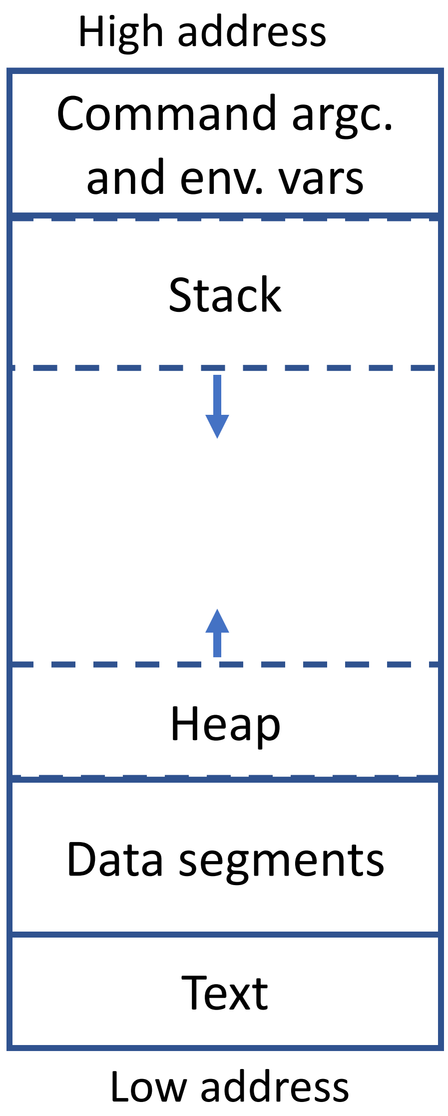
Dynamic Memory Management

Mohammed Bahja
School of Computer Science
University of Birmingham

Recap: Memory layout of C program

- Local variables use Stack ‘temporarily’. They are active only within their functions.
- Static variables are stored in the Data segments. They preserve their values.
- Global variables are stored in the Data segments. They are accessible to all functions of the C program.



[This figure is symbolic. Heap section need not start from the address just after data segment]

Use of Heap will be covered in Dynamic Memory Management.

Application scenario

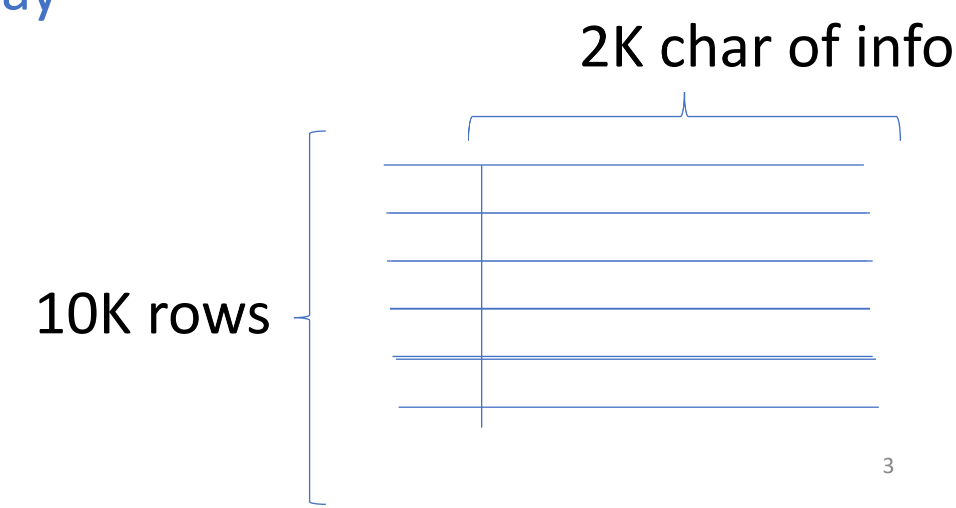
Consider an application where the volume of data is not known beforehand

Example: Store info of the people you meet during office hour

- The number of people is not known
- Each person may provide different amount of info

