ECE 264 Spring 2023

Advanced C Programming

Define New Types

```
// vector.h
#ifndef VECTOR_H
#define VECTOR_H
typedef struct
{
  int x;
  int y;
  int z;
} Vector; /* don't forget ; */
#endif
```

different data types

```
// vector.h
#ifndef VECTOR_H
#define VECTOR_H
typedef struct
{
  int x;
  int y;
  int z;
  double t;
  char name[30];
} Vector; /* don't forget ; */
#endif
```

Why to create new data type?

- Organize information better
- Distinguish data types (abstract) from instances (“objects”)
- Reduce chances of mistakes
- Simplify data passing among functions
- Improve data consistency
- (in Object-Oriented Languages) protect class data from accidental changes

```c
// vector.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  return EXIT_SUCCESS;
}
```

```c
// vector.h
#ifndef VECTOR_H
#define VECTOR_H
typedef struct
{
  int x;
  int y;
  int z;
} Vector; /* don't forget ; */
#endif
```

Symbol	Address	Value
v1.z	308	-2
v1.y	304	6
v1.x	300	3

& v1.y = & v1.x + sizeof(v1.x)

& v1.z = & v1.x + sizeof(v1.x) + sizeof(v1.y)

```c
// vector2.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  Vector v2 = {0};
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v2 = v1;
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v1.x = -4;
  v2.y = 5;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  return EXIT_SUCCESS;
}
```

```
The vector is (3, 6, -2).
The vector is (0, 0, 0).
The vector is (3, 6, -2).
The vector is (-4, 6, -2).
The vector is (3, 5, -2).
```

```c
// vector2.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  Vector v2 = {0};
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v2 = v1;
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v1.x = -4;
  v2.y = 5;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  return EXIT_SUCCESS;
}
```

Initialize all elements to zero

```
The vector is (3, 6, -2).
The vector is (0, 0, 0).
The vector is (3, 6, -2).
The vector is (-4, 6, -2).
The vector is (3, 5, -2).
```

```c
// vector2.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  Vector v2 = {0};
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v2 = v1;
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v1.x = -4;
  v2.y = 5;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  return EXIT_SUCCESS;
}
```

```
The vector is (3, 6, -2).
The vector is (0, 0, 0).
The vector is (3, 6, -2).
The vector is (-4, 6, -2).
The vector is (3, 5, -2).
```

copy the attributes from v1 to v2

= (assignment) is the only supported operator

not supported: !=, <, <=, >, >=, ++, --

```c
// vector2.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  Vector v2 = {0};
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v2 = v1;
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v1.x = -4;
  v2.y = 5;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  return EXIT_SUCCESS;
}
```

```
The vector is (3, 6, -2).
The vector is (0, 0, 0).
The vector is (3, 6, -2).
The vector is (-4, 6, -2).
The vector is (3, 5, -2).
```

changing v1.x does not change v2.x
changing v2.y does not change v1.y

```c
// vector2.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  Vector v2 = {0};
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v2 = v1;
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v1.x = -4;
  v2.y = 5;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  return EXIT_SUCCESS;
}
```

Symbol	Address	Value
v1.z	308	U
v1.y	304	U
v1.x	300	U

```c
// vector2.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  Vector v2 = {0};
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v2 = v1;
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v1.x = -4;
  v2.y = 5;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  return EXIT_SUCCESS;
}
```

Symbol	Address	Value
v1.z	308	-2
v1.y	304	6
v1.x	300	3

```c
// vector2.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  Vector v2 = {0};
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v2 = v1;
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  v1.x = -4;
  v2.y = 5;
  printf("The vector is (%d, %d, %d).\n",
         v1.x, v1.y, v1.z);
  printf("The vector is (%d, %d, %d).\n",
         v2.x, v2.y, v2.z);
  return EXIT_SUCCESS;
}
```

Symbol	Address	Value
v2.z	320	0
v2.y	316	0
v2.x	312	0
v1.z	308	-2
v1.y	304	6
v1.x	300	3

```c
// vector2.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
int main(int argc, char * argv[])
{
   Vector v1;
   v1.x = 3;
   v1.y = 6;
   v1.z = -2;
   printf("The vector is (%d, %d, %d).\n",
          v1.x, v1.y, v1.z);
   Vector v2 = {0};
   printf("The vector is (%d, %d, %d).\n",
          v2.x, v2.y, v2.z);
   v2 = v1;
   printf("The vector is (%d, %d, %d).\n",
          v2.x, v2.y, v2.z);
   v1.x = -4;
   v2.y = 5;
   printf("The vector is (%d, %d, %d).\n",
          v1.x, v1.y, v1.z);
   printf("The vector is (%d, %d, %d).\n",
          v2.x, v2.y, v2.z);
   return EXIT_SUCCESS;
}
```

```
The vector is (3, 6, -2).
The vector is (0, 0, 0).
The vector is (3, 6, -2).
The vector is (-4, 6, -2).
The vector is (3, 5, -2).
```

Symbol	Address	Value
v2.z	320	-2
v2.y	316	6
v2.x	312	3
v1.z	308	-2
v1.y	304	6
v1.x	300	3

```c
// vector4.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
void printVector(Vector v)
{
  printf("The vector is (%d, %d, %d).\n", v.x, v.y, v.z);
}

void changeVector(Vector v)
{
  v.x = 5;
  v.y = -3;
  v.z = 7;
  printVector(v);
}

int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printVector(v1);
  changeVector(v1);
  printVector(v1);
  return EXIT_SUCCESS;
}
```

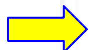
```
The vector is (3, 6, -2).
The vector is (5, -3, 7).
The vector is (3, 6, -2).
```

```c
// vector4.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
void printVector(Vector v)
{
  printf("The vector is (%d, %d, %d).\n", v.x, v.y, v.z);
}

void changeVector(Vector v)
{
  v.x = 5;
  v.y = -3;
  v.z = 7;
  printVector(v);
}

int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printVector(v1);
  changeVector(v1);
  printVector(v1);
  return EXIT_SUCCESS;
}
```

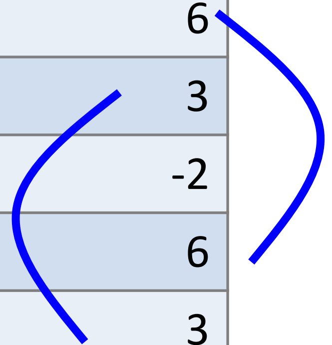
```
The vector is (3, 6, -2).
The vector is (5, -3, 7).
The vector is (3, 6, -2).
```

Vector did not change in main (remember local variables)

```c
// vector4.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
void printVector(Vector v)
{
  printf("The vector is (%d, %d, %d).\n", v.x, v.y, v.z);
}

void changeVector(Vector v)
{
  v.x = 5;
  v.y = -3;
  v.z = 7;
  printVector(v);
}

int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printVector(v1);
  changeVector(v1);
  printVector(v1);
  return EXIT_SUCCESS;
}
```



Frame	Symbol	Address	Value
changeVector	v.z	320	-2
	v.y	316	6
	v.x	312	3
main	v1.z	308	-2
	v1.y	304	6
	v1.x	300	3

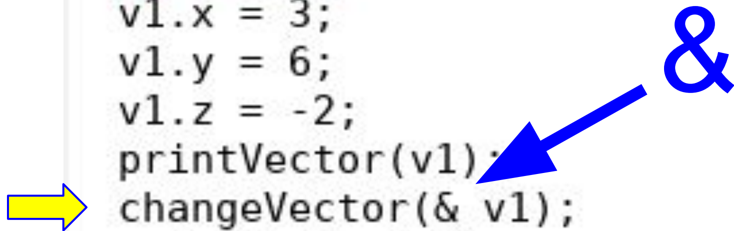


```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
void printVector(Vector v)
{
  printf("The vector is (%d, %d, %d).\n", v.x, v.y, v.z);
}

void changeVector(Vector * v)
{
  v -> x = 5;
  v -> y = -3;
  v -> z = 7;
  printVector(* v);
}

int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printVector(v1);
  changeVector(& v1);
  printVector(v1);
  return EXIT_SUCCESS;
}
```

```
The vector is (3, 6, -2).
The vector is (5, -3, 7).
The vector is (5, -3, 7).
```

Passing structure by pointer

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
void printVector(Vector v)
{
  printf("The vector is (%d, %d, %d).\n", v.x, v.y, v.z);
}

void changeVector(Vector * v)
{
  v -> x = 5;
  v -> y = -3;
  v -> z = 7;
  printVector(* v);
}

int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printVector(v1);
  changeVector(& v1);
  printVector(v1);
  return EXIT_SUCCESS;
}
```




```
The vector is (3, 6, -2).
The vector is (5, -3, 7).
The vector is (5, -3, 7).
```

Frame	Symbol	Address	Value
changeVector	v	320	A300
main	v1.z	308	-2
	v1.y	304	6
	v1.x	300	3

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
void printVector(Vector v)
{
  printf("The vector is (%d, %d, %d).\n", v.x, v.y, v.z);
}

void changeVector(Vector * v)
{
  v -> x = 5;
  v -> y = -3;
  v -> z = 7;
  printVector(* v);
}

int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printVector(v1);
  changeVector(& v1);
  printVector(v1);
  return EXIT_SUCCESS;
}
```

*

```
The vector is (3, 6, -2).
The vector is (5, -3, 7).
The vector is (5, -3, 7).
```

right hand side rule

Frame	Symbol	Address	Value
changeVector	v	320	A300
main	v1.z	308	-2
	v1.y	304	6
	v1.x	300	3

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "vector.h"
void printVector(Vector v)
{
  printf("The vector is (%d, %d, %d).\n", v.x, v.y, v.z);
}

void changeVector(Vector * v)
{
  Vector v2 = {.x = 5, .y = 7, .z = 9};
  * v = v2;
  printVector(* v);
}

int main(int argc, char * argv[])
{
  Vector v1;
  v1.x = 3;
  v1.y = 6;
  v1.z = -2;
  printVector(v1);
  changeVector(& v1);
  printVector(v1);
  return EXIT_SUCCESS;
}
```

another way to assign values

left hand side rule

right hand side rule

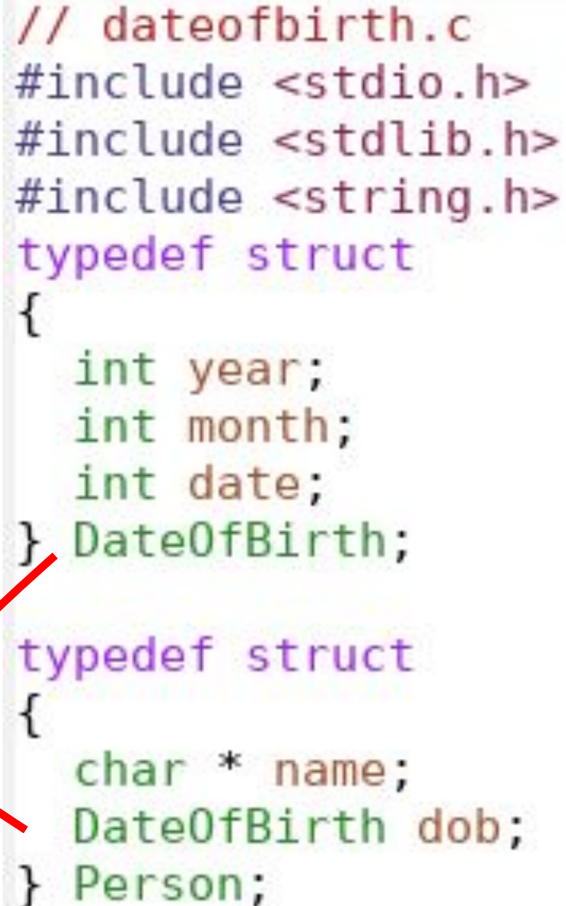
```
The vector is (3, 6, -2).
The vector is (5, 7, 9).
The vector is (5, 7, 9).
```

Syntax . and ->

- If it is a pointer, use ->
- // right hand side and left hand side rules apply
- If it is not a pointer (called “object” in this class), use .

```
Vector v; // object, not a pointer
v.x = 264;
Vector * vp = & v;
vp -> y = 2020;
```

Struct can be use in another struct

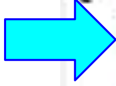


```c
// dateofbirth.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
typedef struct
{
  int year;
  int month;
  int date;
} DateOfBirth;

typedef struct
{
  char * name;
  DateOfBirth dob;
} Person;
```

```c
// vector.h
#ifndef VECTOR_H
#define VECTOR_H
typedef struct
{
  int x;
  int y;
  int z;
} Vector; /* don't forget ; */
#endif
```

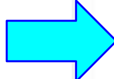
```c
#include "vector.h"
Vector * Vector_construct(int a, int b, int c)
// notice *
{
  Vector * v;
  v = malloc(sizeof(Vector));
  if (v == NULL) // allocation fail
    {
      printf("malloc fail\n");
      return NULL;
    }
  v -> x = a;
  v -> y = b;
  v -> z = c;
  return v;
}

void Vector_destruct(Vector * v)
{
  free (v);
}

void Vector_print(Vector * v)
{
  printf("The vector is (%d, %d, %d).\n",
         v -> x, v -> y, v -> z);
}
```

```c
int main(int argc, char * * argv)
{
  Vector * v1;
  v1 = Vector_construct(3, 6, -2);
  if (v1 == NULL)
    {
      return EXIT_FAILURE;
    }
  Vector_print(v1);
  Vector_destruct(v1);
  return EXIT_SUCCESS;
}
```

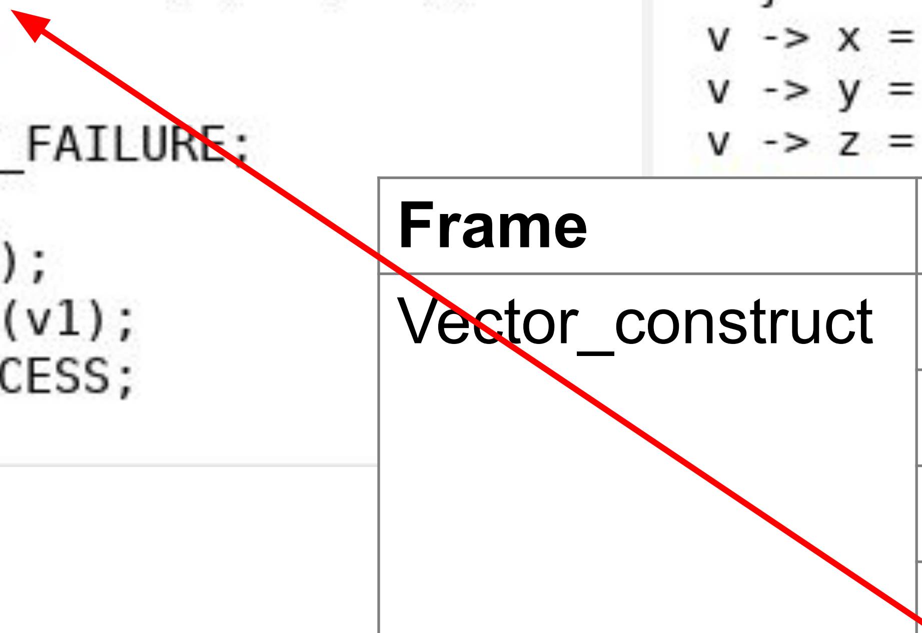


Frame	Symbol	Address	Value
main	v1	100	U

```c
#include "vector.h"
Vector * Vector_construct(int a, int b, int c)
// notice *
{
  Vector * v;
  v = malloc(sizeof(Vector));
  if (v == NULL) // allocation fail
    {
      printf("malloc fail\n");
      return NULL;
    }
  v -> x = a;
  v -> y = b;
  v -> z = c;
```



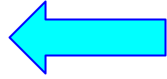
```c
int main(int argc, char * * argv)
{
  Vector * v1;
  v1 = Vector_construct(3, 6, -2);
  if (v1 == NULL)
    {
      return EXIT_FAILURE;
    }
  Vector_print(v1);
  Vector_destruct(v1);
  return EXIT_SUCCESS;
}
```



Frame	Symbol	Address	Value
Vector_construct	c	308	-2
	b	304	6
	a	300	3
	return location		
main	v1	100	U

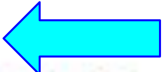
```c
      v -> x, v -> y, v -> z);
}
```

