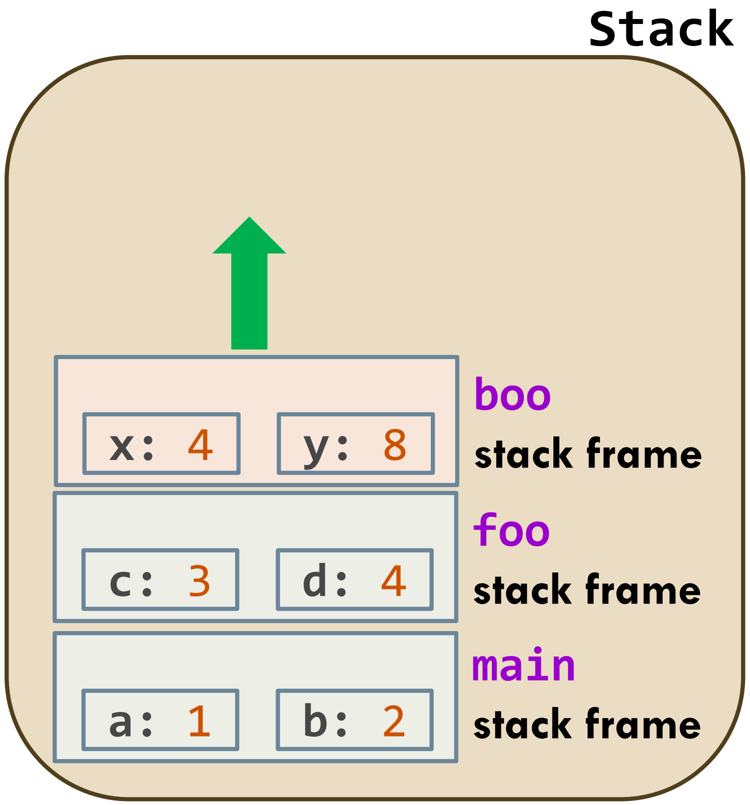

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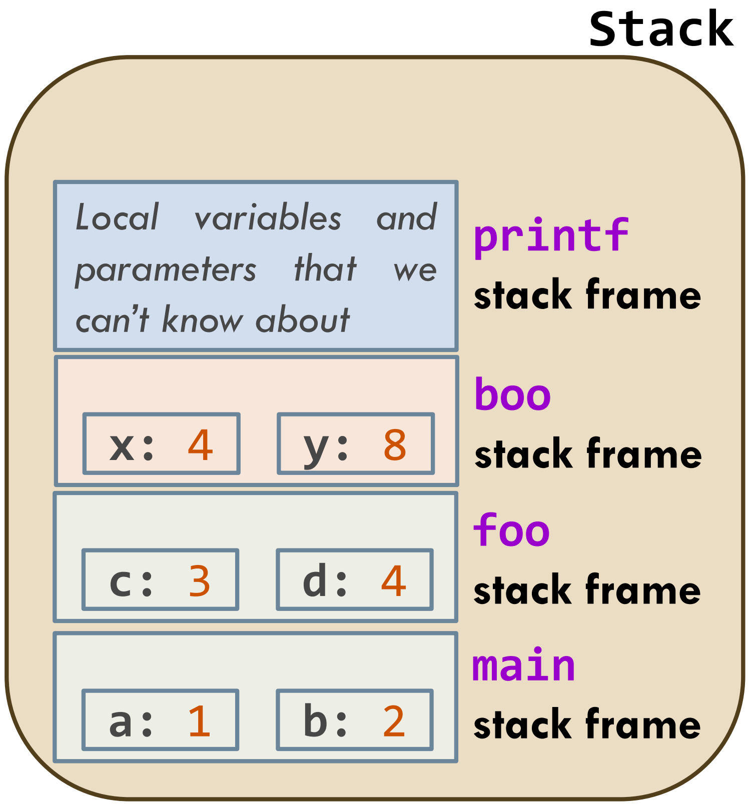

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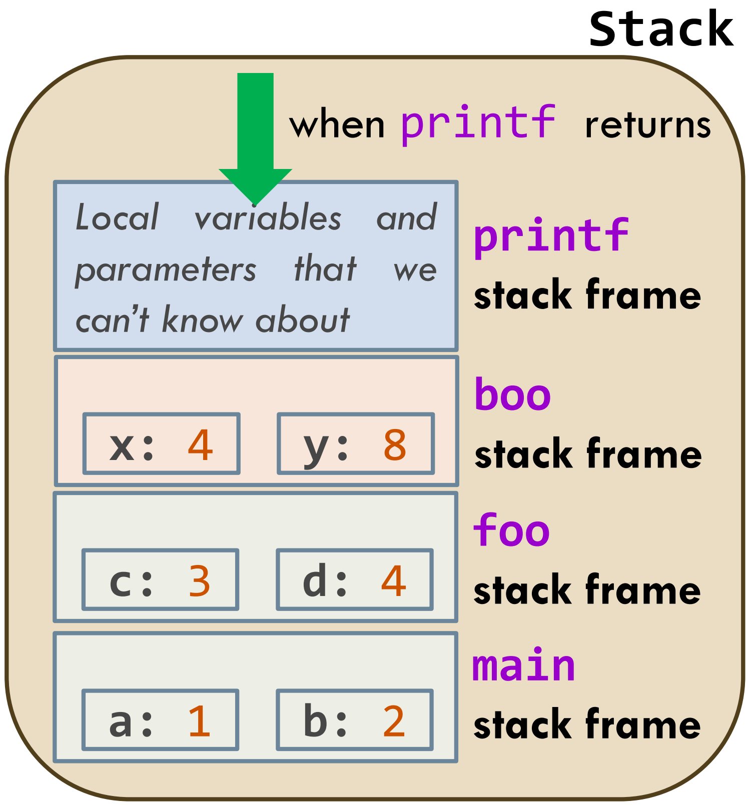

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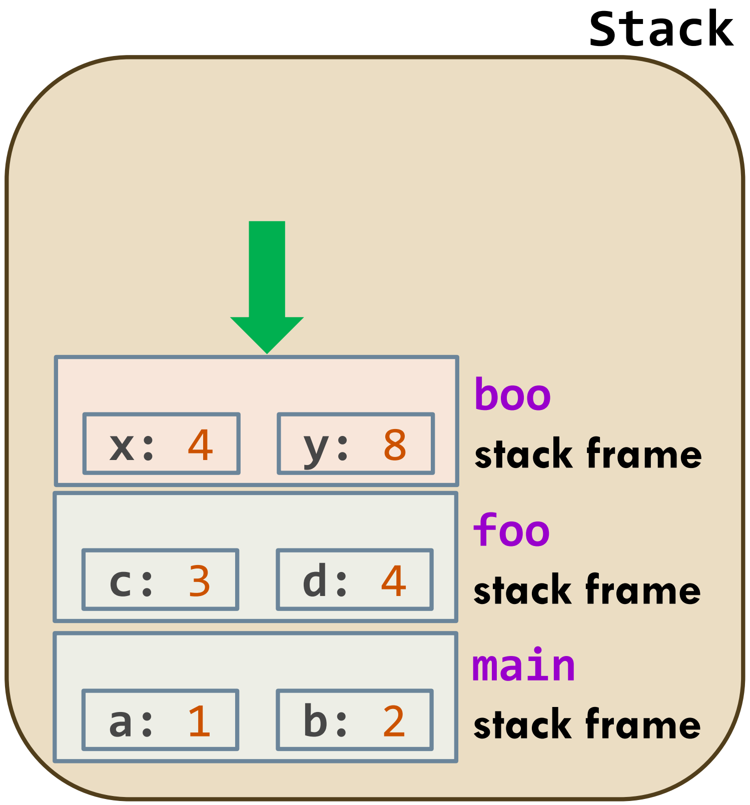