Solution 1: Allocate a large array

```c
char info[10000][2000];
```



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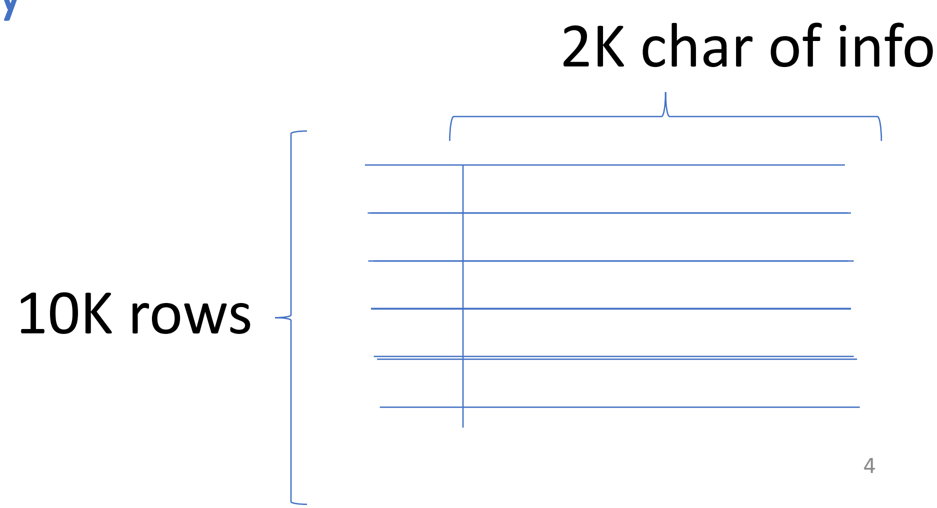
```

Problems:

1. May be wasteful
2. May be insufficient
3. Tiny computes can't afford large amount of space



Application scenario

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Example: Store info of the people you meet during office hour

- The number of people is not known
- Each person may provide different amount of info

Best solution: Allocate memory at **runtime** as per **demand**

Advantages: Optimal memory consumption depending on the current state of the application

Dynamic memory allocation in C

Dynamic memory allocation functions

C provides dynamic memory management functions in `stdlib.h`

- `malloc()`
  1. Allocates requested number of bytes of **contiguous** memory from the **Heap.**
  2. Returns a pointer to the first byte of the allocated space.
  3. If memory allocation fails, then `malloc()` returns NULL pointer.

```
Syntax:

T *p;
p = (T *) malloc(number of bytes);
```

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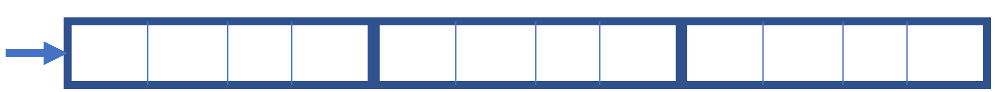
```
Example: Allocate space for 3 int

int *p;
p = (int *) malloc(3*4); // int is 4 bytes
```

p


Allocates 12 bytes of contiguous memory in Heap.
p points to the first byte

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```
Example: Allocate space for 3 int

int *p;
p = (int *) malloc(3*sizeof(int));
// Allocates memory for 3 integers
```

Use `sizeof()` for convenience.

It returns the size of a `data_type` in bytes.

Dynamic memory allocation functions

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  2. Returns a pointer to the first byte of the allocated space.
  3. If memory allocation fails, then `malloc()` returns NULL pointer.

```
Example: Allocate space for 3 int
int *p;
if((p= (int *) malloc(3*sizeof(int)))==NULL){
      printf("Allocation failed");
      exit(-1);
}
```

Good practice: check if a NULL pointer is returned by `malloc()`

Releasing allocated memory using free()

- Dynamically allocated block of memory can be released using free().
- After free(), the block of memory is returned to the Heap.

```
int *p;
// Block of memory is allocated
if((p= (int *) malloc(3*sizeof(int)))==NULL){
      printf("Allocation failed");
      exit(-1);
}

// [Some statements involving p]

// Block of memory pointed by p is released
free(p);
```