```c
#include "vector.h"
Vector * Vector_construct(int a, int b, int c)
// notice *
{
  Vector * v;
  v = malloc(sizeof(Vector));
  if (v == NULL) // allocation fail
    {
      printf("malloc fail\n");
      return NULL;
    }
  v -> x = a;
  v -> y = b;
  v -> z = c;
  return v;
}

void Vector_destruct(Vector * v)
{
  free (v);
}

void Vector_print(Vector * v)
```



Frame	Symbol	Address	Value
Vector_construct	v	312	U
	c	308	-2
	b	304	6
	a	300	3
	return location		
main	v1	100	U

```c
#include "vector.h"
Vector * Vector_construct(int a, int b, int c)
// notice *
{
  Vector * v;
  v = malloc(sizeof(Vector));
  if (v == NULL) // allocation fail
    {
      printf("malloc fail\n");
      return NULL;
    }
  v -> x = a;
  v -> y = b;
  v -> z = c;
  return v;
}

void Vector_destruct(Vector * v)
{
  free (v);
}

void Vector_print(Vector * v)
```



Heap Memory		
Symbol	Address	Value
v -> z	10008	U
v -> y	10004	U
v -> x	10000	U

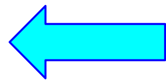
Stack Memory			
Frame	Symbol	Address	Value
Vector_construct	v	312	A10000
	c	308	-2
	b	304	6
	a	300	3
	return location		
main	v1	100	U

```c
#include "vector.h"
Vector * Vector_construct(int a, int b, int c)
// notice *
{
  Vector * v;
  v = malloc(sizeof(Vector));
  if (v == NULL) // allocation fail
    {
      printf("malloc fail\n");
      return NULL;
    }
  v -> x = a;
  v -> y = b;
  v -> z = c;
  return v;
}

void Vector_destruct(Vector * v)
{
  free (v);
}

void Vector_print(Vector * v)
```

Heap Memory		
Symbol	Address	Value
v -> z	10008	-2
v -> y	10004	6
v -> x	10000	3

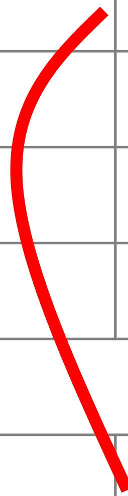
Stack Memory			
Frame	Symbol	Address	Value
Vector_construct	v	312	A10000
	c	308	-2
	b	304	6
	a	300	3
	return location		
main	v1	100	U

```
#include "vector.h"
Vector * Vector_construct(int a, int b, int c)
// notice *
{
  Vector * v;
  v = malloc(sizeof(Vector));
  if (v == NULL) // allocation fail
    {
      printf("malloc fail\n");
      return NULL;
    }
  v -> x = a;
  v -> y = b;
  v -> z = c;
  return v;
}

void Vector_destruct(Vector * v)
{
  free (v);
}

void Vector_print(Vector * v)
```



Heap Memory		
Symbol	Address	Value
v -> z	10008	-2
v -> y	10004	6
v -> x	10000	3

Stack Memory			
Frame	Symbol	Address	Value
Vector_construct	v	312	A10000
	c	308	-2
	b	304	6
	a	300	3
	return location		
main	v1	100	A10000



```c
int main(int argc, char * * argv)
{
  Vector * v1;
  v1 = Vector_construct(3, 6, -2);
  if (v1 == NULL)
    {
      return EXIT_FAILURE;
    }
  Vector_print(v1);
  Vector_destruct(v1);
  return EXIT_SUCCESS;
}
```

Heap Memory		
Symbol	Address	Value
v1 -> z	10008	-2
v1 -> y	10004	6
v1 -> x	10000	3

Frame	Symbol	Address	Value
main	v1	100	A10000

```c
int main(int argc, char * * argv)
{
  Vector * v1;
  v1 = Vector_construct(3, 6, -2);
  if (v1 == NULL)
    {
      return EXIT_FAILURE;
    }
  Vector_print(v1);
  Vector_destruct(v1);
  return EXIT_SUCCESS;
}
```

Heap Memory		
Symbol	Address	Value
v -> z	10008	-2
v -> y	10004	6
v -> x	10000	3

Frame	Symbol	Address	Value
main	v1	100	A10000

```c
int main(int argc, char * * argv)
{
  Vector * v1;
  v1 = Vector_construct(3, 6, -2);
  if (v1 == NULL)
    {
      return EXIT_FAILURE;
    }
  Vector_print(v1);
  Vector_destruct(v1);
  return EXIT_SUCCESS;
}
```

Heap Memory		
Symbol	Address	Value
v -> z	10008	-2
v -> y	10004	6
v -> x	10000	3

Frame	Symbol	Address	Value
main	v1	100	A10000

free does not change v1's value
v1's value is not NULL

```
Vector * p = NULL;
p = malloc(sizeof(Vector));
p -> x = 264; // ok
free (p);
if (p == NULL)  // will be false
…
p -> x = 2020; // segmentation fault
```

```
Vector * p = NULL;
p = malloc(sizeof(Vector));
p -> x = 264; // ok
free (& p);
```

Will this set p’s value to NULL?
No
p is a local variable on stack memory
& p is an address in stack memory

Segmentation Fault

- Computer memory is divided into units called segments.
- Each program is given some segments.
- Segmentation fault: a program intends to access (read from or write to) memory that does not belong to this program.
- Operating systems stop the program.
- To prevent segmentation fault:
  1. malloc before using
  2. do not use after free
  3. do not free twice

```c
// person.h
#ifndef PERSON_H
#define PERSON_H
typedef struct
{
  int year;
  int month;
  int date;
  char * name;
} Person;
```

```c
Person * Person_construct(char * n, int y, int m, int d)
{
  Person * p;
  p = malloc(sizeof(Person));
  if (p == NULL)
    {
      printf("malloc fail\n");
      return NULL;
    }
  p -> name = malloc(sizeof(char) * (strlen(n) + 1));
  /* + 1 for the ending character '\0' */
  strcpy(p -> name, n);
  p -> year = y;
  p -> month = m;
  p -> date = d;
  return p;
}
```

notice the order

```c
int main(int argc, char * argv[])
{
  Person * p1 = Person_construct("Amy", 1989, 8, 21);
  Person * p2 = Person_construct("Jennifer", 1991, 2, 17);
  Person * p3 = Person_copy(p1); // create p3
  Person_print(p1);
  Person_print(p2);
  Person_print(p3);
  p3 = Person_assign(p3, p2);
  Person_print(p3);
  Person_destruct(p1);
  Person_destruct(p2);
  Person_destruct(p3);
  return EXIT_SUCCESS;
}
```

```c
Person * Person_copy(Person * p)
{
  return Person_construct(p -> name, p -> year,
                          p -> month, p -> date);
}

Person * Person_assign(Person * p1, Person * p2)
{
  Person_destruct(p1);
  return Person_copy(p2);
}

void Person_print(Person * p)
{
  printf("Name: %s. ", p -> name);
  printf("Date of Birth: %d/%d/%d\n",
         p -> year, p -> month, p -> date);
}
```

```
Person * Person_construct(char * n, int y, int m, int d)
{
  Person * p;
  p = malloc(sizeof(Person));
  if (p == NULL)
    {
      printf("malloc fail\n");
      return NULL;
    }
  p -> name = malloc(sizeof(char) * (strlen(n) + 1));
  /* + 1 for the ending character '\0' */
  strcpy(p -> name, n);
  p -> year = y;
  p -> month = m;
  p -> date = d;
  return p;
}

void Person_destruct(Person * p)
{
  free (p -> name);
  free (p);
}
```

malloc earlier will be free later

```c
Person * Person_construct(char * n, int y, int m, int d)
{
  Person * p;
  p = malloc(sizeof(Person));
  if (p == NULL)
    {
      printf("malloc fail\n");
      return NULL;
    }
  p -> name = malloc(sizeof(char) * (strlen(n) + 1));
  /* + 1 for the ending character '\0' */
  strcpy(p -> name, n);
  p -> year = y;
  p -> month = m;
  p -> date = d;
  return p;
}

void Person_destruct(Person * p)
{
  free (p -> name);
  free (p);
}
```

malloc p before
malloc p -> name

free p -> name before
free p

shallow vs deep copy

If a structure has one or several pointers, be very careful about assignment.

```
Person * p1 = Person_construct("Amy", 1989, 8, 21);
Person * p2 = Person_construct("Jennifer", 1991, 2, 17);
Person * p3 = Person_copy(p1); // create p3
Person * p4 = p1;
p3 = Person_assign(p3, p2); // change p3
// different from p3 = p2?
```

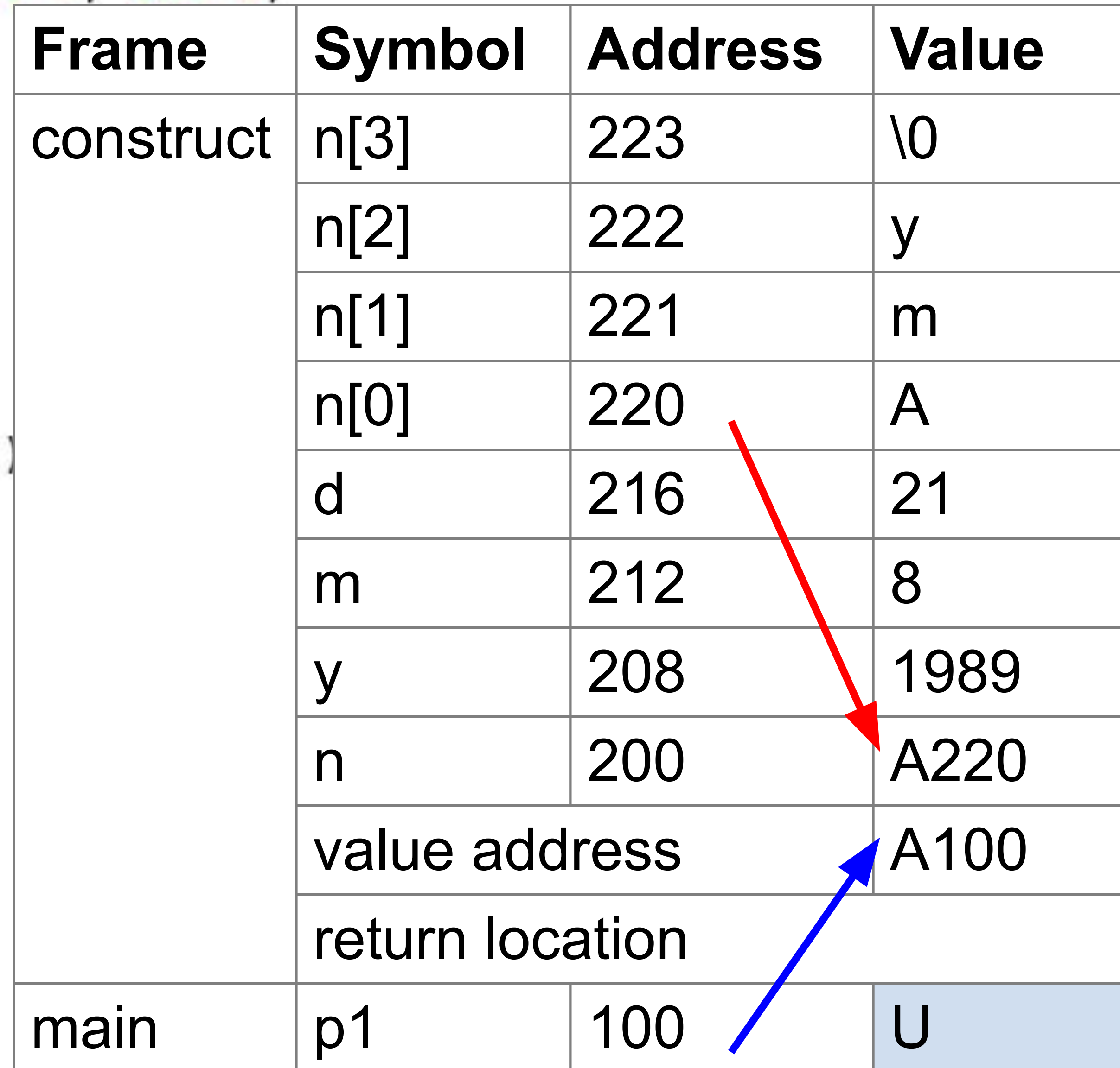
```
Person * p1 = Person_construct("Amy", 1989, 8, 21);
```

```
Person * Person_construct(char * n, int y, int m, int d)
{
  Person * p;
  p = malloc(sizeof(Person));
  if (p == NULL)
    {
      printf("malloc fail\n");
      return NULL;
    }
  p -> name = malloc(sizeof(char) * (strlen(n) + 1));
  /* + 1 for the ending character '\0' */
  strcpy(p -> name, n);
  p -> year = y;
  p -> month = m;
  p -> date = d;
  return p;
}
```

Frame	Symbol	Address	Value
main	p1	100	U

```
Person * p1 = Person_construct("Amy", 1989, 8, 21);
```

```
Person * Person_construct(char * n, int y, int m, int d)
{
  Person * p;
  p = malloc(sizeof(Person));
  if (p == NULL)
    {
      printf("malloc fail\n");
      return NULL;
    }
  p -> name = malloc(sizeof(char) * (strlen(n)
  /* + 1 for the ending character '\0' */
  strcpy(p -> name, n);
  p -> year = y;
  p -> month = m;
  p -> date = d;
  return p;
}
```



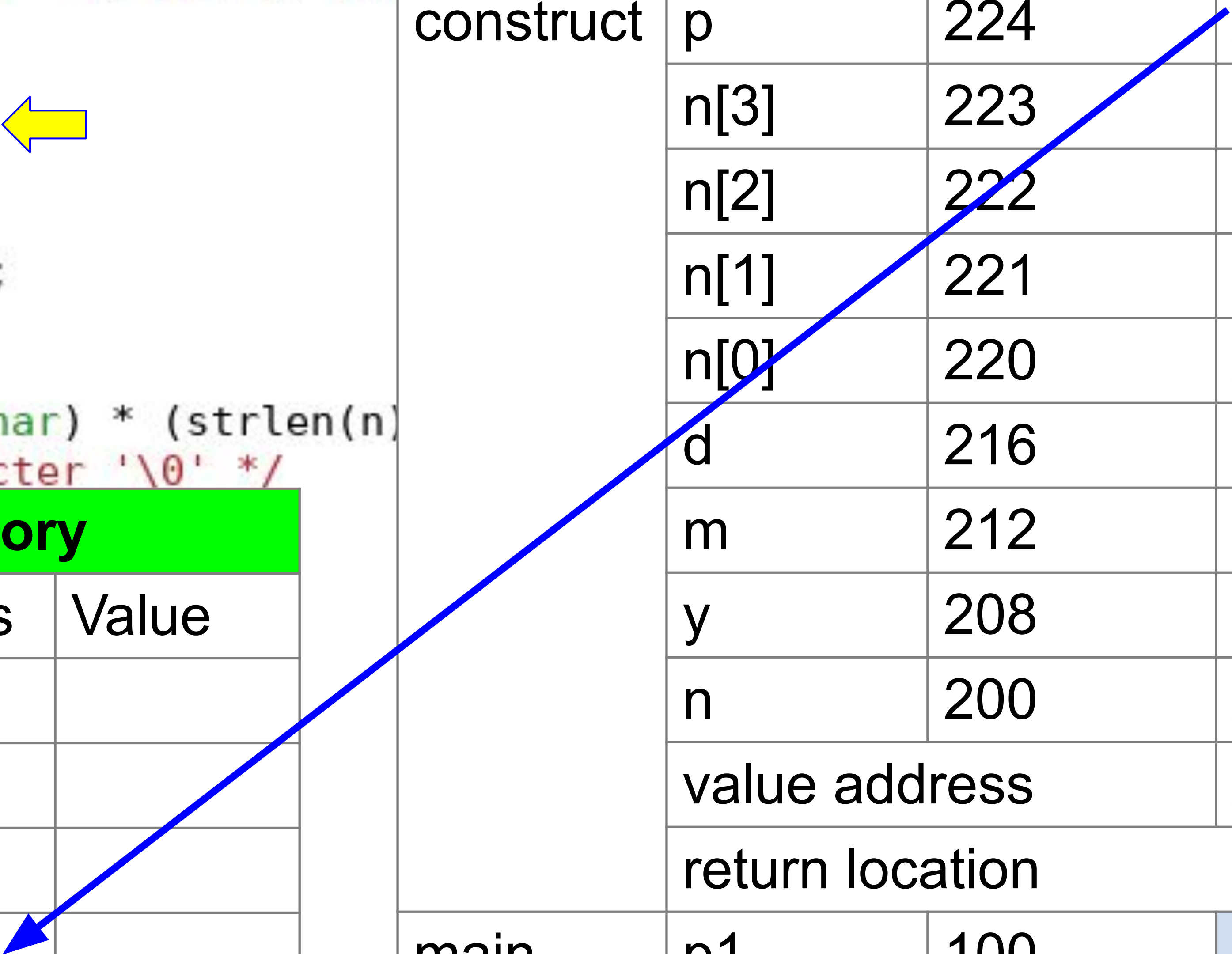
Frame	Symbol	Address	Value
construct	n[3]	223	\0
	n[2]	222	y
	n[1]	221	m
	n[0]	220	A
	d	216	21
	m	212	8
	y	208	1989
	n	200	A220
	value address		A100
	return location		
main	p1	100	U