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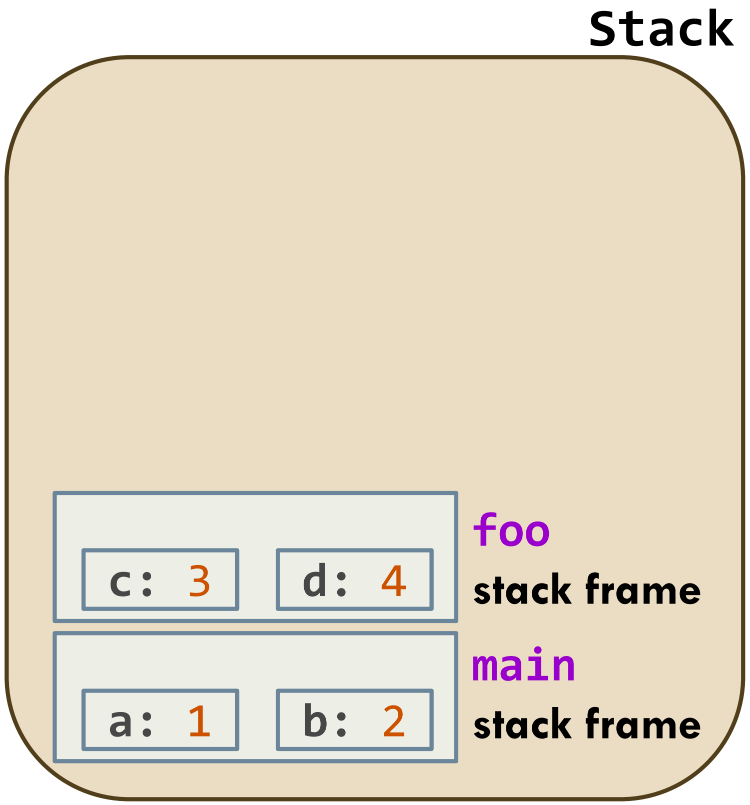

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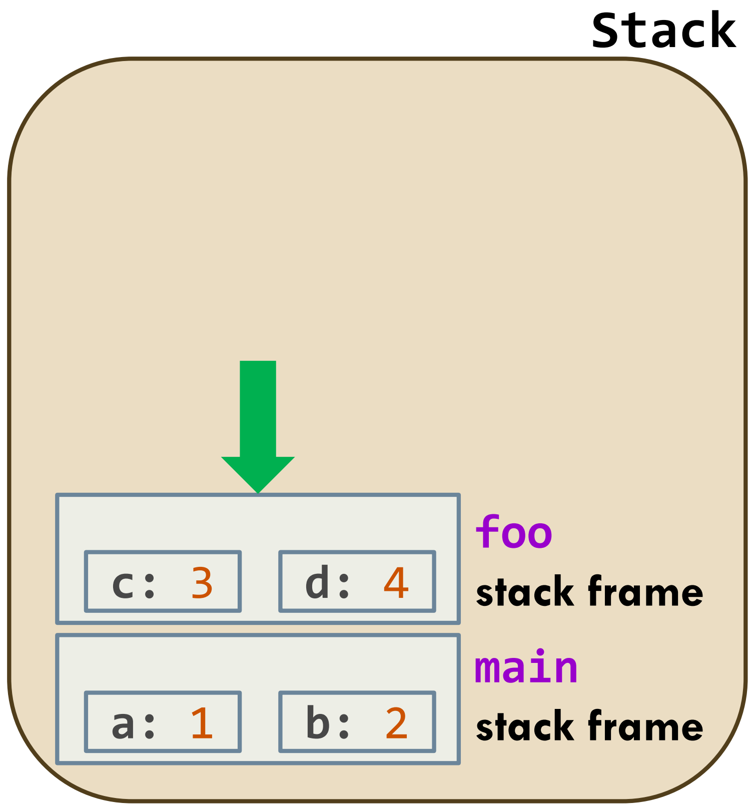

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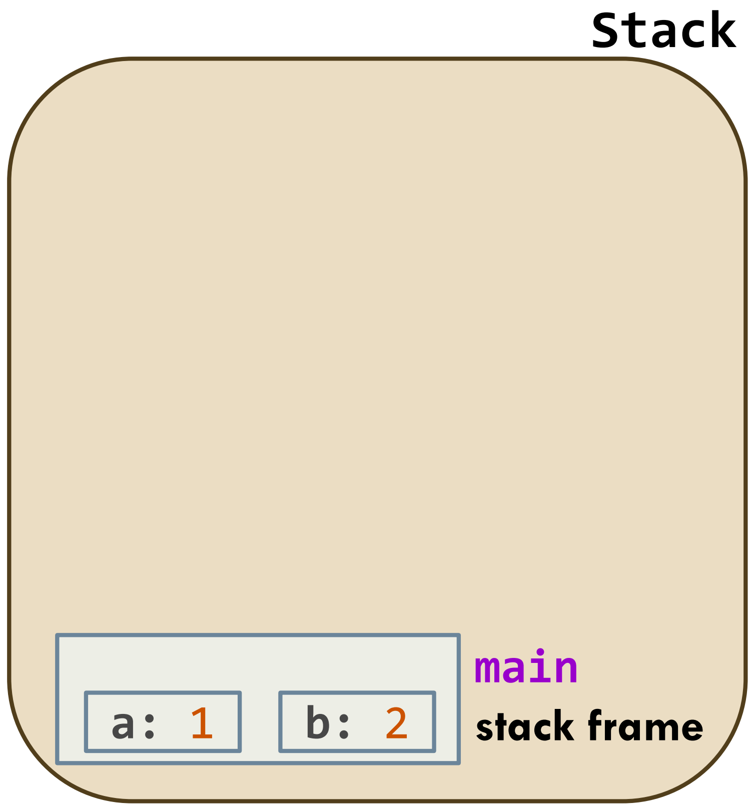

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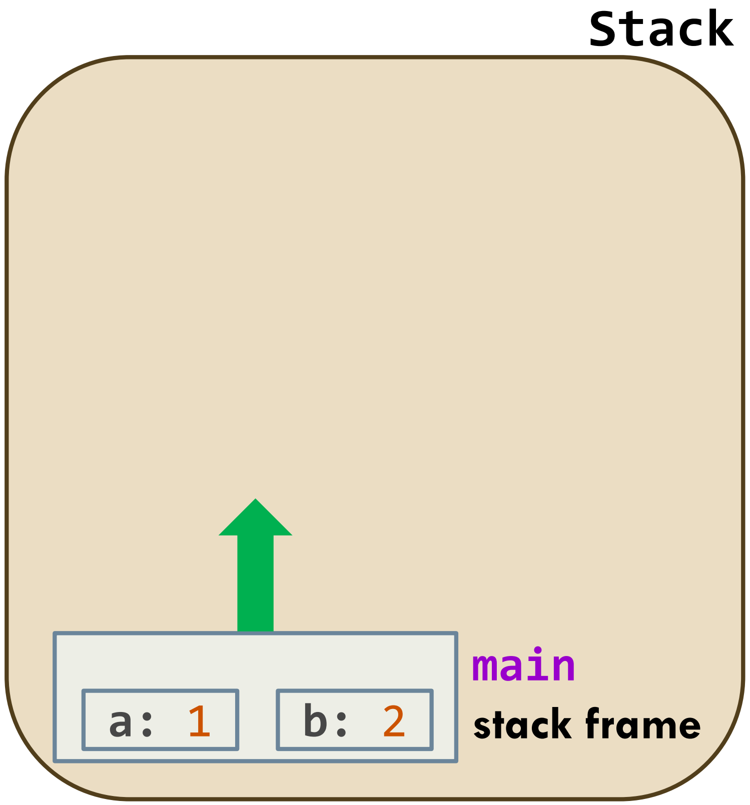

