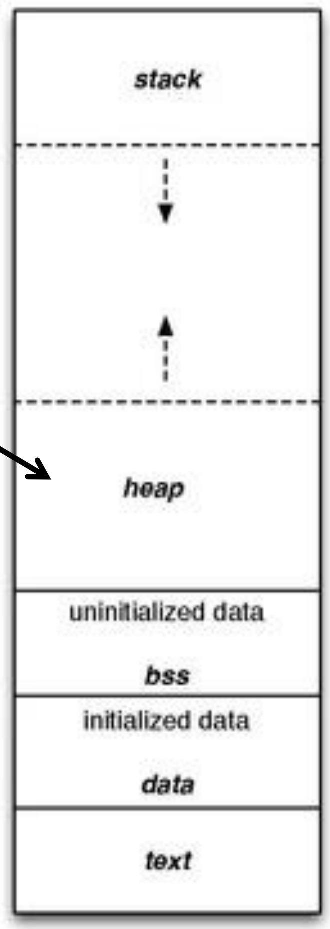
Recitation 10: Malloc Lab

What’s malloc?

- **A function to allocate memory during runtime (dynamic memory allocation).**
  - More useful when the size or number of allocations is unknown until runtime (e.g. data structures)
- **There’s a segment of memory addresses reserved almost exclusively for malloc to use.**
  - Your code directly manipulates the bytes of memory in this section.