```
Person * p1 = Person_construct("Amy", 1989, 8, 21);
```

```
Person * Person_construct(char * n, int y, int
{
  Person * p;
  p = malloc(sizeof(Person));
  if (p == NULL)
    {
      printf("malloc fail\n");
      return NULL;
    }
  p -> name = malloc(sizeof(char) * (strlen(n)
  /* + 1 for the ending character '\0' */
  strcpy(p -> name, n);
  p -> year = y;
  p -> month = m;
  p -> date = d;
  return p;
}
```

Frame	Symbol	Address	Value
construct	p	224	U
	n[3]	223	\0
	n[2]	222	y
	n[1]	221	m
	n[0]	220	A
	d	216	21
	m	212	8
	y	208	1989
	n	200	A220
	value address		A100
	return location		
main	p1	100	U

```
Person * p1 = Person_construct("Amy"

Person * Person_construct(char * n, int y, int
{
  Person * p;
  p = malloc(sizeof(Person));
  if (p == NULL)
    {
      printf("malloc fail\n");
      return NULL;
    }
  p -> name = malloc(sizeof(char) * (strlen(n)
  /* + 1 for the ending character '\0' */
  strcpy(p
  p -> yea
  p -> mon
  p -> dat
  return p
}
```



Heap Memory		
Symbol	Address	Value
p->name	10012	
p->date	10008	
p->month	10004	
p->year	10000	

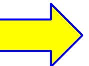
Stack Memory			
Frame	Symbol	Address	Value
construct	p	224	A10000
	n[3]	223	\0
	n[2]	222	y
	n[1]	221	m
	n[0]	220	A
	d	216	21
	m	212	8
	y	208	1989
	n	200	A220
	value address		A100
	return location		
main	p1	100	U

```
Person * p1 = Person_construct("Amy", 1989, 8, 21);
```

```
Person * Person_construct(char * n, int y, int m, int d)
{
  Person * p;
  p = malloc(sizeof(Person));
  if (p == NULL)
    {
      printf("malloc fail\n");
      return NULL;
    }
  p -> name = malloc(sizeof(char) * (strlen(n) + 1));
  /* + 1 for the ending character '\0' */
  strcpy(p -> name, n);
  p -> year = y;
  p -> month = m;
  p -> date = d;
  return p;
}
```

Heap Memory		
Symbol	Address	Value
p->name[3]	25003	
p->name[2]	25002	
p->name[1]	25001	
p->name[0]	25000	
p->name	10012	A25000
p->date	10008	
p->month	10004	
p->year	10000	

```
Person * p1 = Person_construct("Amy"

Person * Person_construct
{
  Person * p;
  p = malloc(sizeof(Perso
  if (p == NULL)
    {
      printf("malloc fail
      return NULL;
    }
  p -> name = malloc(size
  /* + 1 for the ending c
  strcpy(p -> name, n);
  p -> year = y;
  p -> month = m;
  p -> date = d;
  return p;
}
```



Heap Memory

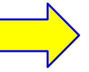
Symbol	Address	Value
p->name[3]	25003	\0
p->name[2]	25002	y
p->name[1]	25001	m
p->name[0]	25000	A
p->name	10012	A25000
p->date	10008	
p->month	10004	
p->year	10000	

Stack Memory

Frame	Symbol	Address	Value
	Symbol	Address	Value
	p	224	A10000
	n[3]	223	\0
	n[2]	222	y
	n[1]	221	m
	n[0]	220	A
	d	216	21
	m	212	8
	y	208	1989
	n	200	A220
	value address		A100
	return location		
main	p1	100	U

```
Person * p1 = Person_construct("Amy"
```

```
Person * Person_construct
{
  Person * p;
  p = malloc(sizeof(Perso
  if (p == NULL)
    {
      printf("malloc fail
      return NULL;
    }
  p -> name = malloc(size
  /* + 1 for the ending c
  strcpy(p -> name, n);
  p -> year = y;
  p -> month = m;
  p -> date = d;
  return p;
}
```



Heap Memory

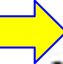
Symbol	Address	Value
p->name[3]	25003	\0
p->name[2]	25002	y
p->name[1]	25001	m
p->name[0]	25000	A
p->name	10012	A25000
p->date	10008	21
p->month	10004	8
p->year	10000	1989

Stack Memory

Frame	Symbol	Address	Value
	p	224	A10000
	n[3]	223	\0
	n[2]	222	y
	n[1]	221	m
	n[0]	220	A
	d	216	21
	m	212	8
	y	208	1989
	n	200	A220
	value address		A100
	return location		
main	p1	100	U

```
Person * p1 = Person_construct("Amy"
```

```
Person * Person_construct
{
  Person * p;
  p = malloc(sizeof(Perso
  if (p == NULL)
    {
      printf("malloc fail
      return NULL;
    }
  p -> name = malloc(size
  /* + 1 for the ending c
  strcpy(p -> name, n);
  p -> year = y;
  p -> month = m;
  p -> date = d;
  return p;
}
```

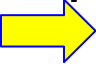


Heap Memory

Symbol	Address	Value
p->name[3]	25003	\0
p->name[2]	25002	y
p->name[1]	25001	m
p->name[0]	25000	A
p->name	10012	A25000
p->date	10008	21
p->month	10004	8
p->year	10000	1989

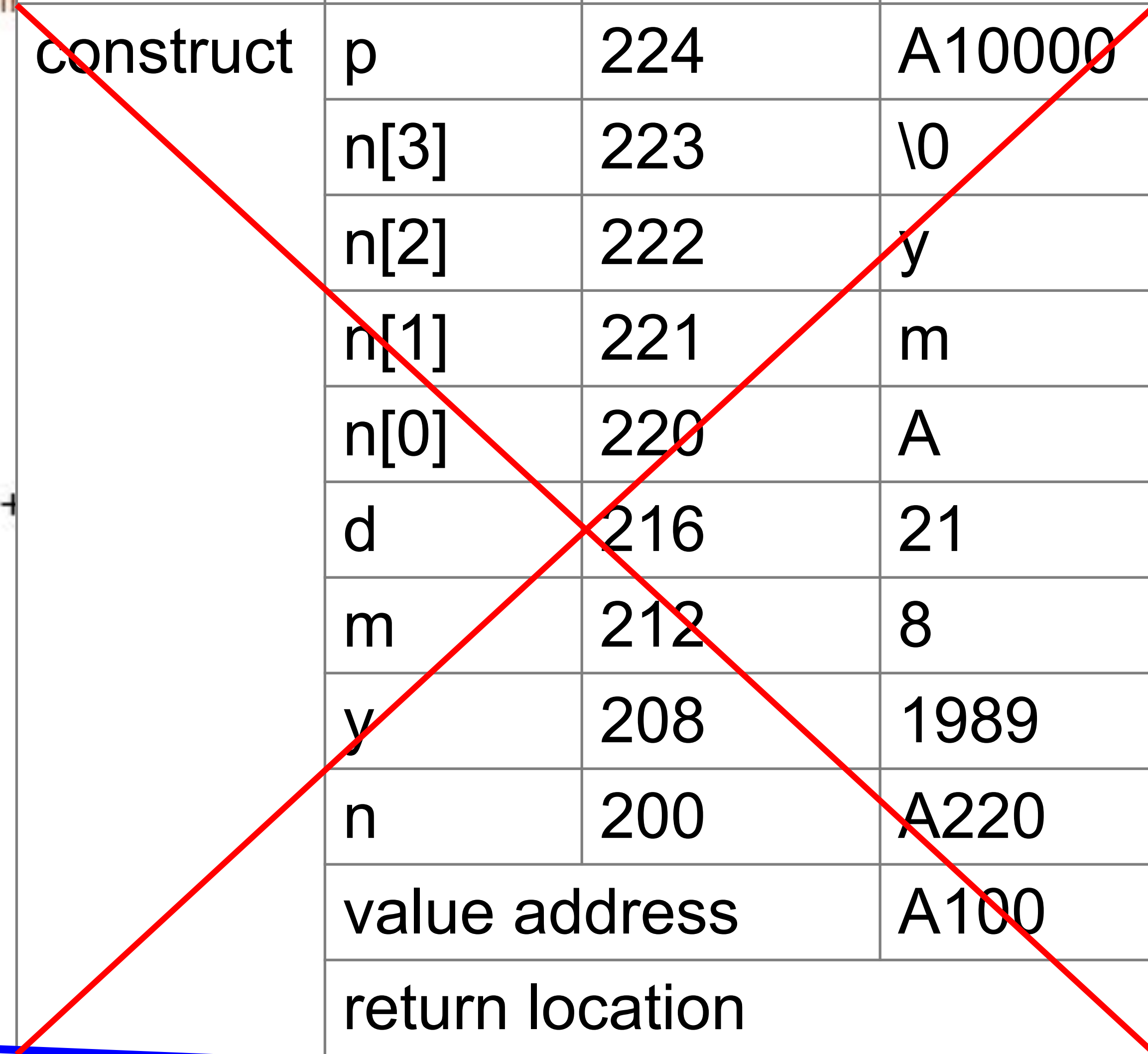
Stack Memory

Frame	Symbol	Address	Value
	Symbol	Address	Value
	p	224	A10000
	n[3]	223	\0
	n[2]	222	y
	n[1]	221	m
	n[0]	220	A
	d	216	21
	m	212	8
	y	208	1989
	n	200	A220
	value address		A100
	return location		
main	p1	100	A10000

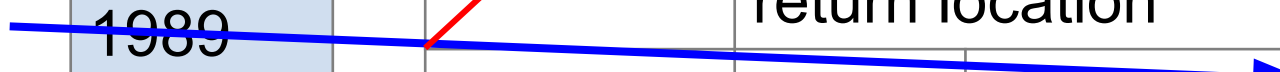


```
Person * p1 = Person_construct("Amy",

Person * Person_construct(char * n, int y, int m
{
  Person * p;
  p = mallo
  if (p ==
    {
      print
      retur
    }
  p -> name                                n) +
  /* + 1 fo
  strcpy(p
  p -> year
  p -> mont
  p -> date
  return p;
}
```

Heap Memory		
Symbol	Address	Value
p->name[3]	25003	\0
p->name[2]	25002	y
p->name[1]	25001	m
p->name[0]	25000	A
p->name	10012	A25000
p->date	10008	21
p->month	10004	8
p->year	10000	1989



Stack Memory			
Frame	Symbol	Address	Value
construct	p	224	A10000
	n[3]	223	\0
	n[2]	222	y
	n[1]	221	m
	n[0]	220	A
	d	216	21
	m	212	8
	y	208	1989
	n	200	A220
	value address		A100
	return location		
main	p1	100	A10000



```
Person * p3 = Person_copy(p1);
```

```
Person * Person_copy(Person * p)
{
  return Person_construct(p -> name, p -> year,
                          p -> month, p -> date);
}

Person * Pe                                        2)
{
  Person_de
  return Pe
}

void Person
{
  printf("N
  printf("D
        p
}
```

Heap Memory		
Symbol	Address	Value
p3->name[3]	45003	\0
p3->name[2]	45002	y
p3->name[1]	45001	m
p3->name[0]	45000	A
p3->name	20012	A45000
p3->date	20008	21
p3->month	20004	8
p3->year	20000	1989

Heap Memory		
Symbol	Address	Value
p1->name[3]	25003	\0
p1->name[2]	25002	y
p1->name[1]	25001	m
p1->name[0]	25000	A
p1->name	10012	A25000
p1->date	10008	21
p1->month	10004	8
p1->year	10000	1989

Stack Memory			
Frame	Symbol	Address	Value
main	p3	108	A20000
	p1	100	A10000

```
Person * p4 = p1;
```

Heap Memory		
Symbol	Address	Value
p->name[3]	25003	\0
p->name[2]	25002	y
p->name[1]	25001	m
p->name[0]	25000	A
p->name	10012	A25000
p->date	10008	21
p->month	10004	8
p->year	10000	1989

Stack Memory			
Frame	Symbol	Address	Value
main	p4	108	A10000
	p1	100	A10000

p1 and p4 point to the same heap memory
Changing p1 -> year changes p4 -> year

```
Person * p3 = Person_copy(p1);
Person * p4 = p1;
p3 = p4; // lose memory
```

Heap Memory		
Symbol	Address	Value
p3->name[3]	45003	\0
p3->name[2]	45002	y
p3->name[1]	45001	m
p3->name[0]	45000	A
p3->name	20012	A45000
p3->date	20008	21
p3->month	20004	8
p3->year	20000	1989

Heap Memory		
Symbol	Address	Value
p1->name[3]	25003	\0
p1->name[2]	25002	y
p1->name[1]	25001	m
p1->name[0]	25000	A
p1->name	10012	A25000
p1->date	10008	21
p1->month	10004	8
p1->year	10000	1989

Stack Memory			
Frame	Symbol	Address	Value
main	p4	116	A10000
	p3	108	A20000
	p1	100	A10000

```
Person * p3 = Person_copy(p1);
Person * p4 = p1;
p3 = p4; // lose memory
```

Heap Memory		
Symbol	Address	Value
p3->name[3]	45003	\0
p3->name[2]	45002	y
p3->name[1]	45001	m
p3->name[0]	45000	A
p3->name	20012	A45000
p3->date	20008	21
p3->month	20004	8
p3->year	20000	1989

Heap Memory		
Symbol	Address	Value
p1->name[3]	25003	\0
p1->name[2]	25002	y
p1->name[1]	25001	m
p1->name[0]	25000	A
p1->name	10012	A25000
p1->date	10008	21
p1->month	10004	8
p1->year	10000	1989

Stack Memory			
Frame	Symbol	Address	Value
main	p4	116	A10000
	p3	108	A10000
	p1	100	A10000

```
Person p1; // no *
p1.year = 2001; // . not ->
p1.month = 3;
p1.date = 9;
p1.name = strdup("Amy");
Person p2 = p1;
```