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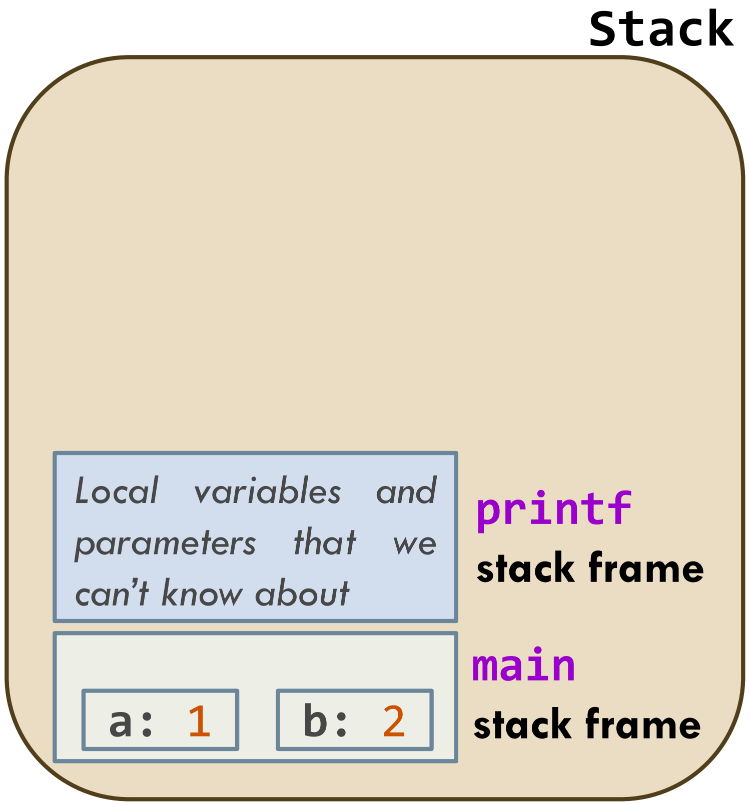

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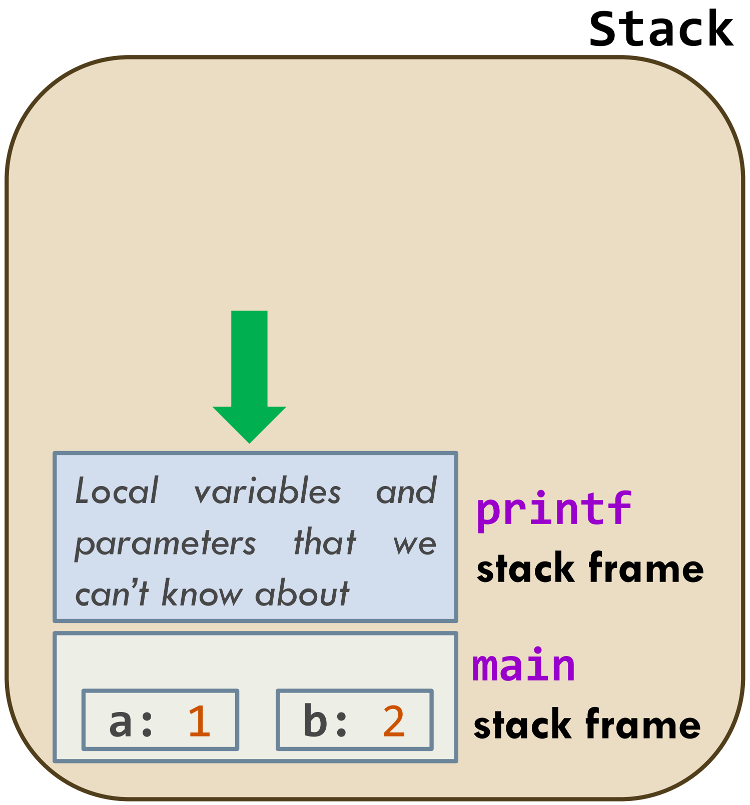

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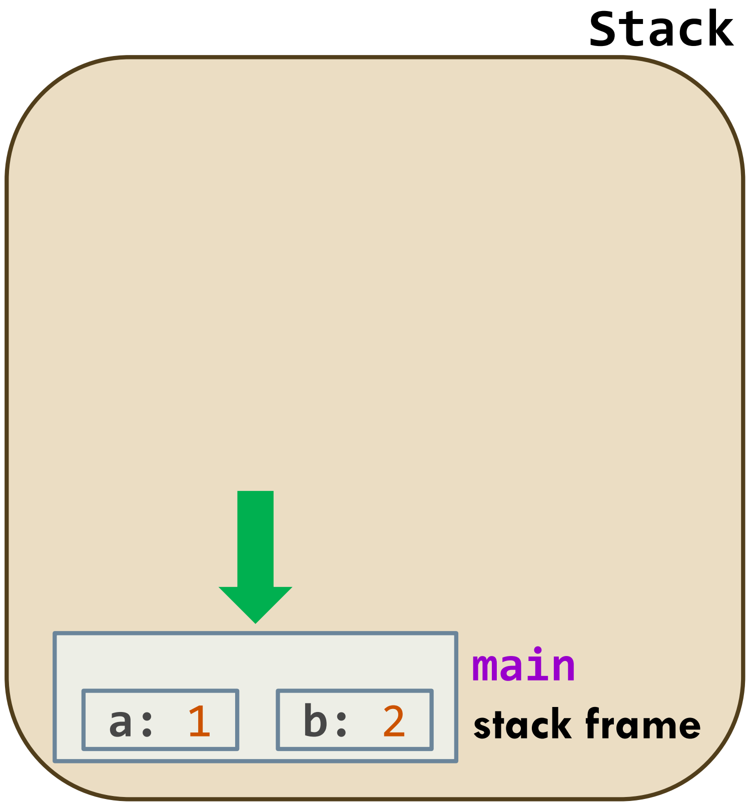

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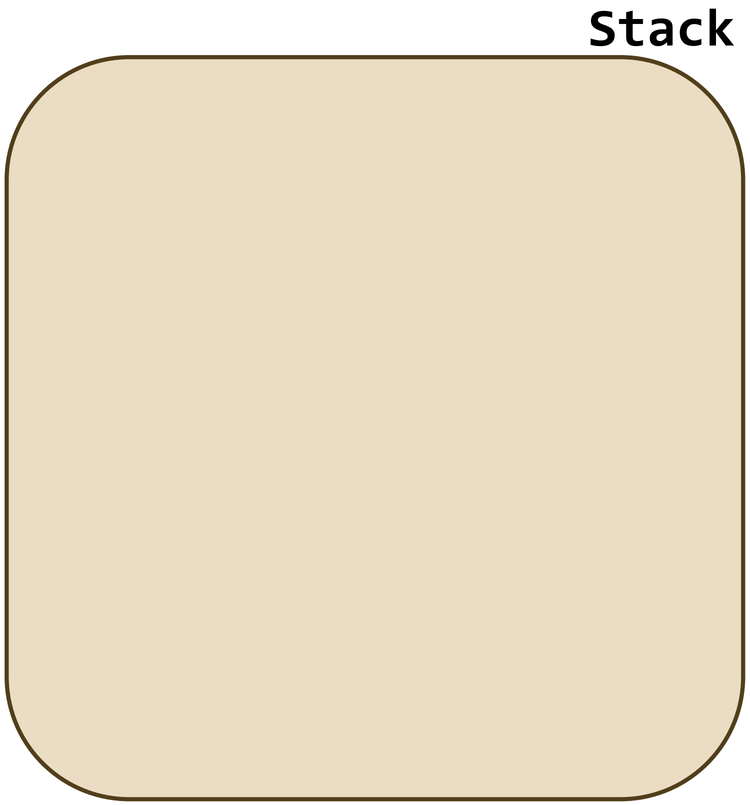

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Main takeaways:

Each function call has separate stack frame for its own copy of variables.

These variables are called ***local variables***.