Example: Array of variable length

```
#include<stdio.h>
#include<stdlib.h>
int main(){
	int N, i;
	int *p;
	printf("Provide array size:");
	scanf("%d", &N);
	// Allocate memory in Heap for
	// array pointed by p
	if((p= (int *) malloc(N*sizeof(int)))==NULL){
		printf("Allocation failed");
		exit(-1);
	}
	printf("Provide %d integers\n", N);
	for(i=0; i<N; i++)
		scanf("%d", p+i);

	free(p);
	return 0;
}
```

Memory leak

If memory allocated using malloc() is not free()-ed, then the system will "leak memory"

- Block of memory is allocated, but not returned to Heap
- The program therefore grows larger over time
- In C, it is **your responsibility** to prevent memory leak

Example: Memory leak

```
int main(){
   int N, i,*p;

   while(1){
        printf("Provide array size:");
        scanf("%d", &N);
        if((p= (int *) malloc(N*sizeof(int)))==NULL){
              printf("Allocation failed");
              exit(-1);
        }
        printf("Provide %d integers\n", N);
        for(i=0; i<N; i++)
              scanf("%d", p+i);

        //free(p);
   }
   return 0;
}
```

Each iteration of while loop allocates memory. But that memory is never freed. This causes memory leak.

Valgrind: a tool for memory leak detection

- We will use the valgrind tool to detect memory leaks
- Quick start info: http://valgrind.org/docs/manual/quick-start.html

Steps to follow:

1. Compile your C code using gcc
2. Then use valgrind to run the compiled code:
   `valgrind --leak-check=full ./a.out`

Example: valgrind output

```
int main()
{
        int *pt = malloc(1*sizeof(int));
        scanf("%d", pt);
        printf("%d\n", *pt);
        return 0;
}
```

Output of valgrind --leak-check=full ./a.out

```
==1057== Memcheck, a memory error detector
==1057== Copyright (C) 2002-2017, and GNU GPL'd, by Julian Seward et al.
==1057== Using Valgrind-3.13.0 and LibVEX; rerun with -h for copyright info
==1057== Command: ./a.out
==1057==
```

... continued

```
==1057== HEAP SUMMARY:
==1057==     in use at exit: 4 bytes in 1 blocks
==1057==   total heap usage: 1 allocs, 0 frees, 4 bytes allocated
==1057==
==1057== LEAK SUMMARY:
==1057==    definitely lost: 0 bytes in 0 blocks
==1057==    indirectly lost: 0 bytes in 0 blocks
==1057==      possibly lost: 0 bytes in 0 blocks
==1057==    still reachable: 4 bytes in 1 blocks
==1057==         suppressed: 0 bytes in 0 blocks
```

Valgrind reports a memory leak of 4 bytes. ☹

Example: valgrind output

```c
int main()
{
        int *pt = malloc(1*sizeof(int));
        scanf("%d", pt);
        printf("%d\n", *pt);
        free(pt);
        return 0;
}
```

Allocated memory is freed here

Output of valgrind --leak-check=full ./a.out

```
==2308== Memcheck, a memory error detector
==2308== Copyright (C) 2002-2017, and GNU GPL'd, by Julian Seward et al.
==2308== Using Valgrind-3.13.0 and LibVEX; rerun with -h for copyright info
==2308== Command: ./a.out
==2308==
5
5
==2308==
==2308== HEAP SUMMARY:
==2308==     in use at exit: 0 bytes in 0 blocks
==2308==   total heap usage: 1 allocs, 1 frees, 4 bytes allocated
==2308==
==2308== All heap blocks were freed -- no leaks are possible
==2308==
```

No memory leak reported! ☺

Consequences of memory leak

- Memory leaks slowdown system performance by reducing the amount of available memory.