```
typedef struct
{
  int year;
  int month;
  int date;
  char * name;
} Person;
```

Heap Memory		
Symbol	Address	Value
p1.name[3]	25003	\0
p1.name[2]	25002	y
p1.name[1]	25001	m
p1.name[0]	25000	A

Stack Memory		
Symbol	Address	Value
p1.name	112	A25000
p1.date	108	9
p1.month	104	3
p1.year	100	2001

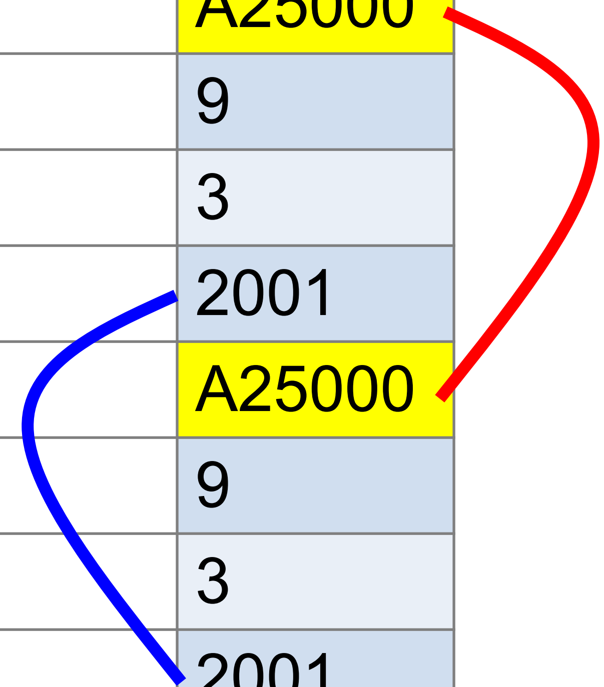
```
Person p1;
p1.year = 2001;
p1.month = 3;
p1.date = 9;
p1.name = strdup(“Amy”);
Person p2 = p1; // no *
```

Heap Memory

Symbol	Address	Value
p1.name[3]	25003	\0
p1.name[2]	25002	y
p1.name[1]	25001	m
p1.name[0]	25000	A

Stack Memory

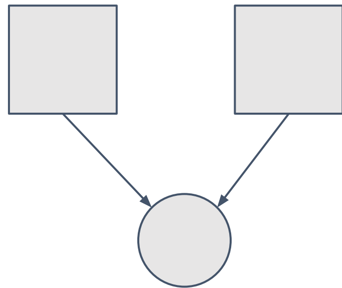
Symbol	Address	Value
p2.name	132	A25000
p2.date	128	9
p2.month	124	3
p2.year	120	2001
p1.name	112	A25000
p1.date	108	9
p1.month	104	3
p1.year	100	2001

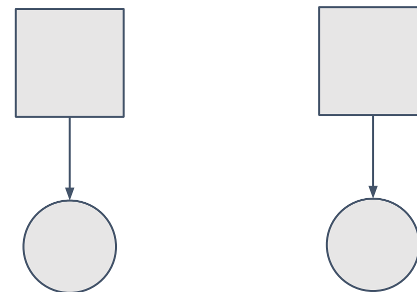


Shallow vs Deep Copy

- If a structure has one (or more) pointer, be very careful.
- Assignment (such as `p2 = p1;`) copies attribute by attribute.
- If an attribute is a pointer, two pointers refer to the same address (shallow copy).
- Shallow copy: changing p2.name[0] also changes p1.name[0]
- Deep copy: allocate memory so that they occupy different heap memory space

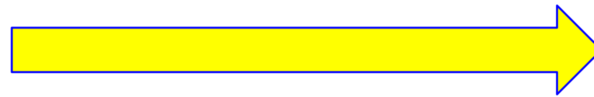
Shallow Copy	Deep Copy
point to the same heap memory	point to different heap memory
save memory space	use more memory
changing one changes the other (s)	changing one does not affect the other (s)
can be used when sharing is desired	can be used when sharing is not preferred
use case: address of employees	use case: address of children
Conclusion: Both are useful. You need to know which one to choose.	
“Copy-on-write”: beyond the scope of ECE 264.	





Homework 06
Count Occurrences of a Word

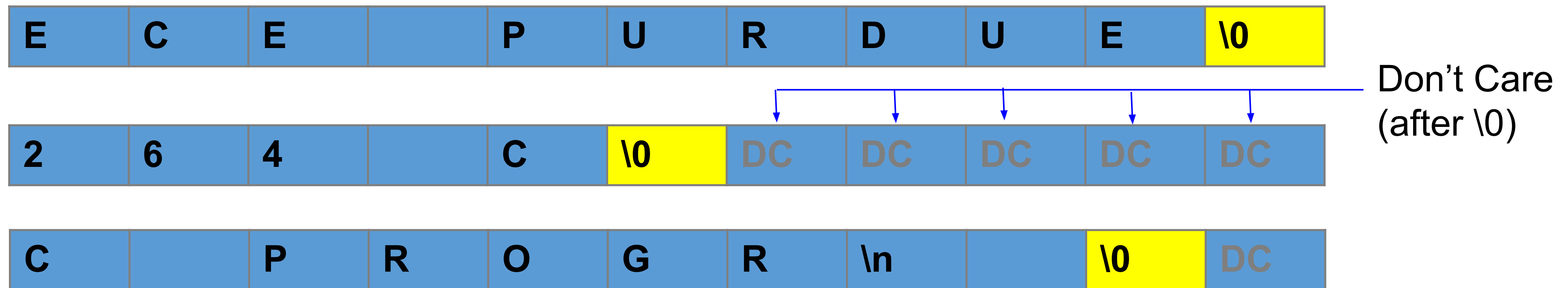
an article (in a file)
+ a word



count (a number)

Understand C Strings

- C has no “string” data type.
- C uses “array of characters + \0” as a string
- Each element can store a value between 0 and 255
- Conversion between numbers and characters based on ASCII



String Functions

```
#include <string.h>

size_t strlen(const char *s);
```

The **strlen**() function calculates the length of the string pointed to by *s*, excluding the terminating null byte ('\0').

```
char *strcpy(char *dest, const char *src);
```

The **strcpy**() function copies the string pointed to by *src*, including the terminating null byte ('\0'), to the buffer pointed to by *dest*. The strings may not overlap, and the destination string *dest* must be large enough to receive the copy. *Beware of buffer overruns!* (See BUGS.)

String Functions

The **strlen**() function calculates the length of the string pointed to by *s*, excluding the terminating null byte ('\0').

```
char *strcpy(char *dest, const char *src);
```

pay attention to the order

The **strcpy**() function copies the string pointed to by *src*, including the terminating null byte ('\0'), to the buffer pointed to by *dest*. The strings may not overlap, and the destination string *dest* must be large enough to receive the copy. *Beware of buffer overruns!* (See BUGS.)

C array is always a pointer

```
char * arr1;
arr1 = malloc(sizeof(char) * 20);
  // arr1 stores the address of the first element
strcpy(arr1, “Purdue ECE”);
char arr2[20];
  // arr2 is equivalent to & arr2[0];
  // i.e., address of the first element
  // cannot free (arr2)
free (arr1);
```

Double quotation automatically add ‘\0’

A pointer may not be an array

```
char ch = ‘A’;
char * p;
p = & ch; // a pointer, but there is no array
```

strcpy, not overlap

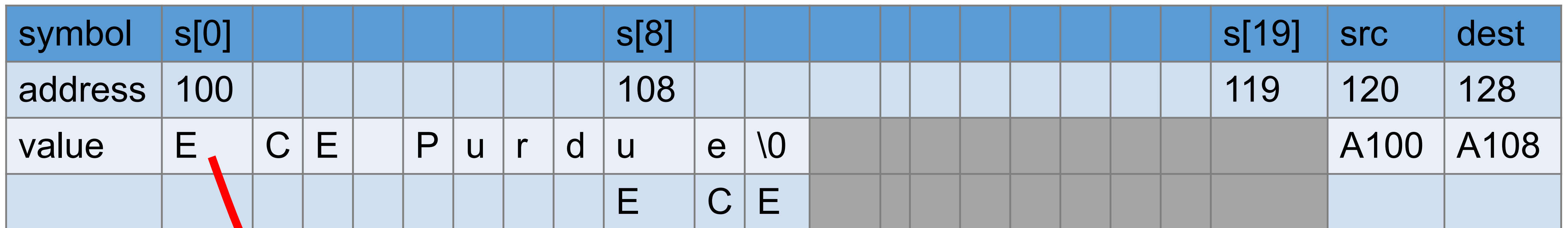
The **strcpy**() function copies the string pointed to by *src*, including the terminating null byte ('\0'), to the buffer pointed to by *dest*. The strings may not overlap, and the destination string *dest* must be large enough to receive the copy. *Beware of buffer overruns!* (See BUGS.)

```
char s[20];
strcpy(s, “ECE Purdue”);
char * src = & s[0];
char * dest = & s[8];
```

```
char s[20];
strcpy(s, "ECE Purdue");
char * src = & s[0];
char * dest = & s[8];
```

symbol	s[0]								s[8]										s[19]	src	dest
address	100								108										119	120	128
value	E	C	E		P	u	r	d	u	e	\0									A100	A108

```c
char s[20];
strcpy(s, “ECE Purdue”);
char * src = & s[0];
char * dest = & s[8];
strcpy(dest, src);
```



symbol	s[0]								s[8]											s[19]	src	dest
address	100								108											119	120	128
value	E	C	E		P	u	r	d	u	e	\0										A100	A108
									E	C	E											

String Functions

The **strlen**() function calculates the length of the string pointed to by *s*, excluding the terminating null byte ('\0').

```
char *strcpy(char *dest, const char *src);
```

The **strcpy**() function copies the string pointed to by *src*, including the terminating null byte ('\0'), to the buffer pointed to by *dest*. The strings may not overlap, and the destination string *dest* must be large enough to receive the copy. *Beware of buffer overruns!* (See BUGS.)

const in argument

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

void func(int * a, int * b)
{
  int t = * a;
  *a = * b;
  *b = t;
}

int main(int argc, char * * argv)
{
  int x = 123;
  int y = -456;
  func(&x, & y);
  printf("x = %d, y = %d\n", x, y);
  return EXIT_SUCCESS;
}
```

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

void func(int * a, const int * b)
{
  int t = * a;
  *a = * b;
  *b = t;
}

int main(int argc, char * * argv)
{
  int x = 123;
  int y = -456;
  func(&x, & y);
  printf("x = %d, y = %d\n", x, y);
  return EXIT_SUCCESS;
}
```

```
bash-4.2$ gcc const1.c
const1.c: In function ‘func’:
const1.c:8:3: error: assignment of read-only location ‘*b’
   *b = t;
   ^
```

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

void func(int * a, const int * b)
{
  int t = * a;
  *a = * b;
  b = a;
  *b = t;
}

int main(int argc, char * * argv)
{
  int x = 123;
  int y = -456;
  func(&x, & y);
  printf("x = %d, y = %d\n", x, y);
  return EXIT_SUCCESS;
}
```

this is ok

this is not allowed (cannot use the LHS rule)

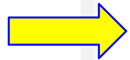
```c
#include <stdio.h>
#include <stdlib.h>

void func(int * a, const int * b)
{
  int t = * a;
  *a = * b;
  b = a;
  *b = t;
}

int main(int argc, char * * argv)
{
  int x = 123;
  int y = -456;
  func(&x, & y);
  printf("x = %d, y = %d\n", x, y);
  return EXIT_SUCCESS;
}
```

Frame	Symbol	Address	Value
func	t	212	123
	b	208	A104
	a	200	A100
main	y	104	-456
	x	100	123

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

void func(int * a, const int * b)
{
  int t = * a;
  *a = * b;
  b = a;
  *b = t;
}

int main(int argc, char * * argv)
{
  int x = 123;
  int y = -456;
  func(&x, & y);
  printf("x = %d, y = %d\n", x, y);
  return EXIT_SUCCESS;
}
```

Frame	Symbol	Address	Value
func	t	212	123
	b	208	A104
	a	200	A100
main	y	104	-456
	x	100	~~123~~ -456

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

void func(int * a, const int * b)
{
  int t = * a;
  *a = * b;
  b = a;
  *b = t;
}

int main(int argc, char * * argv)
{
  int x = 123;
  int y = -456;
  func(&x, & y);
  printf("x = %d, y = %d\n", x, y);
  return EXIT_SUCCESS;
}
```



Frame	Symbol	Address	Value
func	t	212	123
	b	208	**A100**
	a	200	A100
main	y	104	-456
	x	100	-456

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

void func(const int * b)
{
  int * t = b;
  * t = 264;
}

int main(int argc, char * * argv)
{
  int y = -456;
  func(& y);
  printf("y = %d\n", y);
  return EXIT_SUCCESS;
}
```

```
bash-4.2$ gcc const2.c
const2.c: In function ‘func’:
const2.c:6:13: error: initialization discards ‘const’ qualifier from pointer target type [-Werror]
   int * t = b;
             ^
```

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

void func(const int * b)
{
  const int * t = b;
  * t = 264;
}

int main(int argc, char * * argv)
{
  int y = -456;
  func(& y);
  printf("y = %d\n", y);
  return EXIT_SUCCESS;
}
```

```
bash-4.2$ gcc const2.c
const2.c: In function ‘func’:
const2.c:7:3: error: assignment of read-only location ‘*t’
   * t = 264;
   ^
```

```
char *strdup(const char *s);
```

The *strdup*() function shall return a pointer to a new string, which is a duplicate of the string pointed to by *s*. The returned pointer can be passed to *free*(). A null pointer is returned if the new string cannot be created.

```
char *strstr(const char *haystack, const char *needle);
```

The **strstr**() function finds the first occurrence of the substring *needle* in the string *haystack*. The terminating null bytes ('\0') are not compared.

```
char *strdup(const char *s);
```

The *strdup*() function shall return a pointer to a new string, which is a duplicate of the string pointed to by *s*. The returned pointer can be passed to *free*(). A null pointer is returned if the new string cannot be created.

```
char *strstr(const char *haystack, const char *needle);
```

The **strstr**() function finds the first occurrence of the substring *needle* in the string *haystack*. The terminating null bytes ('\0') are not compared.

‘\0’ in string

- The array must have space to store this special character
- strelen does not count it

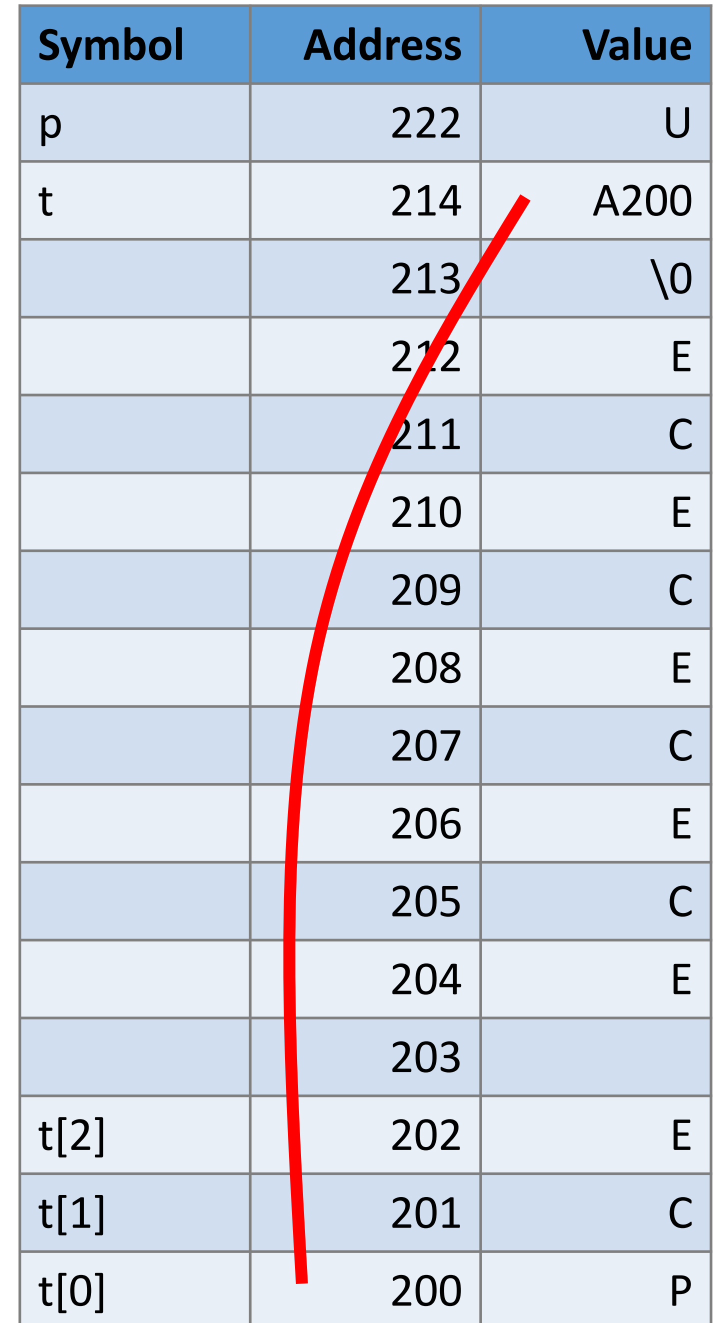
```
char * mystrdup(const char * src)
{
   char * p = malloc(sizeof(char) * (strlen(src) + 1));
   strcpy(p, src);
   return p;
}
```

without + 1,
program behavior undefined

for ‘\0’

strstr

```
char *t = “PCE ECECECECE”;
// How many ECE does t have?
// Does “ECECE” count as one or two?
char * p;
p = strstr(t, “ECE”);
```