Local variables are ***not visible nor accessible*** outside the scope of the function.

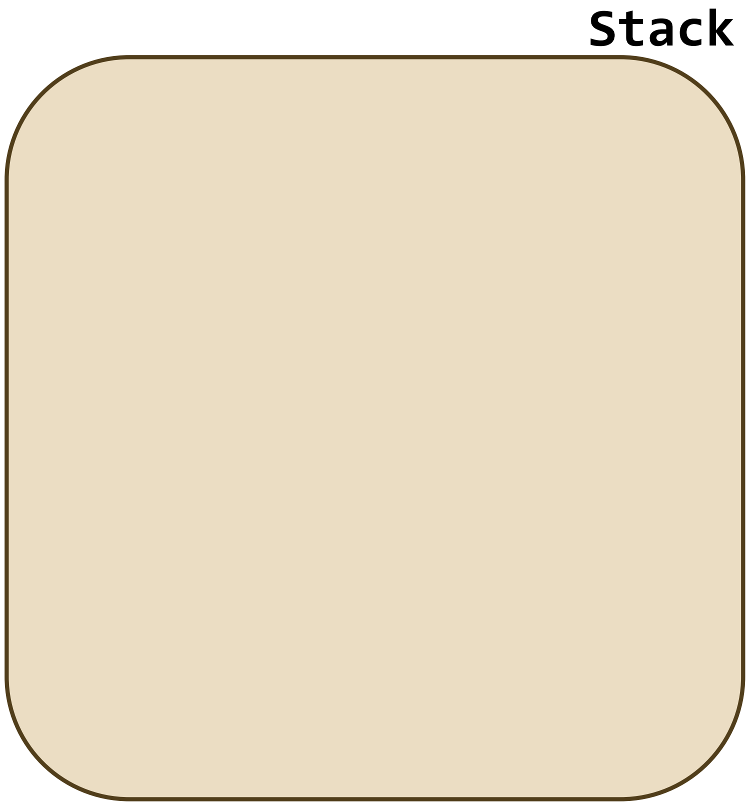
Local variables come alive when function is invoked and die when function returns.

The Stack: Limitations

```c
#include <stdio.h>

char* strfactory(char c, int n) {
  char str[6];
  for (int i = 0; i < n; ++i) {
    str[i] = c;
  }
  str[n] = '\0';
  return str;
}

int main() {
  char *ps = strfactory('z', 5);
  printf("%s", ps);
  return 0;
}
```



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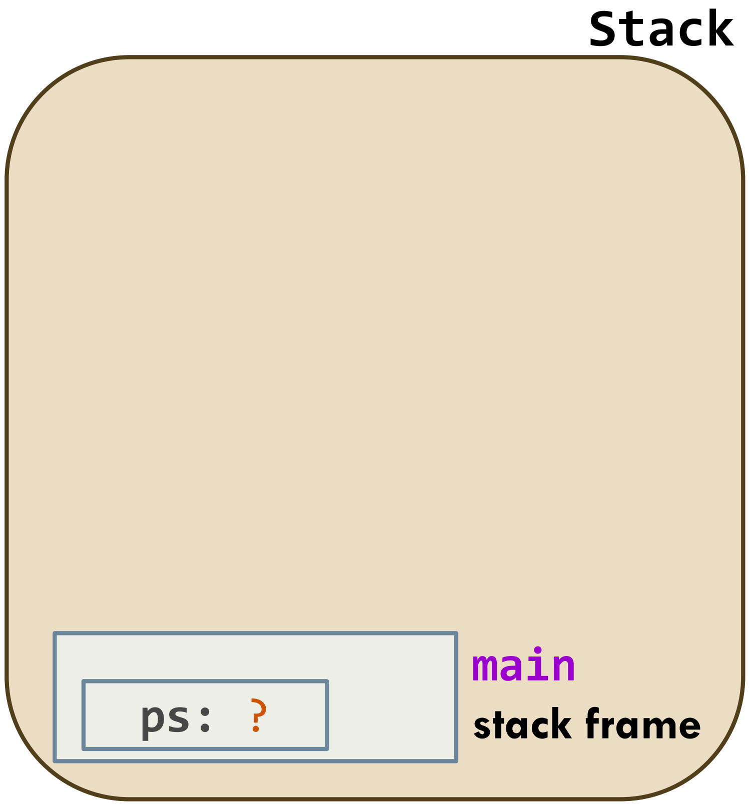

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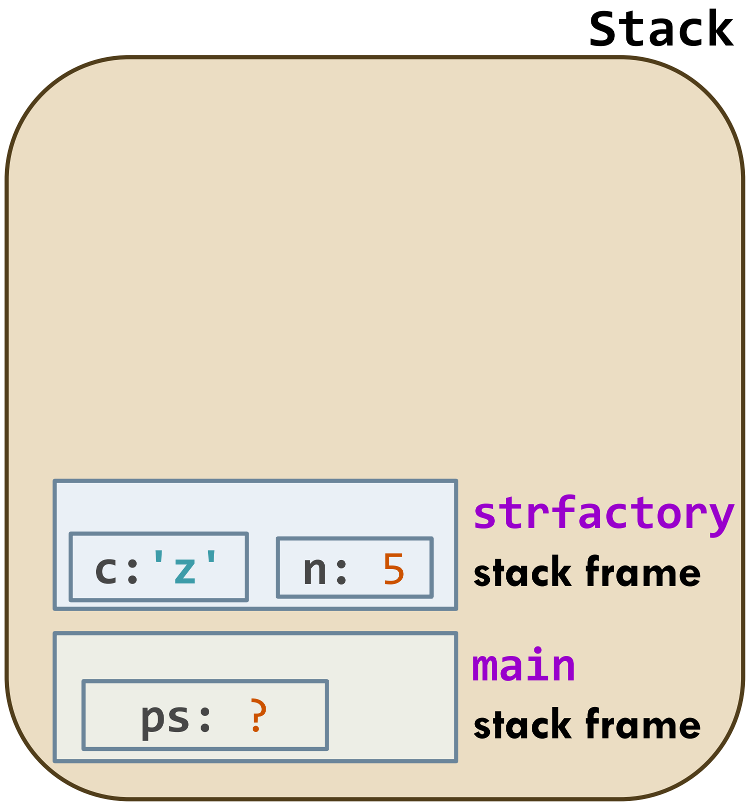

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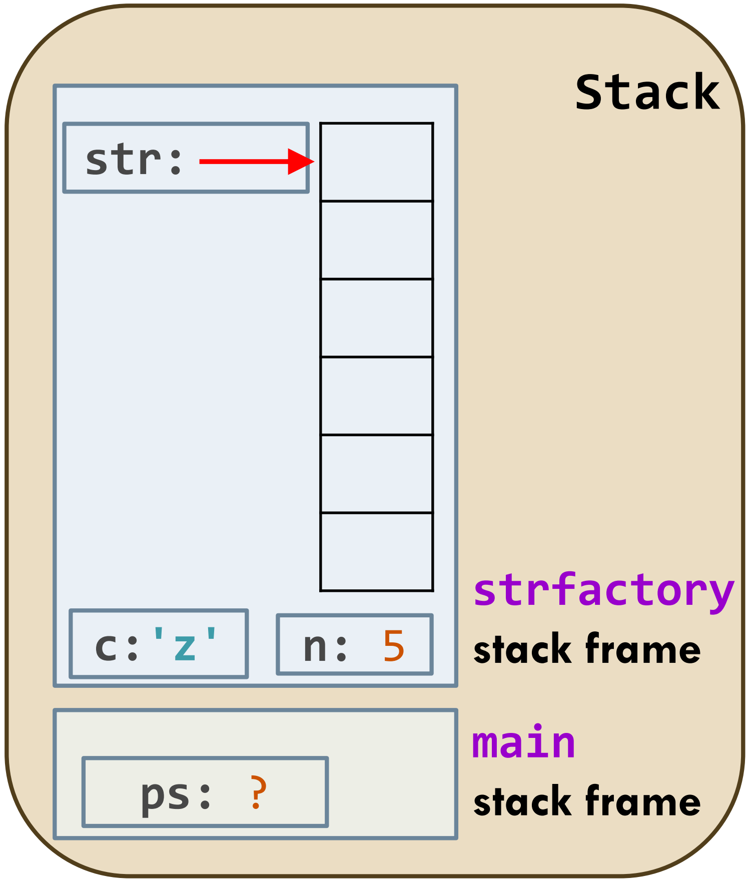