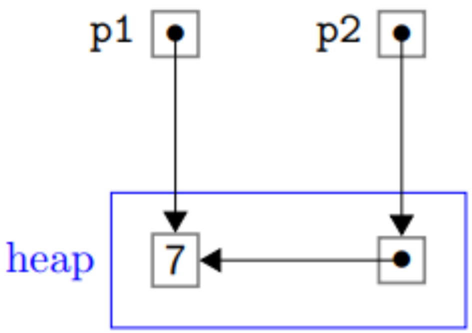
- In modern operating systems, memory used by an application is released when the application terminates
  - If a program (with leak) runs for a short duration, then no serious problem
  - Will be a serious problem when a leaking program runs for long duration

- Memory leak will cause serious issues on resource-constrained embedded devices

Overall, your program should not contain memory leaks

Another memory leak example(1)

```c
int main(){
   int *p1, **p2;
   p1 = malloc(sizeof(int));
   *p1=7;
   p2 = malloc(sizeof(int*));
   *p2=p1;
   return 0;
}
```

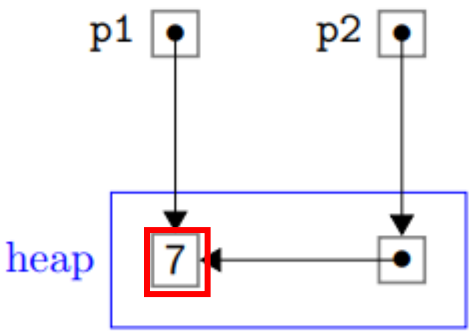


p2 is a pointer to a pointer variable

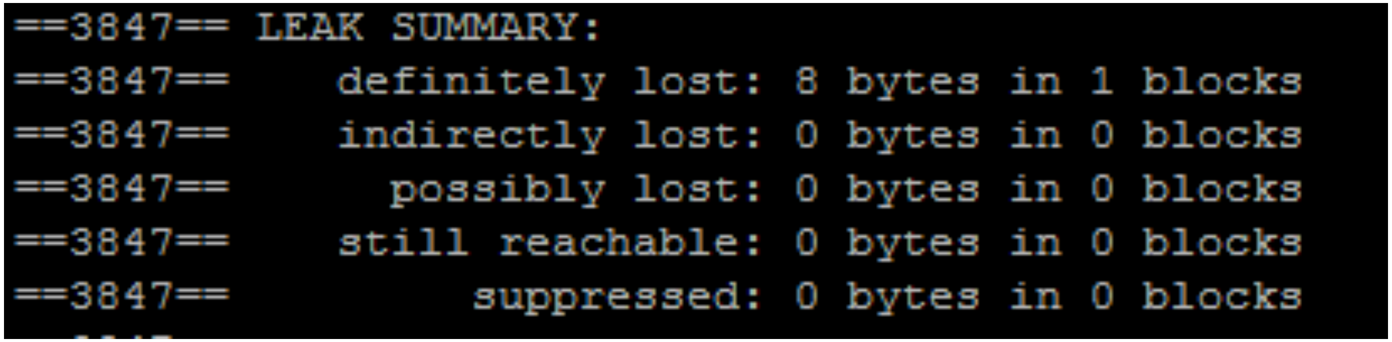
```
==3600== HEAP SUMMARY:
==3600==     in use at exit: 12 bytes in 2 blocks
==3600==   total heap usage: 2 allocs, 0 frees, 12 bytes allocated
==3600==
==3600== 12 (8 direct, 4 indirect) bytes in 1 blocks are definitely lost in loss record 2 of 2
==3600==    at 0x4C29BC3: malloc (vg_replace_malloc.c:299)
==3600==    by 0x400546: main (in /users/cosic/ssinharo/dynamicmem/a.out)
==3600==
==3600== LEAK SUMMARY:
==3600==    definitely lost: 8 bytes in 1 blocks
==3600==    indirectly lost: 4 bytes in 1 blocks
==3600==      possibly lost: 0 bytes in 0 blocks
==3600==    still reachable: 0 bytes in 0 blocks
==3600==         suppressed: 0 bytes in 0 blocks
==3600==
```