Symbol	Address	Value
p	222	U
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

strstr

```
char *t = "PCE ECECECECE";
// How many ECE does t have?
// Does "ECECE" count as one or two?
char * p;
p = strstr(t, "ECE");
```

Symbol	Address	Value
p	222	A204
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

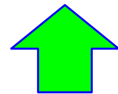
strstr

```
char *t = “PCE ECECECECE”;
// How many ECE does t have?
// Does “ECECE” count as one or two?
char * p;
p = strstr(t, “ECE”);
p = strstr(t, “ECE”); // p is 204
```

Symbol	Address	Value
p	222	A204
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

strstr

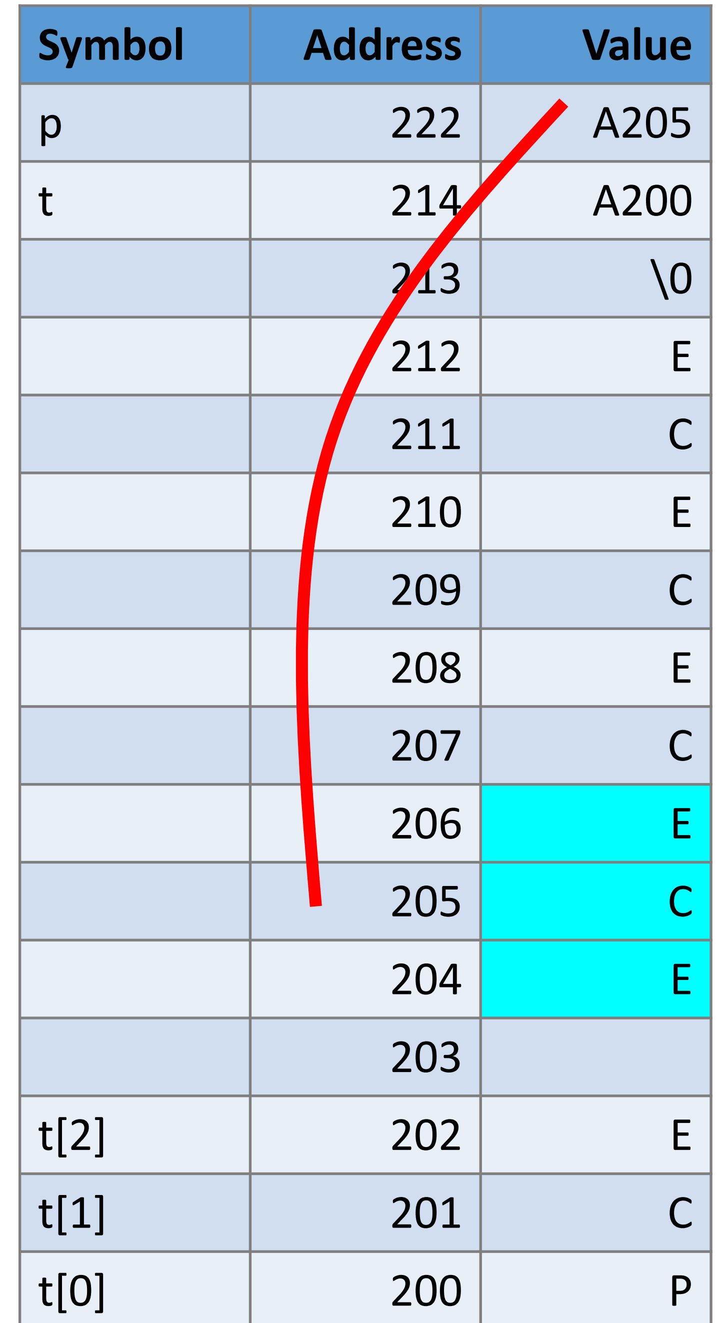
```
char *t = “PCE ECECECECE”;
// How many ECE does t have?
// Does “ECECE” count as one or two?
char * p;
p = strstr(t, “ECE”);
p = strstr(p, “ECE”); // p is 204
```



Symbol	Address	Value
p	222	A204
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

strstr

```
char *t = “PCE ECECECECE”;
// How many ECE does t have?
// Does “ECECE” count as one or two?
char * p;
p = strstr(t, “ECE”);
p ++;
```



Symbol	Address	Value
p	222	A205
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

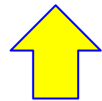
strstr

```
char *t = “PCE ECECECECE”;
// How many ECE does t have?
// Does “ECECE” count as one or two?
char * p;
p = strstr(t, “ECE”);
p ++;
char * q = p;
```

Symbol	Address	Value
q	230	A205
p	222	A206
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

strstr

```
char *t = “PCE ECECECECE”;
// How many ECE does t have?
// Does “ECECE” count as one or two?
char * p;
p = strstr(t, “ECE”);
p ++;
char * q = p;
p = strstr(q, “ECE”); // not t
```



Symbol	Address	Value
q	230	A205
p	222	A206
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

```
char *t = “PCE ECECECECE”;
// How many ECE does t have?
// Does “ECECE” count as one or two?
char * p;
p = strstr(t, “ECE”);
p ++;
char * q = p;
p = strstr(q, “ECE”); // not t
p ++;
q = p;
```

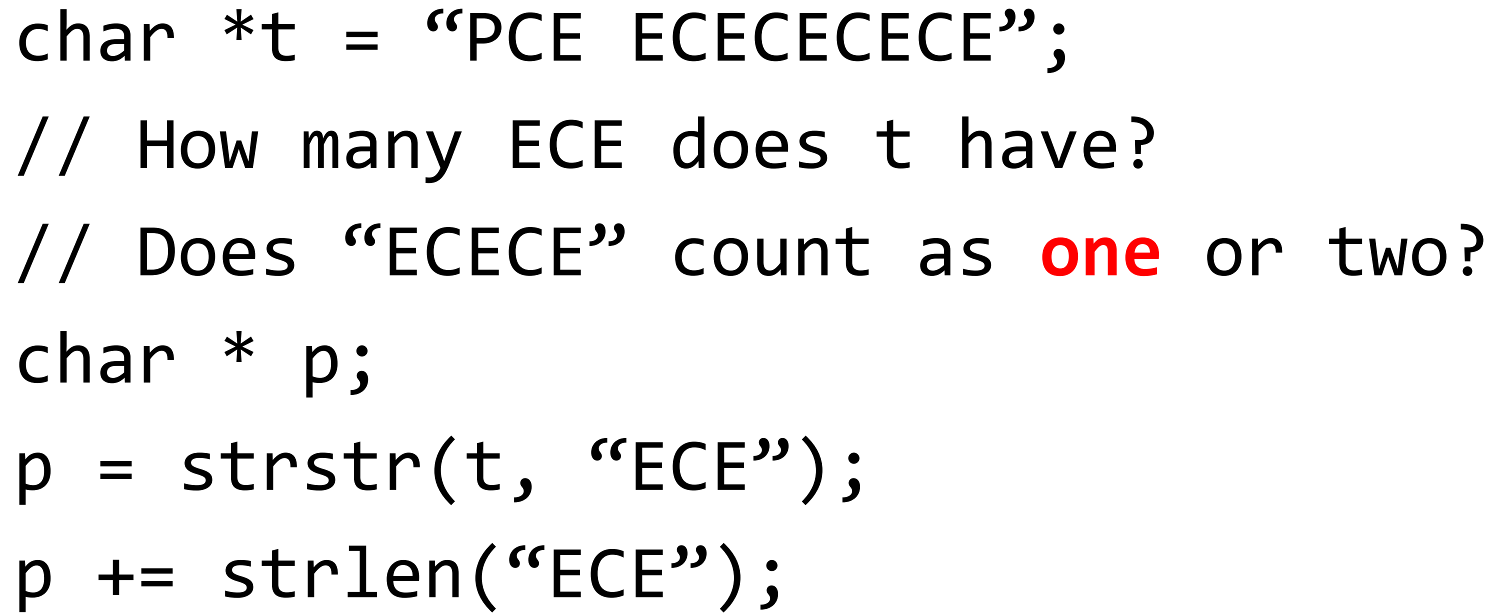
Symbol	Address	Value
q	230	A207
p	222	A207
t	214	A207
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

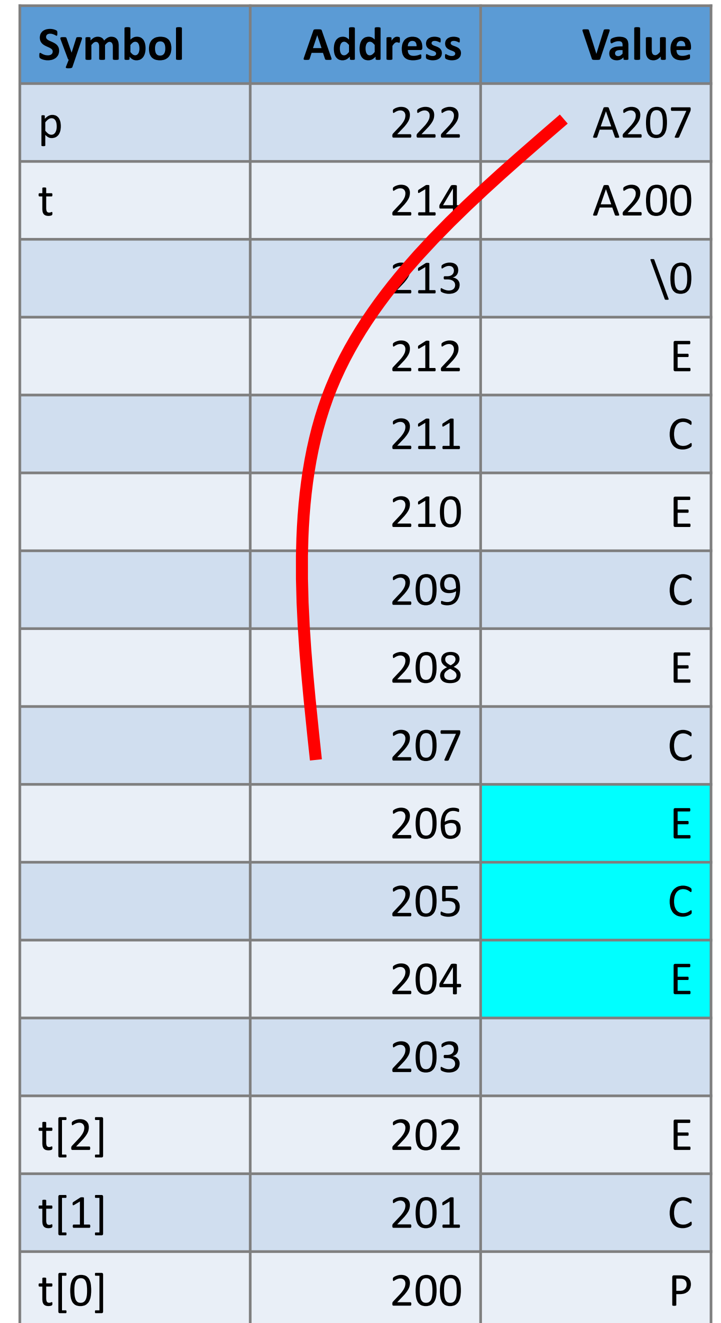
```
char *t = "PCE ECECECECE";
// How many ECE does t have?
// Does "ECECE" count as one or two?
char * p;
p = strstr(t, "ECE");
p ++;
char * q = p;
p = strstr(q, "ECE"); // not t
p ++;
q = p;
p = strstr(q, "ECE");
```

Symbol	Address	Value
q	230	A207
p	222	A208
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

```
char *t = “PCE ECECECECE”;
// How many ECE does t have?
// Does “ECECE” count as one or two?
char * p;
p = strstr(t, “ECE”);
```

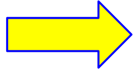
Symbol	Address	Value
p	222	A204
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P





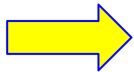
Symbol	Address	Value
p	222	A207
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

```
char *t = “PCE ECECECECE”;
// How many ECE does t have?
// Does “ECECE” count as one or two?
char * p;
p = strstr(t, “ECE”);
p += strlen(“ECE”);
char * q = p;
```



Symbol	Address	Value
q	230	A207
p	222	A207
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

```
char *t = “PCE ECECECECE”;
// How many ECE does t have?
// Does “ECECE” count as one or two?
char * p;
p = strstr(t, “ECE”);
p += strlen(“ECE”);
char * q = p;
p = strstr(q, “ECE”);
```



Symbol	Address	Value
q	230	A207
p	222	A208
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

```
char *t = “PCE ECECECECE”;
char * p;
p = strstr(t, “ECE”);
p += strlen(“ECE”);
char * q = p;
p = strstr(q, “ECE”);
// How many ECE does t have?
// Does “ECECE” count as one or two?
// p += strlen(“ECE”) count as one
// p ++ count as two
```

Symbol	Address	Value
q	230	A207
p	222	A208
t	214	A200
	213	\0
	212	E
	211	C
	210	E
	209	C
	208	E
	207	C
	206	E
	205	C
	204	E
	203	
t[2]	202	E
t[1]	201	C
t[0]	200	P

Homework 07 qsort and Function Pointer

Function Address (HW01 as example)

```
bash-4.2$ gdb main
GNU gdb (GDB) Red Hat Enterprise Linux 7.6.1-119
Copyright (C) 2013 Free Software Foundation, Inc
License GPLv3+: GNU GPL version 3 or later <http
This is free software: you are free to change ar
There is NO WARRANTY, to the extent permitted by
and "show warranty" for details.
This GDB was configured as "x86_64-redhat-linux-
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>...
Reading symbols from /home/shay/a/luece264/ECE26
(gdb) b addop
Breakpoint 1 at 0x400e49: file add.c, line 16.
(gdb) b mulop
Breakpoint 2 at 0x400f15: file mul.c, line 9.
(gdb) b subop
Breakpoint 3 at 0x401236: file sub.c, line 9.
(gdb) b divop
Breakpoint 4 at 0x400e8b: file div.c, line 9.
```

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

int func1(int a, int b)
{
  return (a + b);
}

int func2(int a, int b)
{
  return (a * b);
}

typedef int (*functype)(int a, int b);

int main(int argc, char * * argv)
{
  functype ptr;
  ptr = func1;
  int c = ptr(3, 5);
  printf("c = %d\n", c);
  ptr = func2;
  int d = ptr(3, 5);
  printf("d = %d\n", d);
  return EXIT_SUCCESS;
}
```

Program's Output

```
c = 8
d = 15
```

name of the data type

return type **(*name)**(arguments);

a function pointer

a pointer for function (two int argument) return int

qsort in C

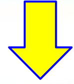
```
#include <stdlib.h>

void qsort(void *base, size_t nmemb, size_t size,
           int (*compar)(const void *, const void *));
```

The **qsort**() function sorts an array with *nmemb* elements of size *size*. The *base* argument points to the start of the array.

The contents of the array are sorted in ascending order according to a comparison function pointed to by *compar*, which is called with two arguments that point to the objects being compared.

The comparison function must return an integer less than, equal to, or greater than zero if the first argument is considered to be respectively less than, equal to, or greater than the second. If two members compare as equal, their order in the sorted array is undefined.

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



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void *: it is a pointer but the type is not specified now

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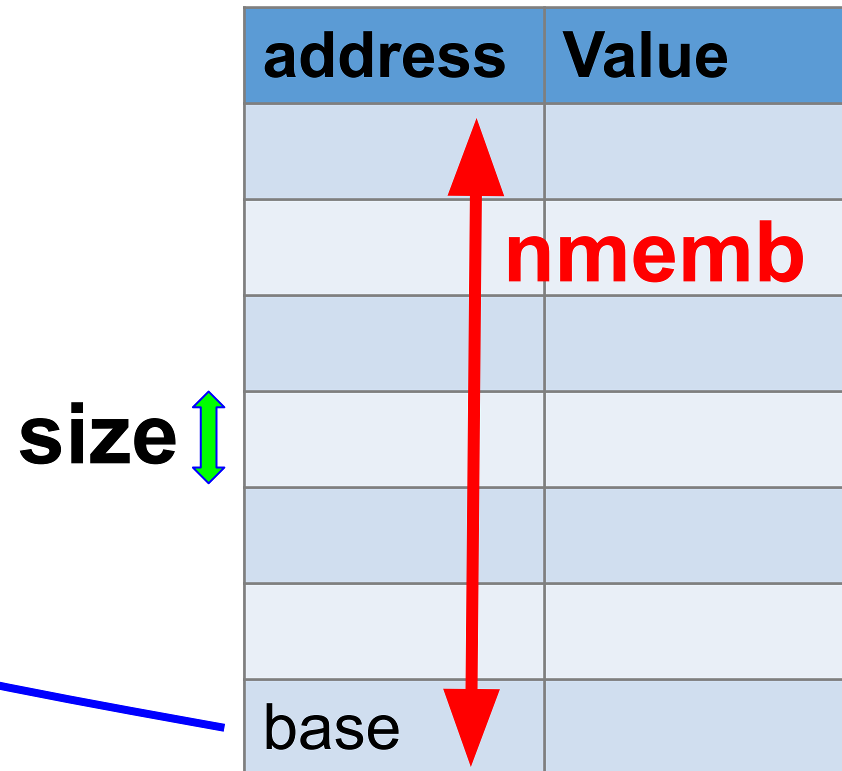