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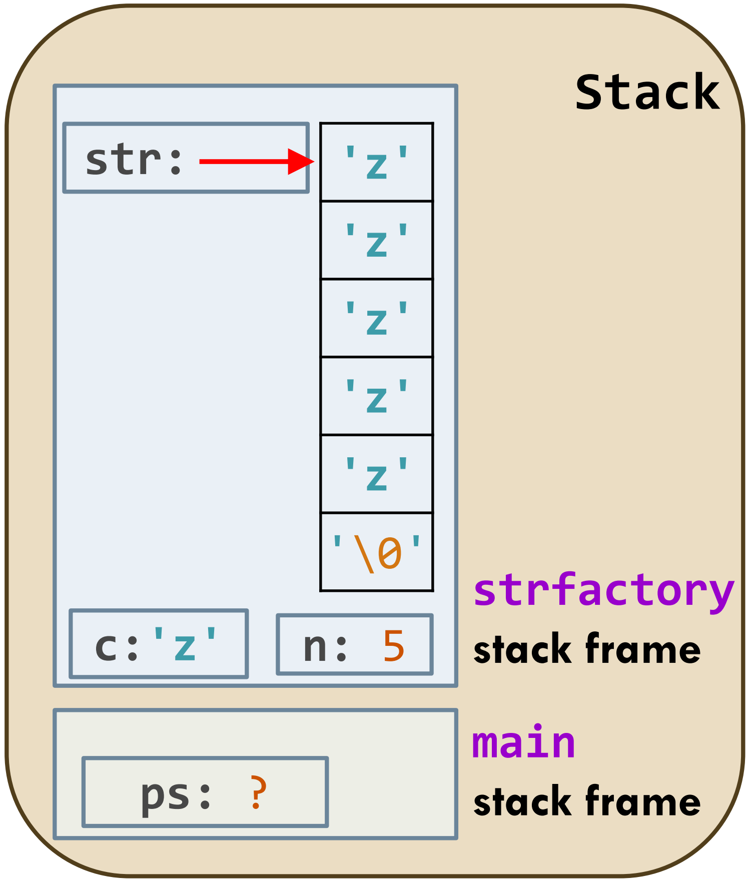

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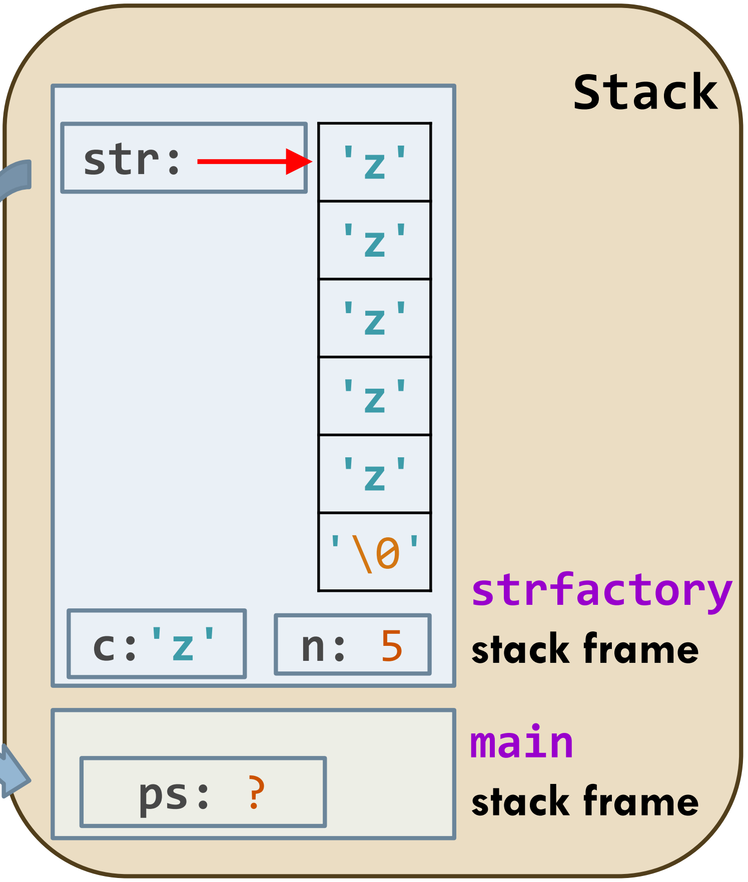
```

Returns base address of array `str` which will be used to initialize ps in `main()`



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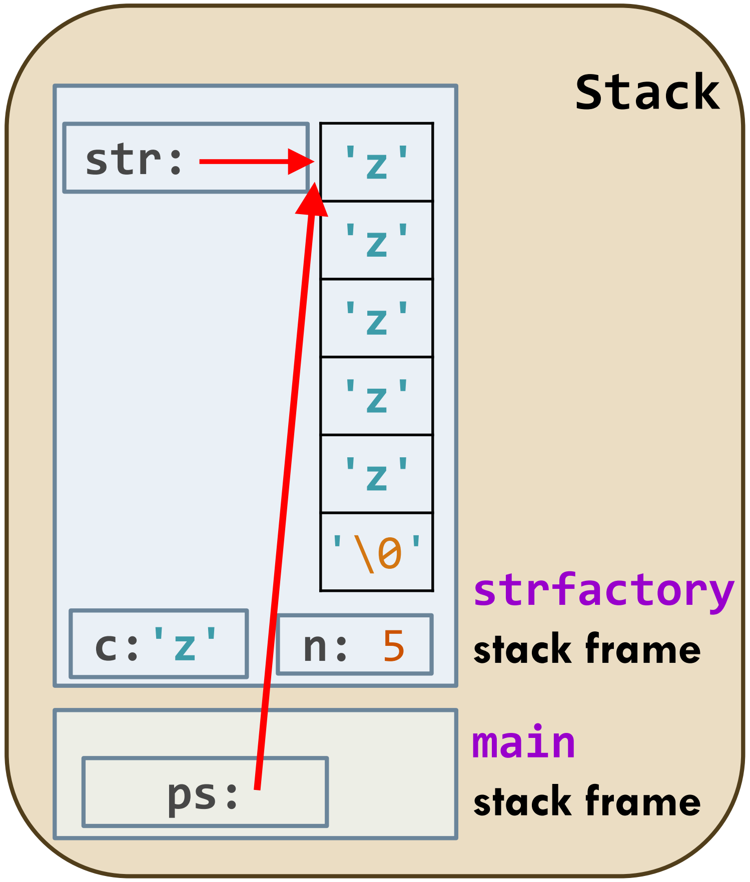

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char* strfactory(char c, int n) {
  char str[6];
  for (int i = 0; i < n; ++i) {
    str[i] = c;
  }
  str[n] = '\0';
  return str;
}

int main() {
  char *ps = strfactory('z', 5);
  printf("%s", ps);
  return 0;
}
```
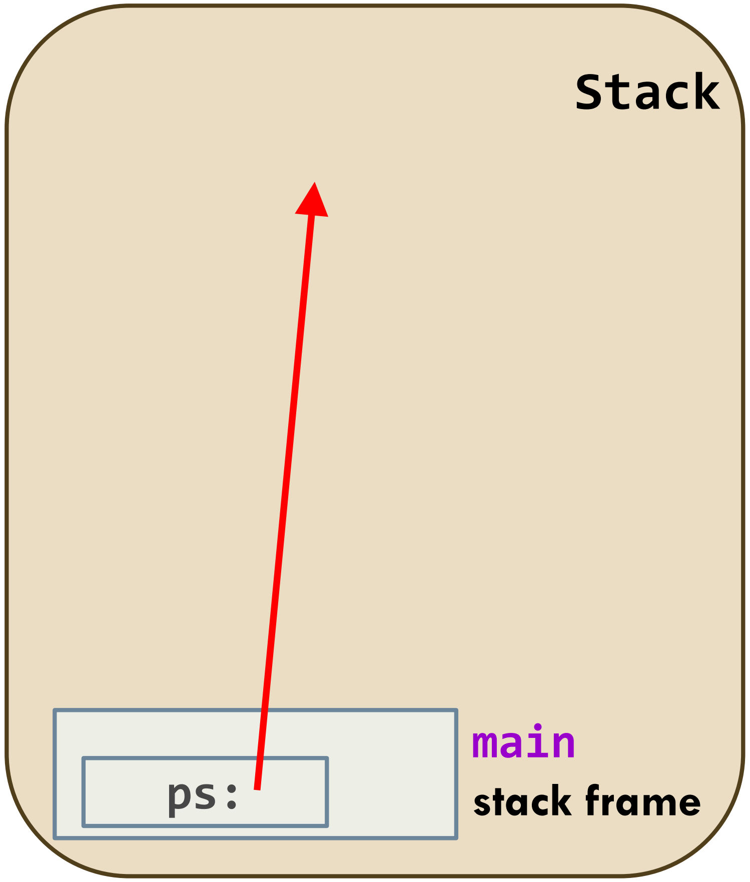
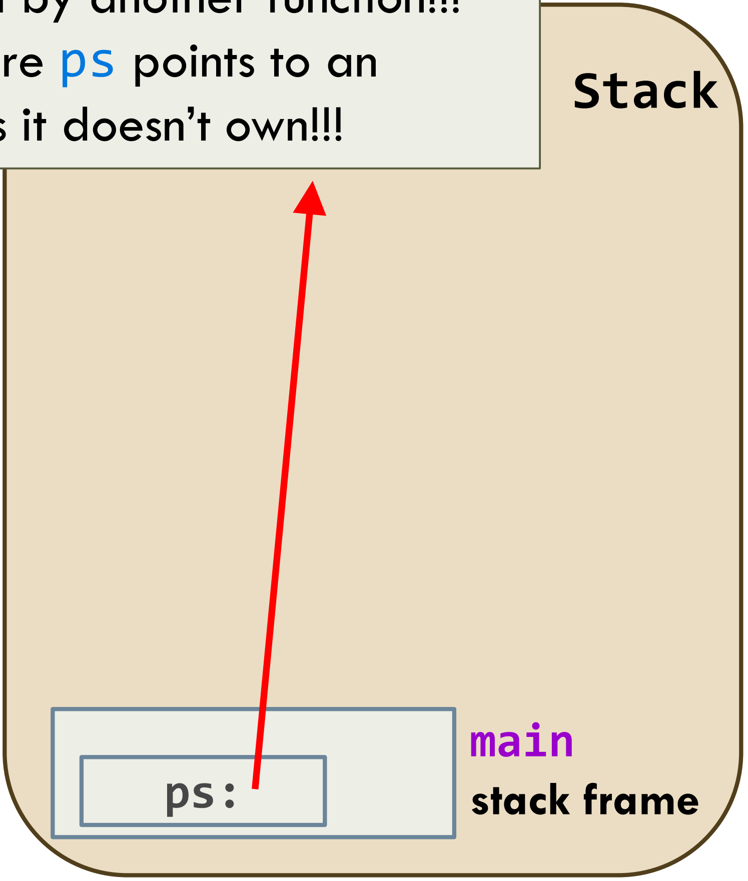