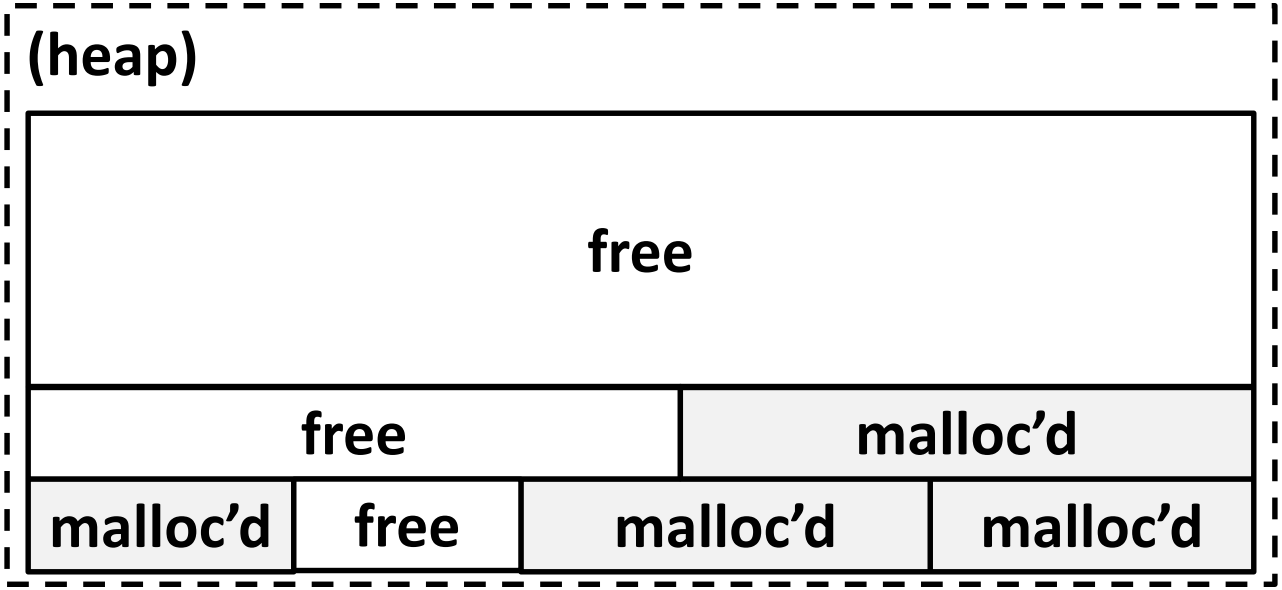


Outline

- Concept
- How to choose blocks
- Metadata
- Debugging / GDB Exercises

Malloc Internals

- The heap consists of blocks of memory



Concept

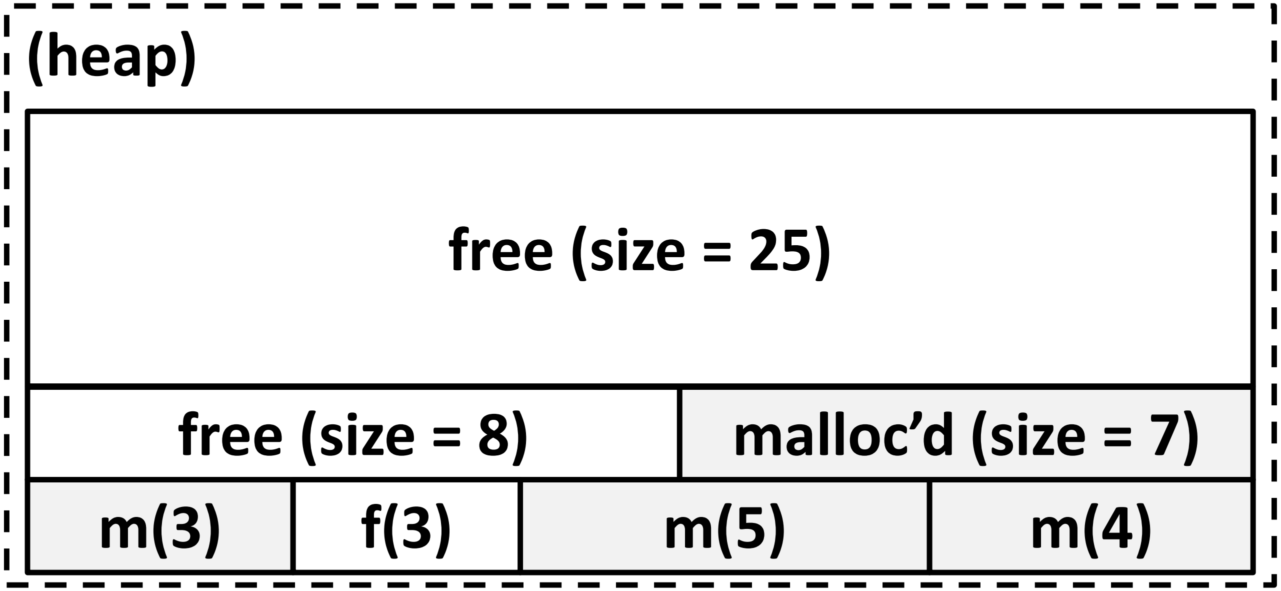
- Really, malloc only does three things:

1. Organize all blocks and store information about them in a structured way.
2. Using the structure made in 1), choose an appropriate location to allocate new memory.
3. Update the structure made in 1) when the user frees a block of memory.

This process occurs even for a complicated algorithm like segregated lists.