```c
#include <stdlib.h>

void qsort(void *base, size_t nmemb, size_t size,
           int (*compar)(const void *, const void *));
```

qsort: selects elements by the addresses based on
$\&\,arr[k] = \&\,arr[0] + k \cdot \text{size of an element}$
sends the addresses to compar to determine the order

$\&\,arr[0] = base$
$0 \le k < nmemb$

address	Value
base	

nmemb

size

int (*_compar_)(const void *, const void *, void *)

- A function
- The function returns int
- The function takes two arguments, both are addresses
- The function must not use the left hand side rule
- Document: *The comparison function must return an integer less than, equal to, or greater than zero if the first argument is considered to be respectively less than, equal to, or greater than the second. If two members compare as equal, their order in the sorted array is undefined*
- The function should compare values, not addresses

```c
#include <stdlib.h>

void qsort(void *base, size_t nmemb, size_t size,
           int (*compar)(const void *, const void *));
```

compar

1. compar < 0: V1 and V2 unchanged
2. compar = 0: undecided
3. compar > 0: V1, V2 swapped

address	Value
A2	V2
A1	V1
base	

```
int compareint(const void * arg1, const void * arg2)
// to sort arry of int
{
  const int * ptr1 = (const int *) arg1;
  const int * ptr2 = (const int *) arg2;
  int val1 = * ptr1;
  int val2 = * ptr2;
  if (val1 < val2)  { return -1; }
  if (val1 == val2) { return 0; }
  return 1;
}
```

1 (lines 1–2: casts), 2 (lines 3–4: values), 3 (lines 5–7: comparisons)

1. **cast void * to the right type ***
2. **get values at the two addresses**
3. **compare and return <0, 0, or > 0**

```
int comparevector(const void *arg1, const void *arg2)
// sort vectors by x
{
  // ptr1 and ptr2 are Vector *
  const Vector * ptr1 = (const Vector *) arg1;
  const Vector * ptr2 = (const Vector *) arg2;
  int val1 = ptr1 -> x;
  int val2 = ptr2 -> x;
  if (val1 < val2)  { return -1; }
  if (val1 == val2) { return 0; }
  return 1;
}
```

1 (lines 5–6), 2 (lines 7–8), 3 (lines 9–11)

1. **cast void * to the right type ***
2. **get values at the two addresses**
3. **compare and return <0, 0, or > 0**

```
int cmpstring(const void *arg1, const void *arg2)
// sort array of strings
{
  // arg1 and arg2 are string *
  // string is char *, thus ptr1 and ptr2 are char * *
  const char * const * ptr1 = (const char * *) arg1;
  const char * const * ptr2 = (const char * *) arg2;
  const char * str1 = * ptr1; // type: string
  const char * str2 = * ptr2;
  return strcmp(str1, str2);
}
```

1

2

3

```
#include <stdio.h>
#include <stdlib.h>
int main(int argc, char *argv[])
{
  char str1[20];
  char str2[20];
  strcpy(str1, "First");
  strcpy(str2, "Second");
  const char * chptr1 = & str1[0]; // cannot use left hand side rule
  char * const chptr2 = & str1[0]; // cannot change chptr2’s value
  const char * const chptr3 = & str1[0]; // neither
  // * chptr1 = 'C';         // not allowed
  * chptr2 = 'C';            // OK
  chptr1 = & str2[0];        // OK
  // chptr2 = & str2[0]; // not allowed
  // chptr3 = & str2[0]; // not allowed
  // * chptr3 = 'C';         // not allowed
  return EXIT_SUCCESS;
}
```

```
int cmpstring(const void *arg1, const void *arg2)
// sort array of strings
{
  // arg1 and arg2 are string *
  // string is char *, thus ptr1 and ptr2 are char * *
  const char * const * ptr1 = (const char * *) arg1;
  const char * const * ptr2 = (const char * *) arg2;
  const char * str1 = * ptr1; // type: string
  const char * str2 = * ptr2;
  return strcmp(str1, str2);
}
```