The Stack: Limitations

```
#include <stdio.h>

char* strfactory(char c, int n) {
  char str[6];
  for (int i = 0; i < n; ++i) {
    str[i] = c;
  }
  str[n] = '\0';
  return str;
}

int main() {
  char *ps = strfactory('z', 5);
  printf("%s", ps);
  return 0;
}
```

Local variables go away when function strfactory returns!!! Array str no longer exists!!! The memory exists but it will be used by another function!!! Therefore ps points to an address it doesn't own!!!



.stack segment

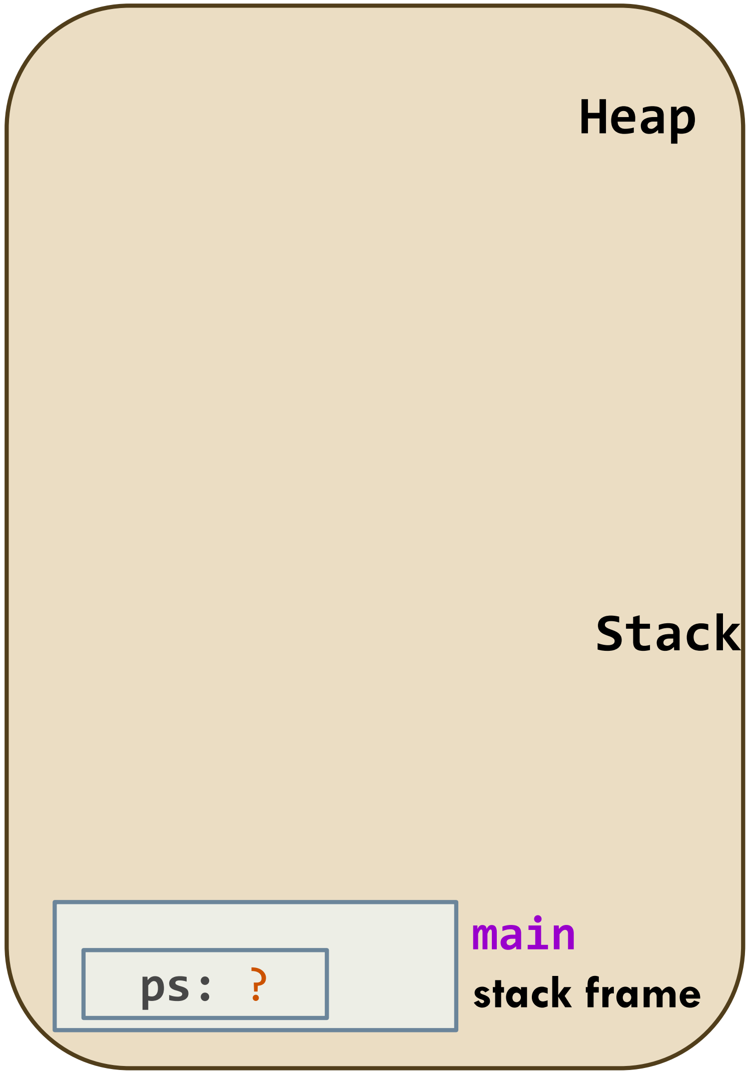
- Fact that local variables are cleaned up when function returns is sometimes a problem
- How can we have memory that exists independent of whether a function is executing or not?