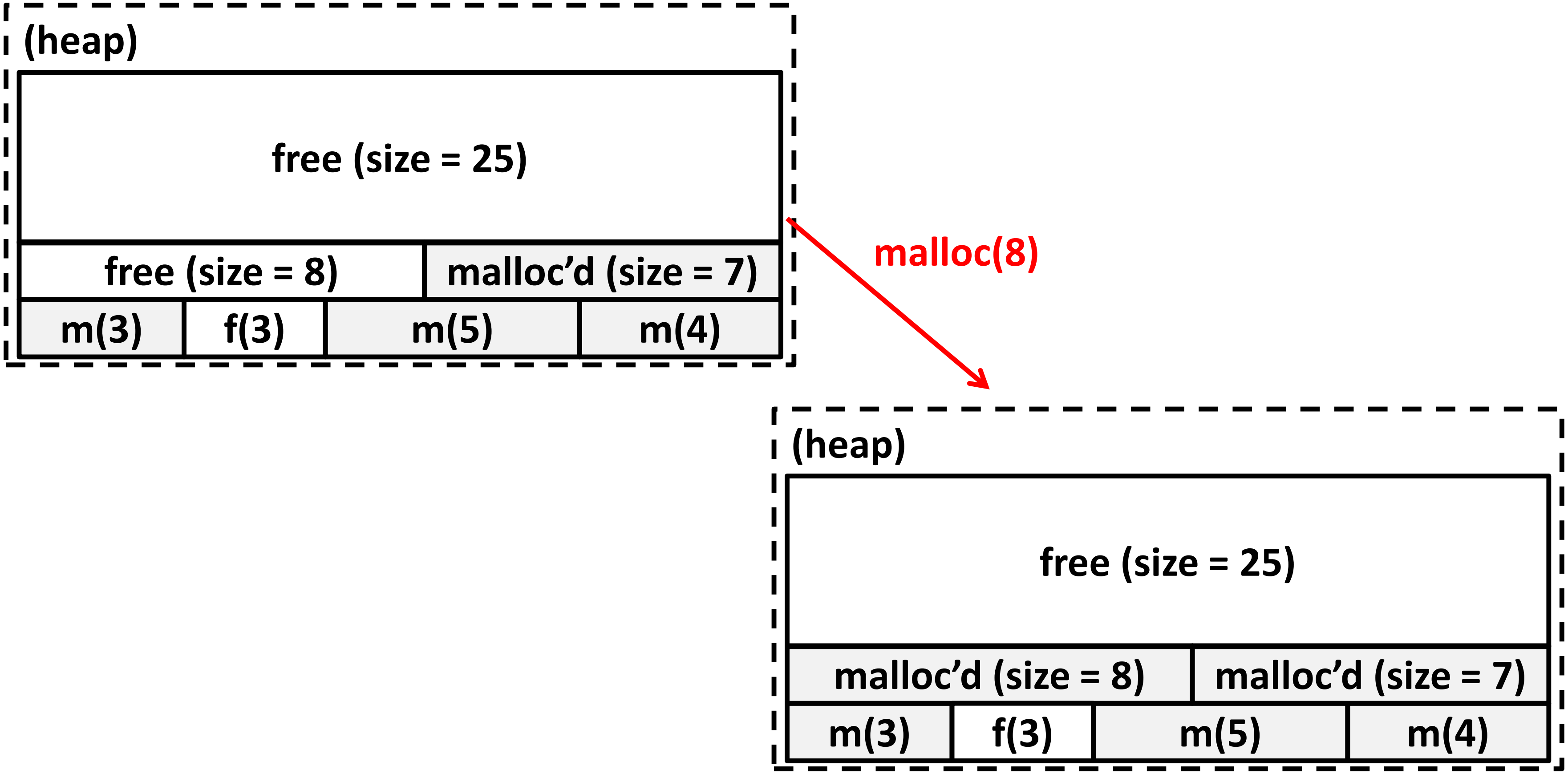
Concept (Implicit list)

1. Organize all blocks and store information about them in a structured way.



Concept (Implicit list)

2. **Using the structure made in 1), choose an appropriate location to allocate new memory.**



(heap)

free (size = 25)

free (size = 8) | malloc'd (size = 7)

m(3) | f(3) | m(5) | m(4)

malloc(8)

(heap)