```
int cmpstring(const void *arg1, const void *arg2)
// sort array of strings
{
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  const char * const * ptr2 = (const char * *) arg2;
  const char * str1 = * ptr1; // type: string
  const char * str2 = * ptr2;
  return strcmp(str1, str2);
}
```

1

2

3

1. **cast void * to the right type ***
2. **get values at the two addresses**
3. **compare and return <0, 0, or > 0**

Quick Sort

- Quick Sort uses transitivity to avoid unnecessary comparisons
- transitivity: if a > b and b > c, then a > c. No need to compare a and c.
- Selection sort and bubble sort do not use transitivity. Thus, they are not as fast as quick sort.
- The algorithm of quick sort will be explained later.

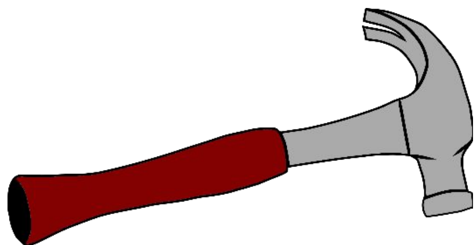
Recursion 01

Common Misunderstanding

- Wrong: Slow, Useless, Difficult to understand, Use too much memory, For exams only
- Truth: Recursion is slow, useless, difficult to understand, inefficient, …., really bad, ***if you do not understand it***.
- Many books do not explain recursion well.
- If you understand recursion and use it properly, it can be fast and efficient.

Where Recursion is Used?

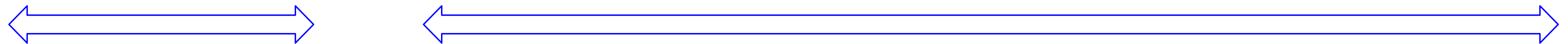
- Sorting (almost everywhere, such as quick sort)
- Strategy games (chess, go)
- Optimization
- …
- Recursion is one of many tools. Recursion is good for solving some problems.



Recursion is natural

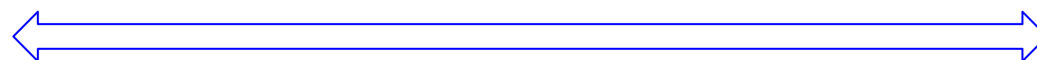
- You have parents. Your parents have their parents. They have their parents. This is recursion.
- You are younger than your parents. Your parents are younger than your grandparents. Different generations are different.
- If you have no child, the recursion stops at you. If you have a child (or several children) and no grandchild, recursion stops at your child (or children).
- Three essential components of recursion: recurring patterns, changes, and stop condition.

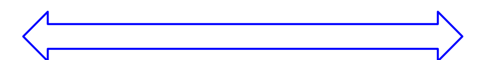
Recursion in Quick Sort



< R1 > R1

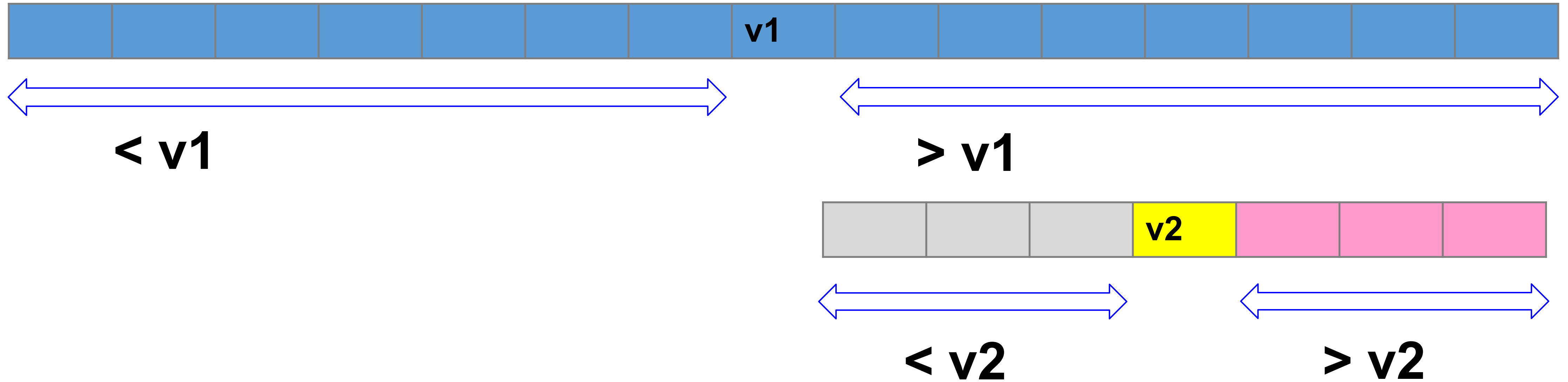
transitivity: if a > b and b > c, then a > c



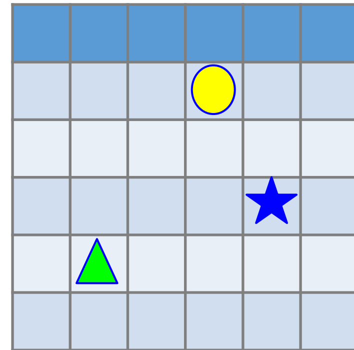


< R2 > R2

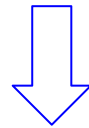
Recursion in Binary Search (sorted data)



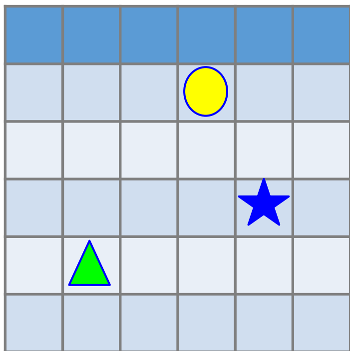
Recursion in Board Games

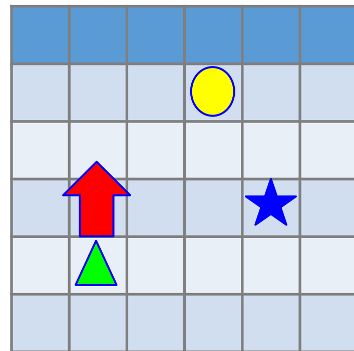


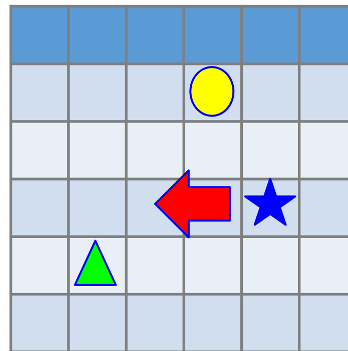
current state

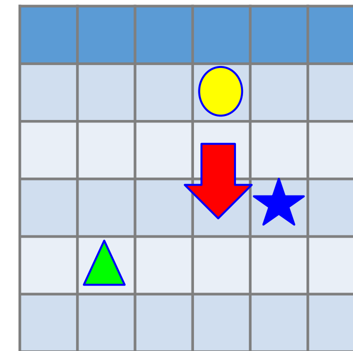


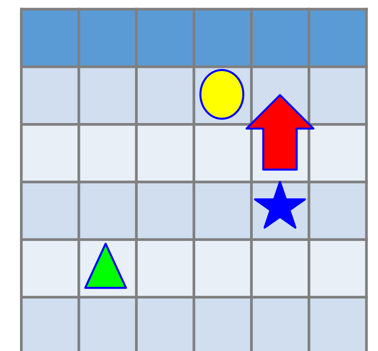
different states after one move







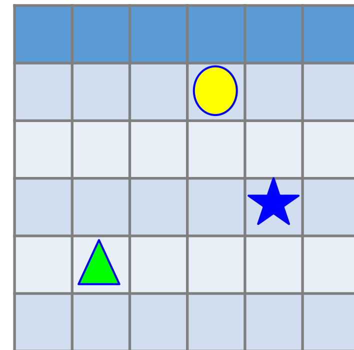




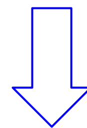
3 Essential Components in Recursion

- Stop condition (or conditions), also call terminating conditions: when nothing needs to be done.
- Changes.
- Recurring pattern.

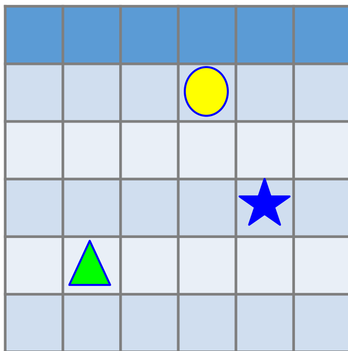
Recursion good for "branches"

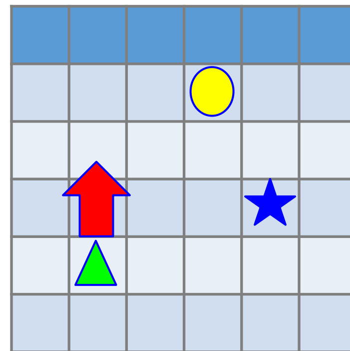


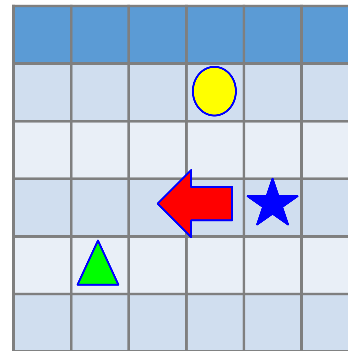
current state

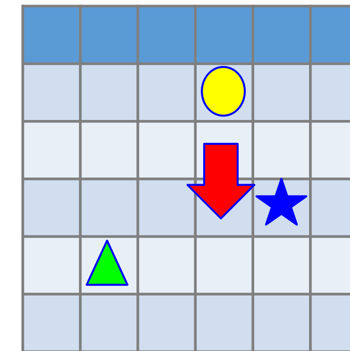


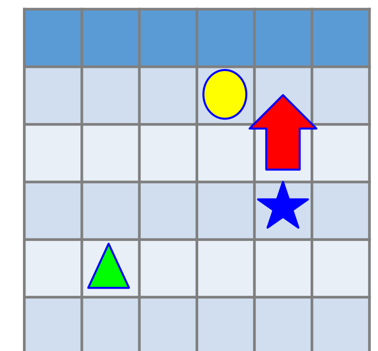
different states after one move



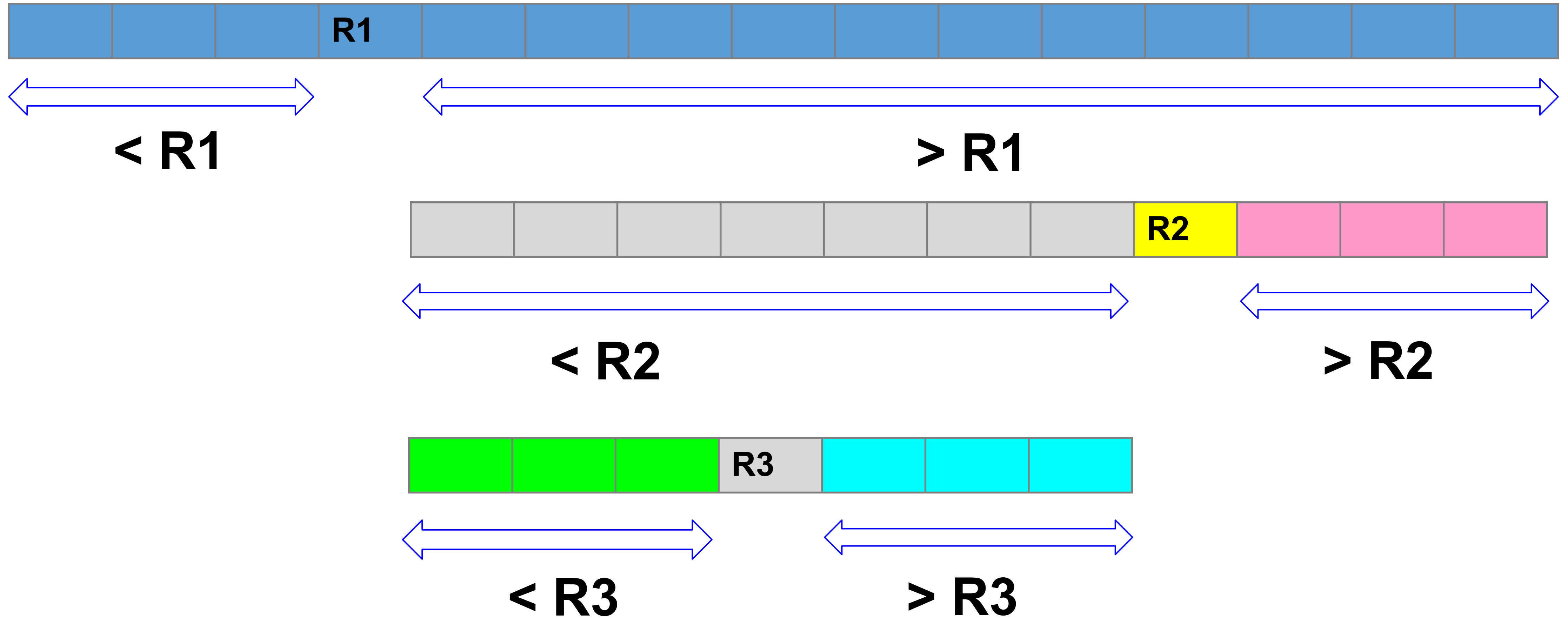






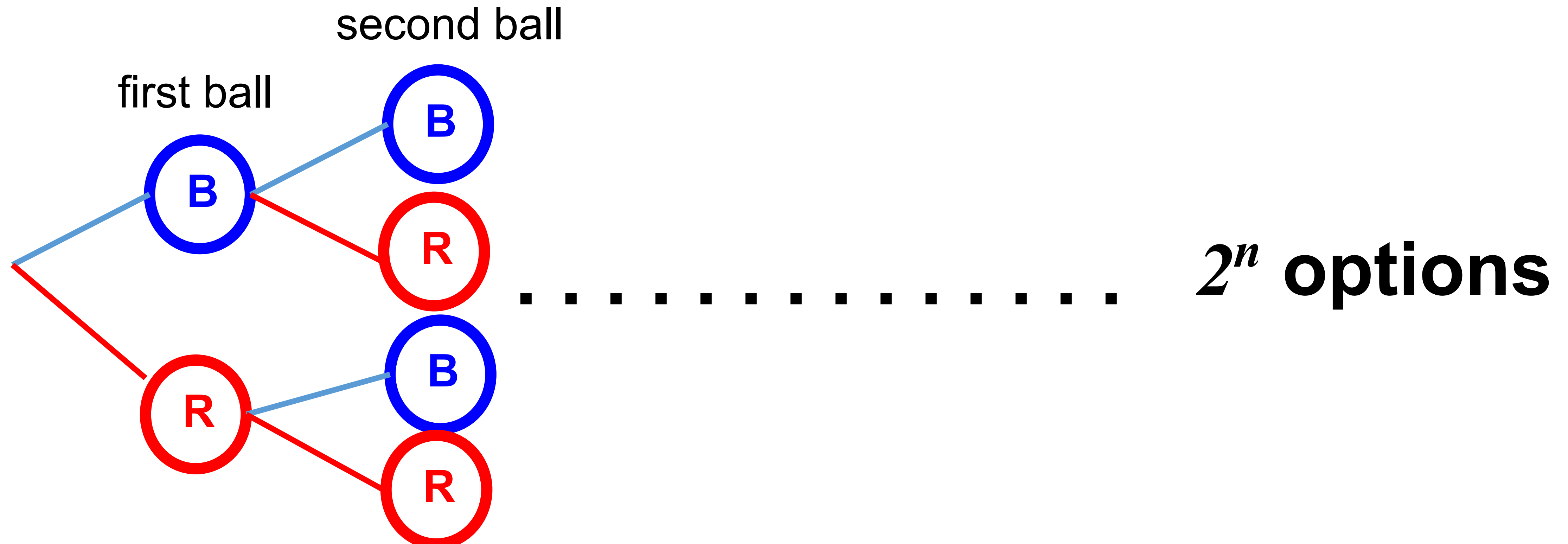


Branch in Quick Sort (sorted data)

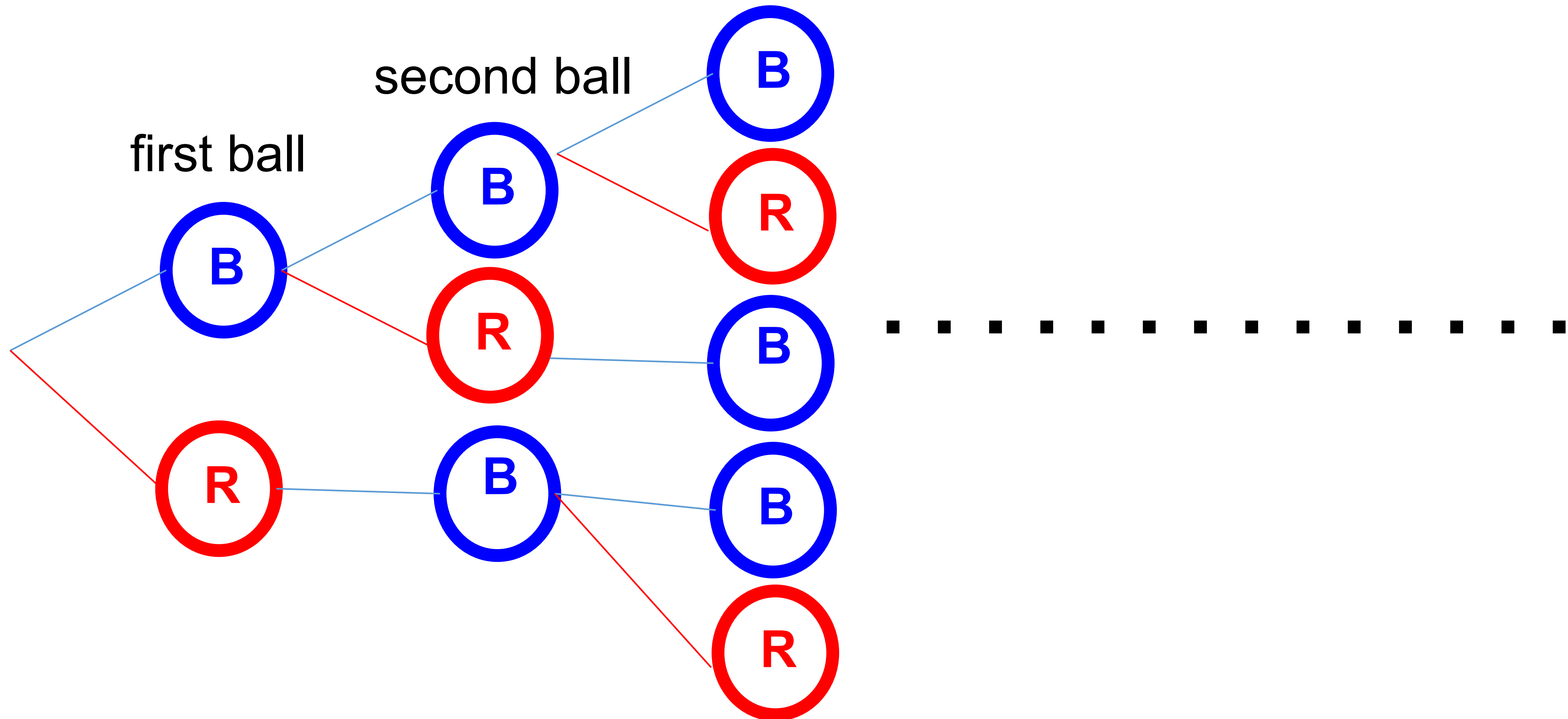


Select Balls

- If you have an unlimited supply for red and blue balls, how many ways can you select n balls?
- Orders matter: Red – Blue is different from Blue – Red.



You have an unlimited supply for red and blue balls. Two adjacent balls cannot be both Red. How many ways can you select n balls? Orders matter.

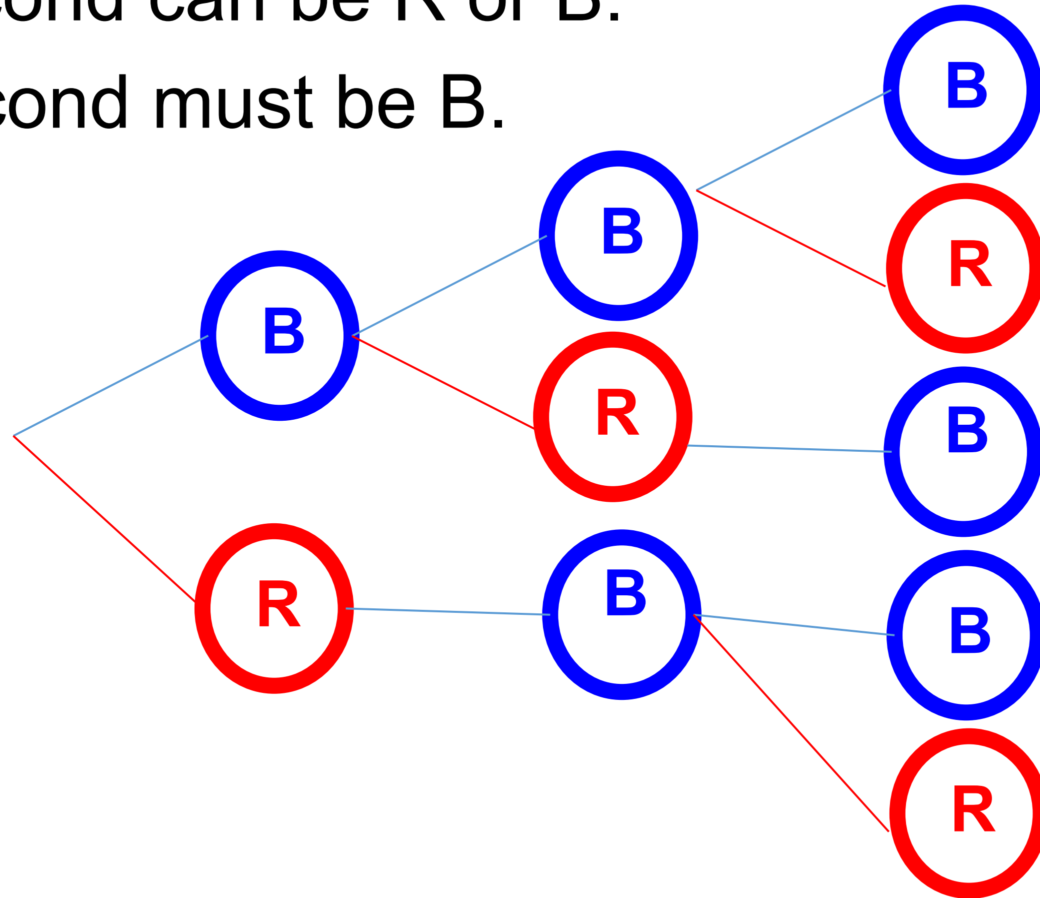


First Approach: list answers

- one ball: two solutions: R or B
- two balls: three solutions: RB, BR, or BB
- three balls: five solutions: RBR, RBB, BRB, BBR, BBB

Divide the problem

- If the first ball is B, the second can be R or B.
- If the first ball is R, the second must be B.



Divide the problem

- If the first ball is B, the second can be R or B.
- If the first ball is R, the second must be B.
- Suppose $f(n)$ means the number of options to select n balls.
- $f(1)$ = 2 because there are two options to select 1 ball.
- $f(2)$ = 3 because there are three options to select 2 balls.
- When n is larger, we shrink the problem slightly by selecting only one ball.

Shrink the problem by one ball

- To select n balls, select one ball only.
- If B is selected, there is no restriction of the next ball.
- If the selected ball is B, the next can be R or B. The problem becomes selecting $n-1$ balls.
- If the selected ball is R, the next must be B. . The problem becomes selecting $n-2$ balls.
- Suppose $f(n)$ means the number of options to select n balls.

$$f(n) = \begin{cases} f(n-1) & \text{first ball is B} \\ f(n-2) & \text{first ball is R} \end{cases}$$

Addition or Multiplication?

$$f(n) = \begin{cases} f(n-1) & \text{first ball is B} \\ f(n-2) & \text{first ball is R} \end{cases}$$

$f(n) = f(n\text{-}1) + f(n\text{-}2)$ or

$f(n) = f(n\text{-}1) \times f(n\text{-}2)$

Addition or Multiplication?

$$f(n) = \begin{cases} f(n-1) & \text{first ball is B} \\ f(n-2) & \text{first ball is R} \end{cases}$$

$f(n) = f(n\text{-}1) + f(n\text{-}2)$ or

$f(n) = f(n\text{-}1) \times f(n\text{-}2)$

if the two are either A or B, then add

if the two are independent, then multiply

Order meal in a restaurant

- If a restaurant offers 4 options of beef, 3 options of chicken, 4 options of fish, and 5 options of salad, how much options do you have? $4 + 3 + 4 + 5 = 16$

- If there are three options of dessert, how many ways can you order meal + dessert? $16 \times 3 = 48$.

Addition or Multiplication?

$$f(n) = \begin{cases} f(n-1) & \text{first ball is B} \\ f(n-2) & \text{first ball is R} \end{cases}$$

$f(n) = f(n\text{-}1) + f(n\text{-}2)$ or

$f(n) = f(n\text{-}1) \times f(n\text{-}2)$

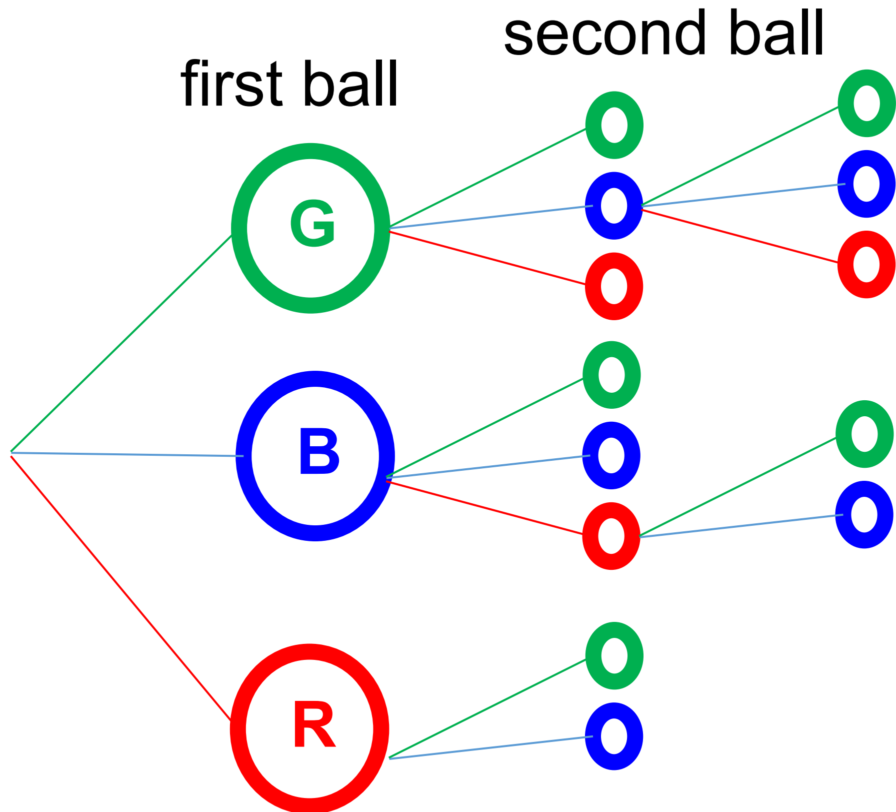
if the two are either A or B, then add

if the two are independent, then multiply

Shrink the problem by one ball

- $f(1)$ = 2 and $f(2)$ = 3: stop condition: when n is 1 or 2
- $f(n) = f(n - 1) + f(n - 2)$
- $f(n - 1) = f(n - 2) + f(n - 3)$
- $f(n - 2) = f(n - 3) + f(n - 4)$
- $f(n - 3) = f(n - 4) + f(n - 5)$
- ...
- change: n becomes smaller and smaller
- recurring pattern

You have an unlimited supply for green, red, and blue balls. Two adjacent balls cannot be both Red. How many ways can you select n balls? Orders matter.



. . . .

First Approach: list answers

- one ball: 3 solutions: G or R or B
- two balls: 8 solutions:
  1. RB, RG
  2. BR, BG, BB
  3. GR, GB, GG

Divide the problem

- If the first ball is B or G, the second can be G, R, or B.
- If the first ball is R, the second can be G or B, not R.
- Suppose $f(n)$ means the number of options to select n balls.
- $f(1)$ = 3 because there are three options to select 1 ball.
- $f(2)$ = 8 because there are eight options to select 2 balls.
- When n is larger, we shrink the problem slightly by selecting only one ball.

- Suppose $f(n)$ means the number of options to select n balls.
- $g(n)$: number of options to select n balls and first is G
- $b(n)$: number of options to select n balls and first is B
- $r(n)$: number of options to select n balls and first is R
- $g(n) = g(n-1) + r(n-1) + b(n-1)$
- $b(n) = g(n-1) + r(n-1) + b(n-1)$
- $r(n) = g(n-1) + b(n-1)$
- $f(n) = g(n) + r(n) + b(n)$
- $g(n) = f(n-1)$
- $b(n) = f(n-1)$
- $g(1) = b(1) = r(1) = 1$

n	**1**	**2**	**3**	**4**	**5**
g(n)	1	3	8	22	60
b(n)	1	3	8	22	60
r(n)	1	2	6	16	44
f(n)	3	8	22	60	164

Integer Partition

Divide a positive integer into the sum of one (the original integer) of multiple positive integers.

1 =	1					4 =	1 +	1 +	1 +	1
2 =	1 +	1					1 +	1 +	2	
	2						1 +	2 +	1	
3 =	1 +	1 +	1				1 +	3		
	1 +	2					2 +	1 +	1	
	2 +	1					2 +	2		
	3						3 +	1		
							4			

How many ways can n be positioned?

n	1	2	3	4	…
partitions	1	2	4	8	?

How many ways can n be positioned?

n	**1**	**2**	**3**	**4**	**…**
partitions	1	2	4	8	?

- wrong ways to solve the problem: It ***seems*** that the answer is 2^{n-1} ways to partition ***n***
- Why is this invalid? You cannot observe some examples to reach a conclusion.
- West Lafayette has no snow from May to September, can you conclude that it will not snow?
- For any number of (x, y) pairs, there is an infinite number of polynomials (with sufficient degrees) passing the pairs.

Decide the first number

- If the original number is n, the first number can be 1, 2, …, n
- The remaining number is n-1, n-2, …, 0
- Let f(n) be the number of ways to partition number n
- If the first number is 1, there are f(n-1) ways to partition n – 1
- If the first number is 2, there are f(n-2) ways to partition n – 2
- …
- If the first number is n-1, there are f(1) ways to partition 1
- If the first number is n, nothing is left
- $f(n) = f(n-1) + f(n-2) + \ldots + f(1) + 1$

- $f(1) = 1$
- $f(n) = f(n-1) + f(n-2) + \ldots + f(1) + 1$
- $f(n + 1) = f(n) + f(n-1) + f(n-2) + \ldots + f(1) + 1$

-

- $f(n+1) - f(n) = f(n)$

- $f(1) = 1$
- $f(n) = f(n-1) + f(n-2) + \ldots + f(1) + 1$
- $f(n + 1) = f(n) + f(n-1) + f(n-2) + \ldots + f(1) + 1$

-

- $f(n+1) - f(n) = f(n)$
- $f(n+1) = 2f(n)$
- $f(n) = 2^{n-1}$

Three components in recursion

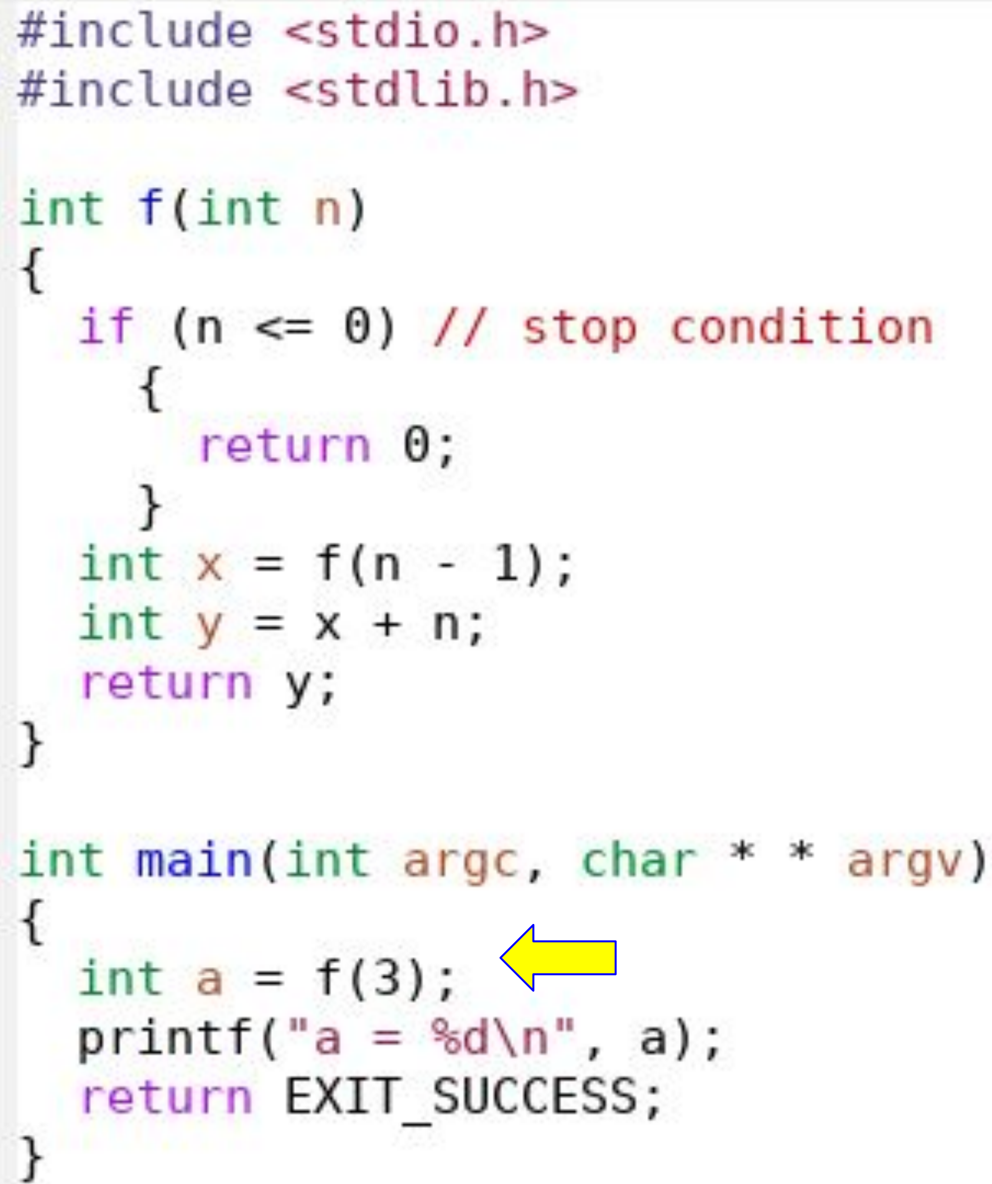
- Stop Condition: $f(1) = 1$
- Recurring pattern: $f(n) = f(n-1) + f(n-2) + \ldots + f(1) + 1$
- Changes: $f(n)$ is expressed by $n - 1$, $n - 2$ …

Recursive Functions