.heap segment

- Part of program memory that is managed by programmer
- You grab some memory, pass address around among functions, and then you return that memory back to heap manager

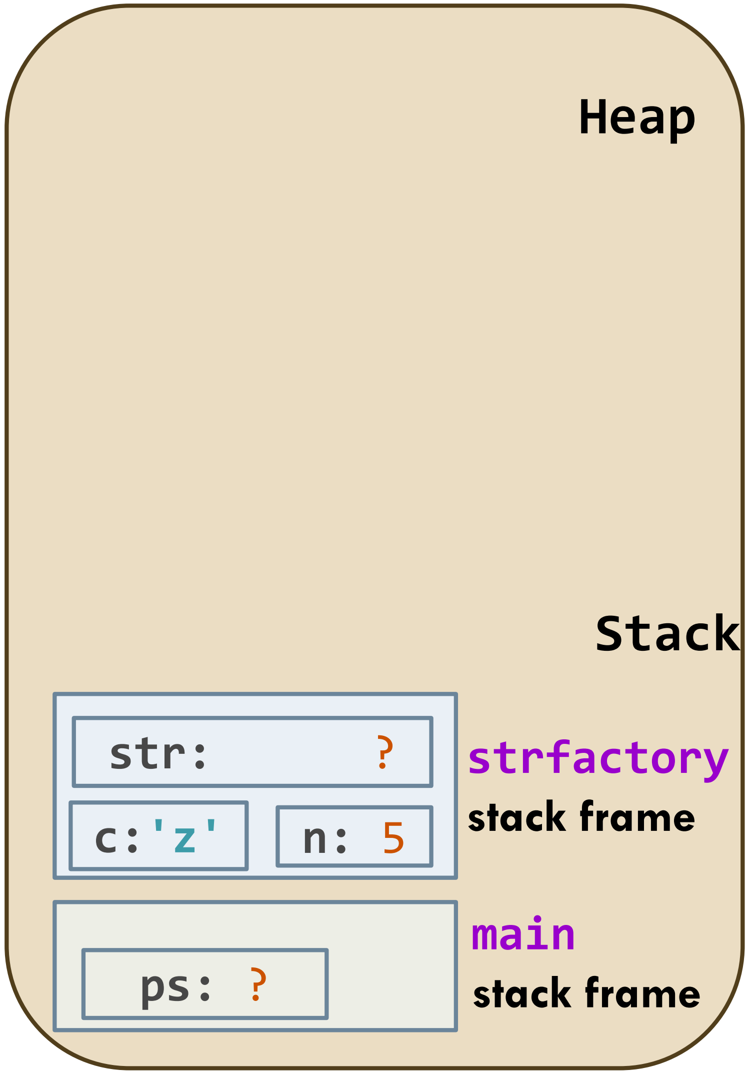
The Heap

```
#include <stdio.h>
#include <stdlib.h>

char* str_factory(char ch, int n) {
   char *str = malloc(n+1);
   for (int i = 0; i < n; ++i) {
      str[i] = ch;
   }
   str[n] = '\0';
   return str;
}

int main() {
   char *ps = str_factory('z', 5);
   printf("%s\n", ps);
   return 0;
}
```



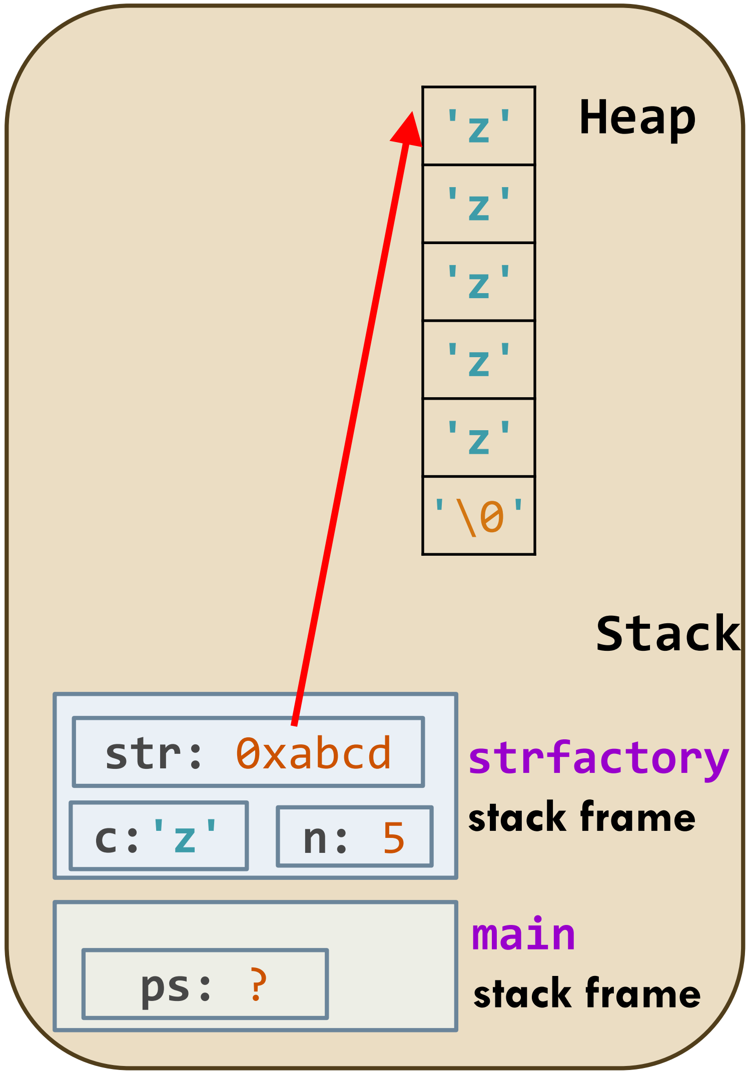
The Heap

```
#include <stdio.h>
#include <stdlib.h>

char* str_factory(char ch, int n) {
  char *str = malloc(n+1);
  for (int i = 0; i < n; ++i) {
    str[i] = ch;
  }
  str[n] = '\0';
  return str;
}

int main() {
  char *ps = str_factory('z', 5);
  printf("%s\n", ps);
  return 0;
}
```



The Heap

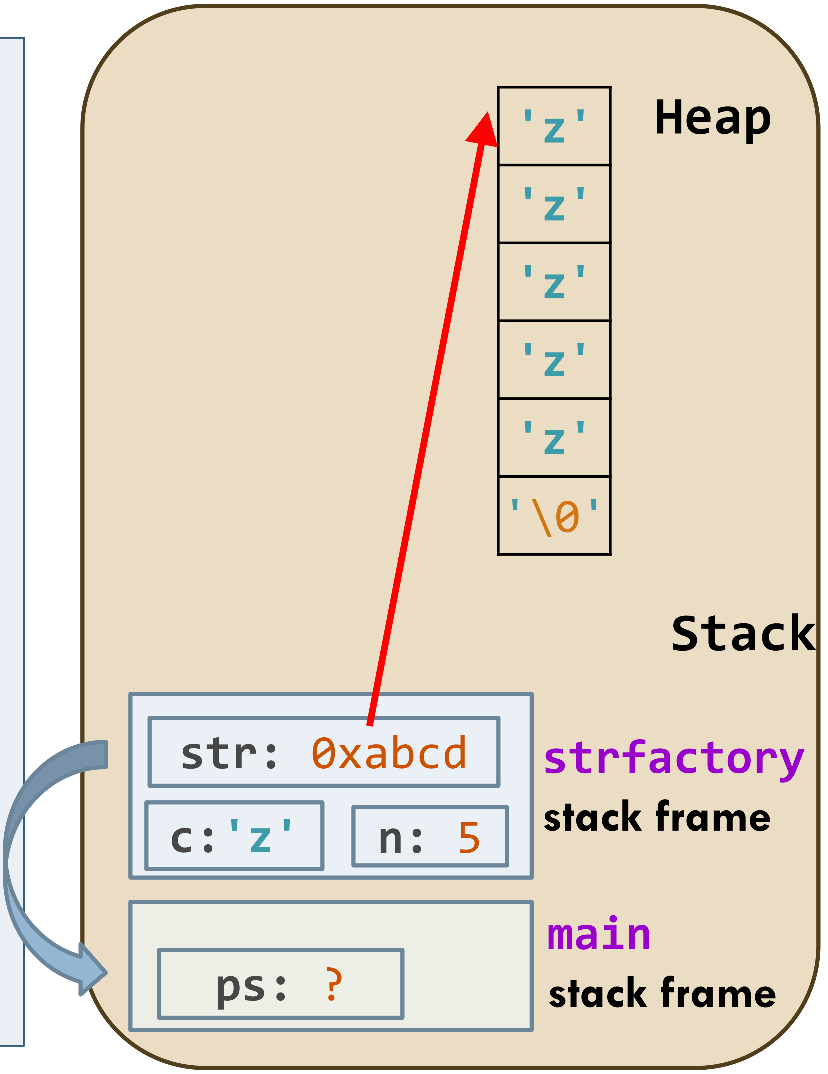
```
#include <stdio.h>
#include <stdlib.h>

char* str_factory(char ch, int n) {
  char *str = malloc(n+1);
  for (int i = 0; i < n; ++i) {
    str[i] = ch;
  }
  str[n] = '\0';
  return str;
}

int main() {
  char *ps = str_factory('z', 5);
  printf("%s\n", ps);
  return 0;
}
```