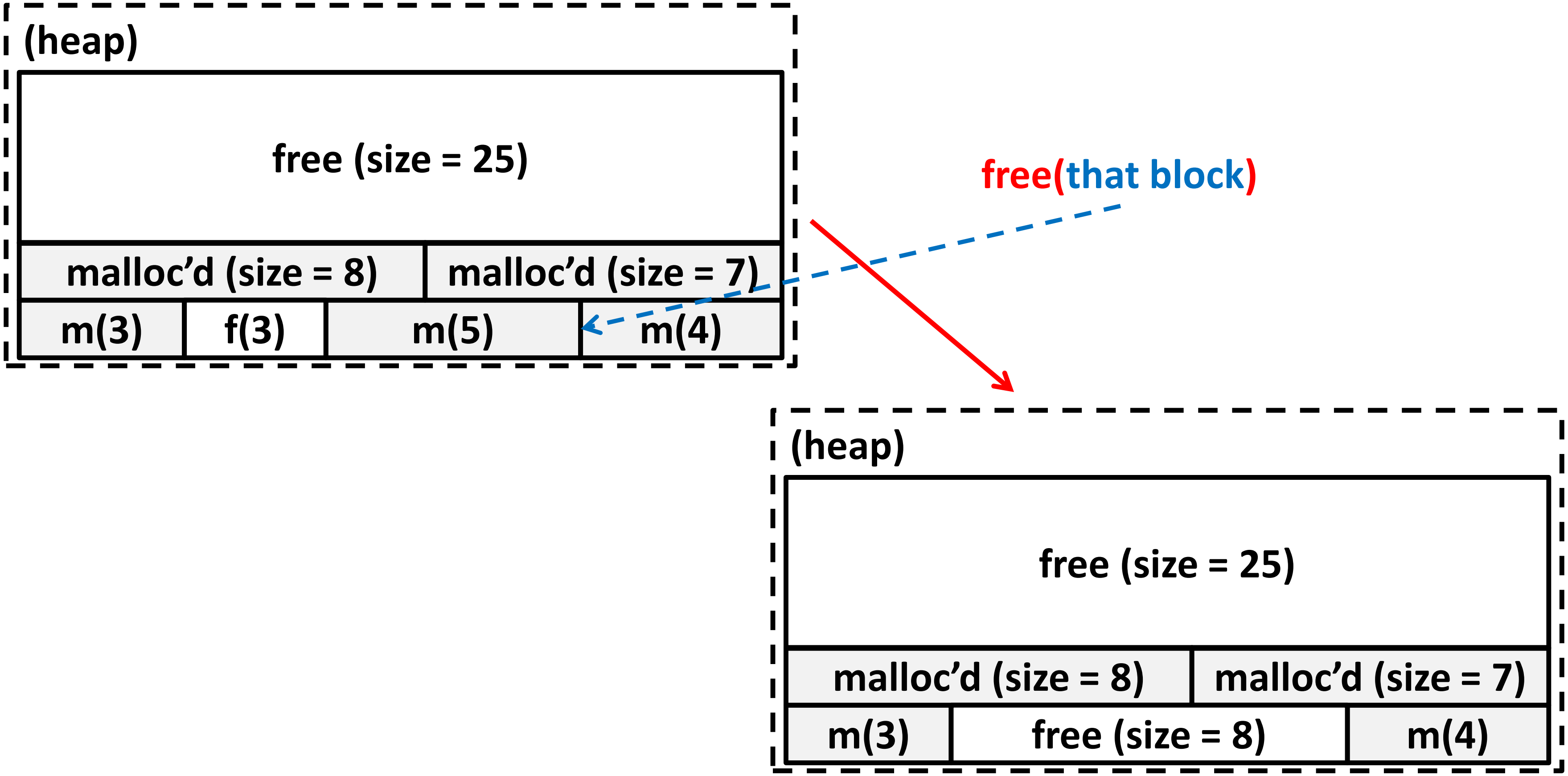
free (size = 25)

malloc'd (size = 8) | malloc'd (size = 7)

m(3) | f(3) | m(5) | m(4)

Concept (Implicit list)

3. Update the structure made in 1) when the user frees a block of memory.



(heap)

free (size = 25)

malloc’d (size = 8)

malloc’d (size = 7)

m(3)

f(3)

m(5)

m(4)

free(that block)

(heap)

free (size = 25)

malloc’d (size = 8)

malloc’d (size = 7)

m(3)