```
function(arguments)
{
    check arguments for stop conditions
    if the stop conditions are not met.
    {
        change the arguments
        call function using the new arguments
    }
}
```

To understand recursive functions, we need to understand stack memory

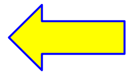
```c
#include <stdio.h>
#include <stdlib.h>

int f(int n)
{
  if (n <= 0) // stop condition
    {
      return 0;
    }
  int x = f(n - 1);
  int y = x + n;
  return y;
}

int main(int argc, char * * argv)
{
  int a = f(3);
  printf("a = %d\n", a);
  return EXIT_SUCCESS;
}
```



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

int f(int n)
{
  if (n <= 0) // stop condition
    {
      return 0;
    }
  int x = f(n - 1);
  int y = x + n;
  return y;
}

int main(int argc, char * * argv)
{
  int a = f(3);
  printf("a = %d\n", a);
  return EXIT_SUCCESS;
}
```

Frame	Symbol	Address	Value
main	a	100	U

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

int f(int n)
{
  if (n <= 0) // stop condition
    {
      return 0;
    }
  int x = f(n - 1);
  int y = x + n;
  return y;
}

int main(int argc, char * * argv)
{
  int a = f(3);
  printf("a = %d\n", a);
  return EXIT_SUCCESS;
}
```



Frame	Symbol	Address	Value
f	n	200	3
	value address 100		
	return location		
main	a	100	U

```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21    _
```

Frame	Symbol	Address	Value
f	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21
```

Frame	Symbol	Address	Value
f	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21
```

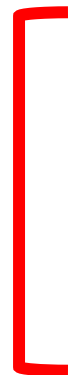
Frame	Symbol	Address	Value
f	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21
```

Frame	Symbol	Address	Value
f	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21
```

- f is called twice
- two frames in stack
- the frames are not “merged”

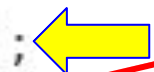


Frame	Symbol	Address	Value
f	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int f(int n)
5  {
6    if (n <= 0) // stop condition
7      {
8        return 0;
9      }
10   int x = f(n - 1);
11   int y = x + n;
12   return y;
13 }
14
15 int main(int argc, char * * argv)
16 {
17   int a = f(3);
18   printf("a = %d\n", a);
19   return EXIT_SUCCESS;
20 }
21
```

Frame	Symbol	Address	Value
f	y	308	U
	x	304	U
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```c
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int f(int n)
5  {
6    if (n <= 0) // stop condition
7      {
8        return 0;
9      }
10   int x = f(n - 1);
11   int y = x + n;
12   return y;
13 }
14
15 int main(int argc, char * * argv)
16 {
17   int a = f(3);
18   printf("a = %d\n", a);
19   return EXIT_SUCCESS;
20 }
21
```

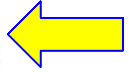


Frame	Symbol	Address	Value
f	n	400	1
	value address 304		
	return location line 11		
f	y	308	U
	x	304	U
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21
      _
```

Frame	Symbol	Address	Value
f	n	400	1
	value address **304**		
	return location line 11		
f	y	308	U
	x	304	U
	n	300	2
	value address **204**		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

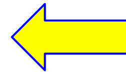
```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int a
16  {
17    int a = f(3)
18    printf("a =
19    return EXIT_
20  }
21    _
```



Frame	Symbol	Address	Value
f	n	500	0
	value address 404		
	return location line 11		

Frame	Symbol	Address	Value
f	y	408	U
	x	404	U
	n	400	1
	value address 304		
	return location line 11		
f	y	308	U
	x	304	U
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int f(int n)
5  {
6    if (n <= 0) // stop condition
7      {
8        return 0;
9      }
10   int x = f(n - 1);
11   int y = x + n;
12   return y;
13 }
14
15 int main(int a
16 {
17   int a = f(3)
18   printf("a = 
19   return EXIT_
20 }
21
```



Frame	Symbol	Address	Value
f	n	500	0
	value address 404		
	return location line 11		

Frame	Symbol	Address	Value
f	y	408	U
	x	404	U
	n	400	1
	value address 304		
	return location line 11		
f	y	308	U
	x	304	U
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```c
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int a
16  {
17    int a = f(3)
18    printf("a = 
19    return EXIT_
20  }
21    _
```

Frame	Symbol	Address	Value
f	n	500	0
	value address 404		
	return location line 11		

Frame	Symbol	Address	Value
f	y	408	U
	x	404	U → 0
	n	400	1
	value address 304		
	return location line 11		
f	y	308	U
	x	304	U
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```c
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int f(int n)
5  {
6    if (n <= 0) // stop condition
7      {
8        return 0;
9      }
10   int x = f(n - 1);
11   int y = x + n;
12   return y;
13 }
14
15 int main(int argc, char * * argv)
16 {
17   int a = f(3);
18   printf("a = %d\n", a);
19   return EXIT_SUCCESS;
20 }
21
```

Frame	Symbol	Address	Value
f	y	408	U
	x	404	0
	n	400	1
	value address 304		
	return location line 11		
f	y	308	U
	x	304	U
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21    _
```

Frame	Symbol	Address	Value
f	y	408	1
	x	404	0
	n	400	1
	value address 304		
	return location line 11		
f	y	308	U
	x	304	U
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21
```

Frame	Symbol	Address	Value
f	y	408	1
	x	404	0
	n	400	1
	value address 304		
	return location line 11		
f	y	308	U
	x	304	U → 1
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```c
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int f(int n)
5  {
6    if (n <= 0) // stop condition
7      {
8        return 0;
9      }
10   int x = f(n - 1);
11   int y = x + n;
12   return y;
13 }
14
15 int main(int argc, char * * argv)
16 {
17   int a = f(3);
18   printf("a = %d\n", a);
19   return EXIT_SUCCESS;
20 }
21
```

Frame	Symbol	Address	Value
f	y	408	1
	x	404	0
	n	400	1
	value address 304		
	return location line 11		
f	y	308	U
	x	304	1
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```c
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int f(int n)
5  {
6    if (n <= 0) // stop condition
7      {
8        return 0;
9      }
10   int x = f(n - 1);
11   int y = x + n;
12   return y;
13 }
14
15 int main(int argc, char * * argv)
16 {
17   int a = f(3);
18   printf("a = %d\n", a);
19   return EXIT_SUCCESS;
20 }
21   _
```

Frame	Symbol	Address	Value
f	y	308	3
	x	304	1
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	U
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21    _
```

Frame	Symbol	Address	Value
f	y	308	3
	x	304	1
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	~~U~~ → 3
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```c
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int f(int n)
5  {
6    if (n <= 0) // stop condition
7      {
8        return 0;
9      }
10   int x = f(n - 1);
11   int y = x + n;
12   return y;
13 }
14
15 int main(int argc, char * * argv)
16 {
17   int a = f(3);
18   printf("a = %d\n", a);
19   return EXIT_SUCCESS;
20 }
21
```

Frame	Symbol	Address	Value
f	y	308	3
	x	304	1
	n	300	2
	value address 204		
	return location line 11		
f	y	208	U
	x	204	3
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

```
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int f(int n)
5  {
6    if (n <= 0) // stop condition
7      {
8        return 0;
9      }
10   int x = f(n - 1);
11   int y = x + n;
12   return y;
13 }
14
15 int main(int argc, char * * argv)
16 {
17   int a = f(3);
18   printf("a = %d\n", a);
19   return EXIT_SUCCESS;
20 }
21   _
```

Frame	Symbol	Address	Value
f	y	208	6
	x	204	3
	n	200	3
	value address 100		
	return location line 18		
main	a	100	U

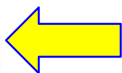
```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21
```

Frame	Symbol	Address	Value
f	y	208	6
	x	204	3
	n	200	3
	value address 100		
	return location line 18		
main	a	100	~~U~~ → **6**

```c
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21    _
```

Frame	Symbol	Address	Value
f	y	208	6
	x	204	3
	n	200	3
	value address 100		
	return location line 18		
main	a	100	6

```
1   #include <stdio.h>
2   #include <stdlib.h>
3
4   int f(int n)
5   {
6     if (n <= 0) // stop condition
7       {
8         return 0;
9       }
10    int x = f(n - 1);
11    int y = x + n;
12    return y;
13  }
14
15  int main(int argc, char * * argv)
16  {
17    int a = f(3);
18    printf("a = %d\n", a);
19    return EXIT_SUCCESS;
20  }
21
```



Frame	Symbol	Address	Value
main	a	100	6