The Heap

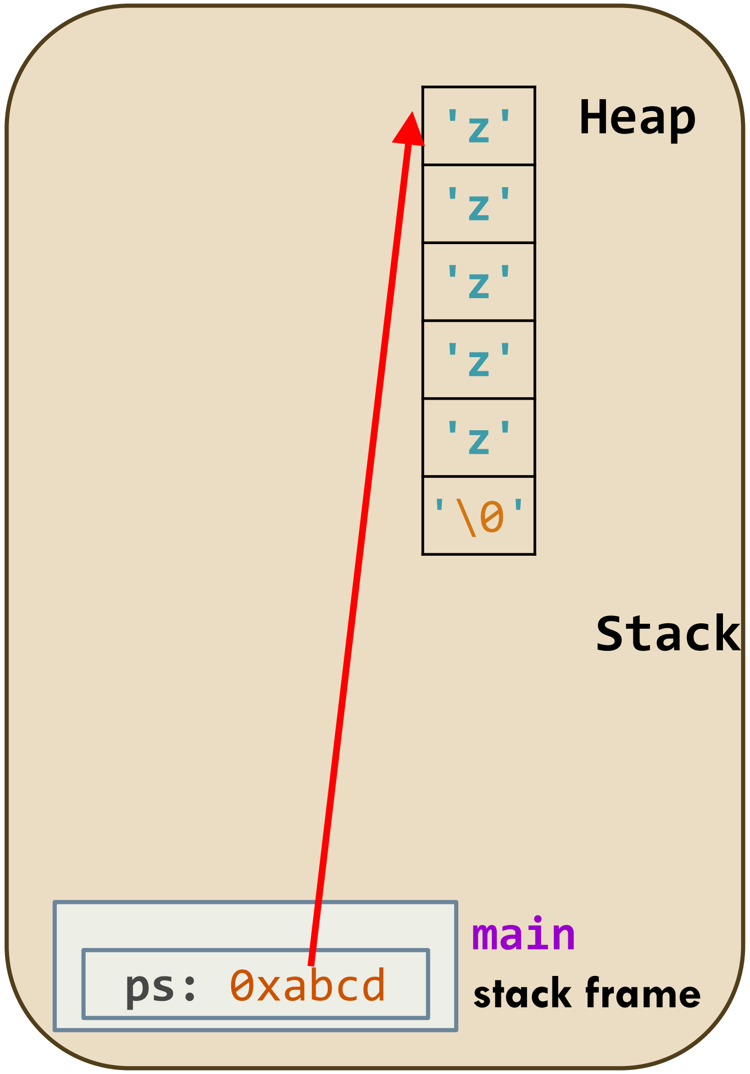
```
#include <stdio.h>
#include <stdlib.h>

char* str_factory(char ch, int n) {
  char *str = malloc(n+1);
  for (int i = 0; i < n; ++i) {
    str[i] = ch;
  }
  str[n] = '\0';
  return str;
}

int main() {
  char *ps = str_factory('z', 5);
  printf("%s\n", ps);
  return 0;
}
```

Returns address 0xabcd



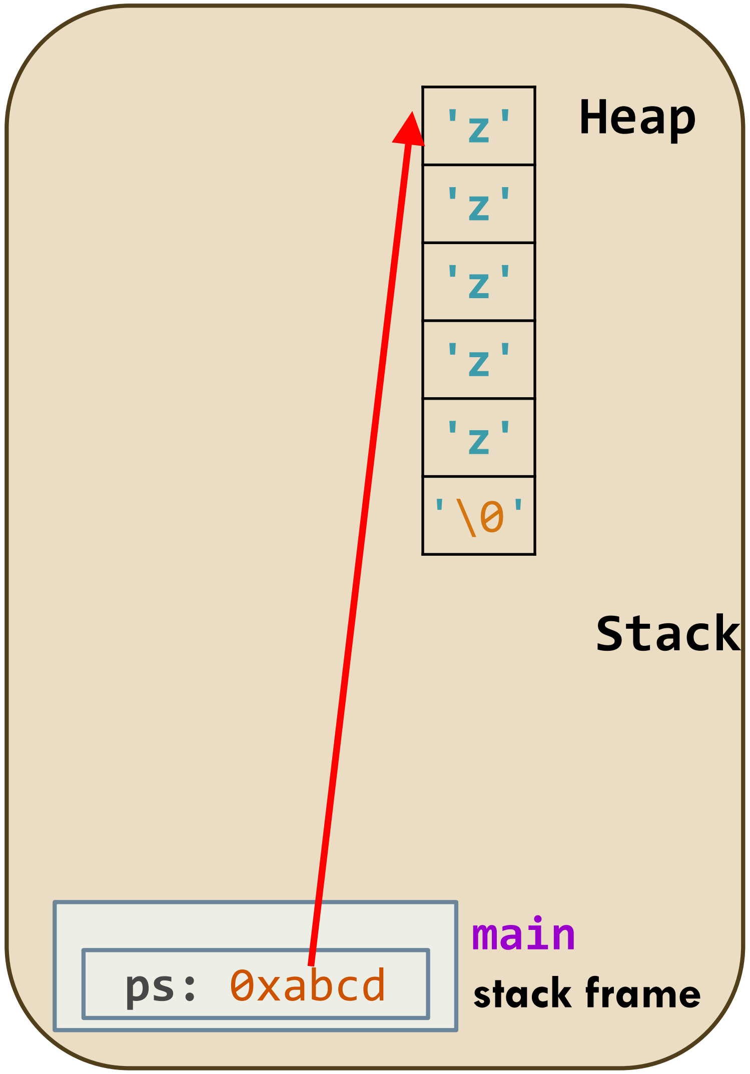
The Heap

```c
#include <stdio.h>
#include <stdlib.h>

char* str_factory(char ch, int n) {
  char *str = malloc(n+1);
  for (int i = 0; i < n; ++i) {
    str[i] = ch;
  }
  str[n] = '\0';
  return str;
}

int main() {
  char *ps = str_factory('z', 5);
  printf("%s\n", ps);
  return 0;
}
```



The Heap

```c
#include <stdio.h>
#include <stdlib.h>

char* str_factory(char ch, int n) {
  char *str = malloc(n+1);
  for (int i = 0; i < n; ++i) {
    str[i] = ch;
  }
  str[n] = '\0';
  return str;
}

int main() {
  char *ps = str_factory('z', 5);
  printf("%s\n", ps);
  return 0;
}
```



Heap Memory Allocation & Deallocation Functions

```c
// declared in <stdlib.h>

// functions for dynamically allocating heap memory
void *malloc(size_t size);
void *calloc(size_t count, size_t size);
void *realloc(void *ptr, size_t size);

// function for returning dynamically allocated
// memory back to heap
void free(void *ptr);
```

Memory Errors

- Dynamic memory is error-prone!!!
- Possible problems:
  - Leaked or orphaned memory
  - Premature deletion
  - Double deletion
  - Dereferencing uninitialized pointers
  - Accessing freed memory