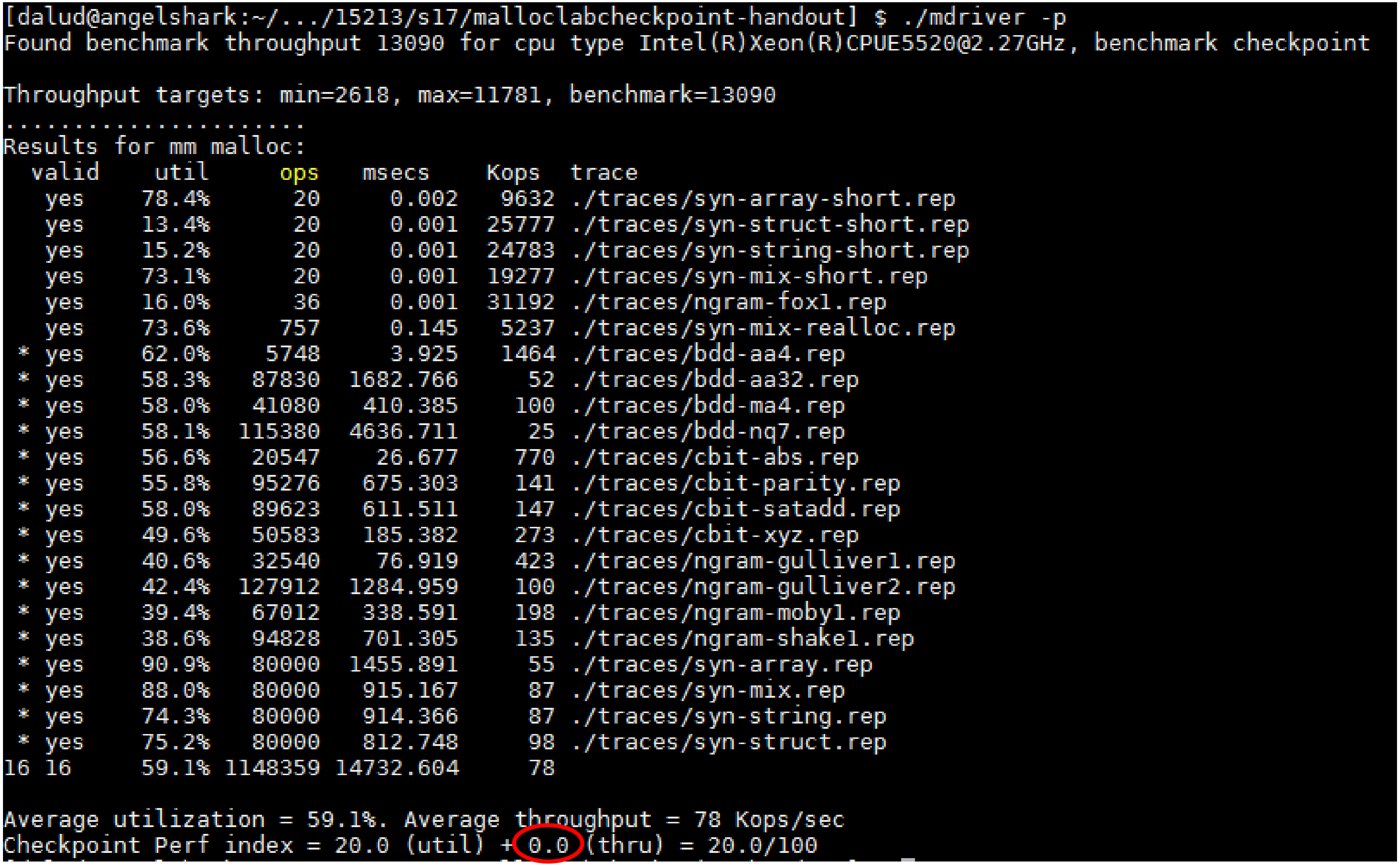
free (size = 8)

m(4)

Goals

- **Run as fast as possible**
- **Waste as little memory as possible**
  - Seemingly conflicting goals, but with cleverness you can do very well in both areas.