Another memory leak example(2)

```c
int main(){
   int *p1, **p2;
   p1 = malloc(sizeof(int));
   *p1=7;
   p2 = malloc(sizeof(int*));
   *p2=p1;
   free(p1);
   return 0;
}
```



p2 is a pointer to a pointer variable

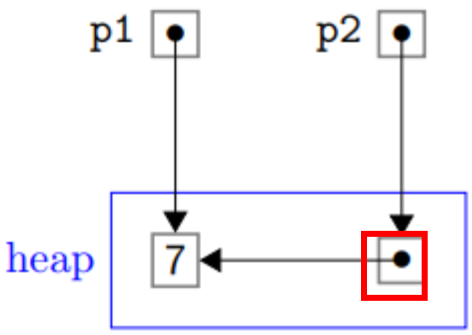


```
==3847== LEAK SUMMARY:
==3847==    definitely lost: 8 bytes in 1 blocks
==3847==    indirectly lost: 0 bytes in 0 blocks
==3847==      possibly lost: 0 bytes in 0 blocks
==3847==    still reachable: 0 bytes in 0 blocks
==3847==         suppressed: 0 bytes in 0 blocks
```

Still 8 bytes are leaked!

Another memory leak example(3)

```c
int main(){
   int *p1, **p2;
   p1 = malloc(sizeof(int));
   *p1=7;
   p2 = malloc(sizeof(int*));
   *p2=p1;
   free(p2);
   return 0;
}
```



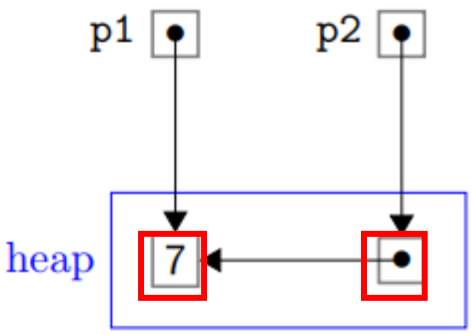
p2 is a pointer to a pointer variable

```
==6994== LEAK SUMMARY:
==6994==    definitely lost: 4 bytes in 1 blocks
==6994==    indirectly lost: 0 bytes in 0 blocks
==6994==      possibly lost: 0 bytes in 0 blocks
==6994==    still reachable: 0 bytes in 0 blocks
==6994==         suppressed: 0 bytes in 0 blocks
```

4 bytes are leaked!

Another memory leak example(4)

```
int main(){
   int *p1, **p2;
   p1 = malloc(sizeof(int));
   *p1=7;
   p2 = malloc(sizeof(int*));
   *p2=p1;
   free(p1);
   free(p2);
   return 0;
}
```



p2 is a pointer to a pointer variable

No memory leak!

Accessing memory after free( )

- After free(p), the memory is no longer owned by the program.

  - Some other program may be using the memory! Data is lost

- Re-accessing the memory pointed by p causes undefined behaviour

```
int main(){
      int sum, *p;
      p = (int *) malloc(4*sizeof(int));
      // [some code here]
      free(p);
      sum = sum + *p; //Use after free issue
      // [some code here]
}
```

Memory pointed by p was freed and then used.
Program will cause undefined behaviour.
Valgrind reports memory error.

Don’t free something that did not come from malloc()

```
foo(int a){
   int b;
   int c[]={1,2,3};
   free(&a);
   free(&b);
   free(c);
}
```

- Only, dynamically created objects are stored in heap
- gcc gives warnings: “attempt to free a non-heap object”
- However, program crashes with segmentation fault

Valgrind reports memory errors

Double free problem

- Double free errors occur when free() is called more than once with the same memory address as an argument.

```
int main(){
        char *p1=malloc(1);
        char *p2=malloc(1);
        free(p1);
        free(p1);
}
```

- When free() is called twice with the same argument, the program's memory management data structures become corrupted

- Consequences: Program malfunction including security vulnerabilities

At runtime, modern OS detects double-free operation.
Program is aborted.

How to think about double free

```c
int main(){
      char *p1=malloc(1);
      char *p2=malloc(1);
      free(p1);
      free(p1);
}
```

Heap manager

Available blocks
…
…
p1
p1

- Every time free() is called, the address is added in the list of available memory blocks
- The last address added to the list can by the next malloc() call
- Since p1 is present twice in the list, next two memory allocations will have the same address (which is a problem)
- Valgrind reports memory error