- **The simplest implementation is the implicit list. mm-baseline uses this method.**
  - Unfortunately…



```
[dalud@angelshark:~/.../15213/s17/malloclabcheckpoint-handout] $ ./mdriver -p
Found benchmark throughput 13090 for cpu type Intel(R)Xeon(R)CPUE5520@2.27GHz, benchmark checkpoint

Throughput targets: min=2618, max=11781, benchmark=13090
.....................
Results for mm malloc:
  valid    util      ops    msecs    Kops  trace
   yes    78.4%       20      0.002   9632 ./traces/syn-array-short.rep
   yes    13.4%       20      0.001  25777 ./traces/syn-struct-short.rep
   yes    15.2%       20      0.001  24783 ./traces/syn-string-short.rep
   yes    73.1%       20      0.001  19277 ./traces/syn-mix-short.rep
   yes    16.0%       36      0.001  31192 ./traces/ngram-fox1.rep
   yes    73.6%      757      0.145   5237 ./traces/syn-mix-realloc.rep
 * yes    62.0%     5748      3.925   1464 ./traces/bdd-aa4.rep
 * yes    58.3%    87830   1682.766     52 ./traces/bdd-aa32.rep
 * yes    58.0%    41080    410.385    100 ./traces/bdd-ma4.rep
 * yes    58.1%   115380   4636.711     25 ./traces/bdd-nq7.rep
 * yes    56.6%    20547     26.677    770 ./traces/cbit-abs.rep
 * yes    55.8%    95276    675.303    141 ./traces/cbit-parity.rep
 * yes    58.0%    89623    611.511    147 ./traces/cbit-satadd.rep
 * yes    49.6%    50583    185.382    273 ./traces/cbit-xyz.rep
 * yes    40.6%    32540     76.919    423 ./traces/ngram-gulliver1.rep
 * yes    42.4%   127912   1284.959    100 ./traces/ngram-gulliver2.rep
 * yes    39.4%    67012    338.591    198 ./traces/ngram-moby1.rep
 * yes    38.6%    94828    701.305    135 ./traces/ngram-shake1.rep
 * yes    90.9%    80000   1455.891     55 ./traces/syn-array.rep
 * yes    88.0%    80000    915.167     87 ./traces/syn-mix.rep
 * yes    74.3%    80000    914.366     87 ./traces/syn-string.rep
 * yes    75.2%    80000    812.748     98 ./traces/syn-struct.rep
16 16     59.1%  1148359  14732.604     78

Average utilization = 59.1%. Average throughput = 78 Kops/sec
Checkpoint Perf index = 20.0 (util) + 0.0 (thru) = 20.0/100
```

In case you didn't preview

- **Allocation methods, in a nutshell**
- **Implicit list: A list is implicitly formed by jumping between blocks, using knowledge about their sizes.**
- **Explicit list: Free blocks explicitly point to other blocks, like in a linked list.**
  - Understanding explicit list requires understanding implicit list
- **Segregated list: Multiple linked lists, each containing blocks in a certain range of sizes.**
  - Understanding segregated lists requires understanding explicit list

Choices

- **What kind of implementation to use?**
  - Implicit list, explicit list, segregated lists, binary tree methods …etc
  - Can use specialized strategies depending on the size of allocations
  - Adaptive algorithms are fine, though not necessary to get 100%.
    - But please, don’t directly test for which trace file is running.

- **What fit algorithm to use?**
  - Best fit: choose the smallest block that is big enough to fit the requested allocation size
  - First fit / next fit: search linearly starting from some location, and pick the first block that fits.
  - Which one’s faster, and which one uses less memory?

- **This lab has many more ways to get an A+ than, say, Cache lab part 2**

Finding a Best Block

- **Suppose you have implemented the explicit list approach**
  - You were using best fit with explicit lists

- **You experiment with using segregated lists instead. Still using best fits.**
  - Will your memory utilization score improve?

    Note: you don't have to implement seglists and run mdriver to answer this. That's, uh, hard to do within one recitation session.

  - What other advantages does segregated lists provide?
- **Losing memory because of the way you choose your free blocks is called external fragmentation.**

Metadata

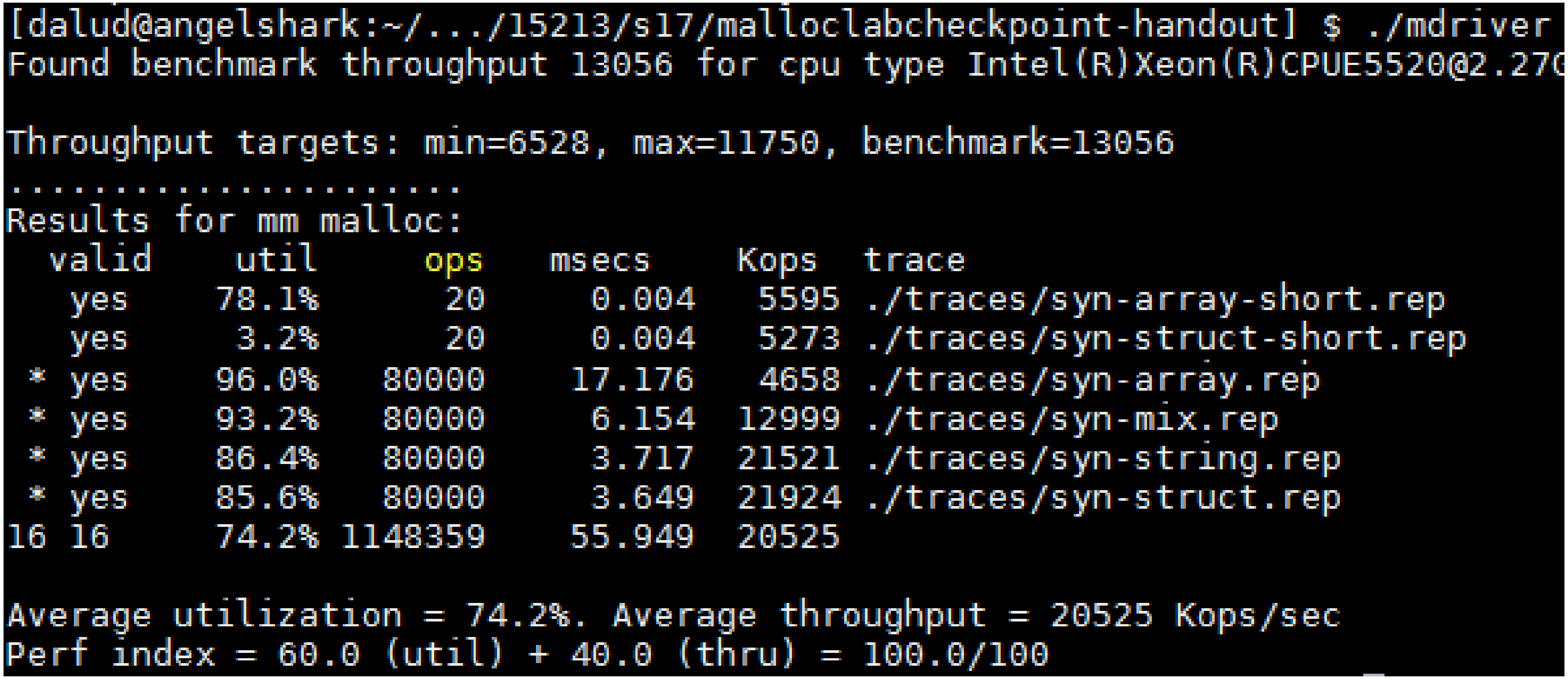
- **All blocks need to store some data about themselves in order for `malloc` to keep track of them (e.g. headers)**
  - This takes memory too…
  - Losing memory for this reason is called internal fragmentation.
- **What data might a block need?**
  - Does it depend on the malloc implementation you use?
  - Is it different between free and allocated blocks?
- **Can we use the extra space in free blocks?**
  - Or do we have to leave the space alone?
- **How can we overlap two different types of data at the same location?**

Hey, your malloc worked! GJ.

Setting up the blocks, metadata, lists… etc (500 LoC)

+ Finding and allocating the right blocks (500 LoC)

+ Updating your heap structure when you free (500 LoC) =



```
[dalud@angelshark:~/.../15213/s17/malloclabcheckpoint-handout] $ ./mdriver
Found benchmark throughput 13056 for cpu type Intel(R)Xeon(R)CPUE5520@2.27G

Throughput targets: min=6528, max=11750, benchmark=13056
......................
Results for mm malloc:
  valid    util      ops    msecs    Kops  trace
   yes    78.1%       20    0.004    5595 ./traces/syn-array-short.rep
   yes     3.2%       20    0.004    5273 ./traces/syn-struct-short.rep
 * yes    96.0%    80000   17.176    4658 ./traces/syn-array.rep
 * yes    93.2%    80000    6.154   12999 ./traces/syn-mix.rep
 * yes    86.4%    80000    3.717   21521 ./traces/syn-string.rep
 * yes    85.6%    80000    3.649   21924 ./traces/syn-struct.rep
16 16     74.2%  1148359   55.949   20525

Average utilization = 74.2%. Average throughput = 20525 Kops/sec
Perf index = 60.0 (util) + 40.0 (thru) = 100.0/100
```

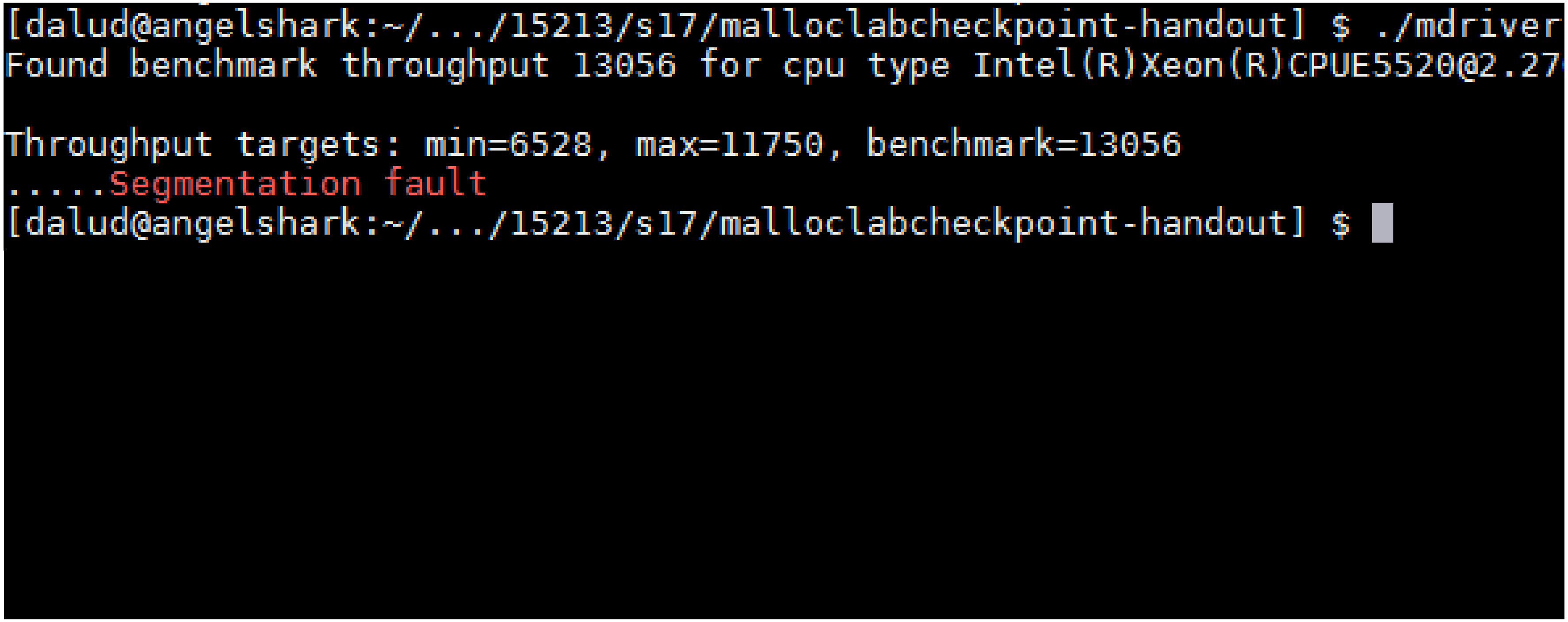
Nope. Have fun debugging your code!

Setting up the blocks, metadata, lists… etc (500 LoC)

+ Finding and allocating the right blocks (500 LoC)

+ Updating your heap structure when you free (500 LoC)

+ One bug, somewhere lost in those 1500 LoC =



```
[dalud@angelshark:~/.../15213/s17/malloclabcheckpoint-handout] $ ./mdriver
Found benchmark throughput 13056 for cpu type Intel(R)Xeon(R)CPUE5520@2.27

Throughput targets: min=6528, max=11750, benchmark=13056
.....Segmentation fault
[dalud@angelshark:~/.../15213/s17/malloclabcheckpoint-handout] $ 
```

GDB Practice

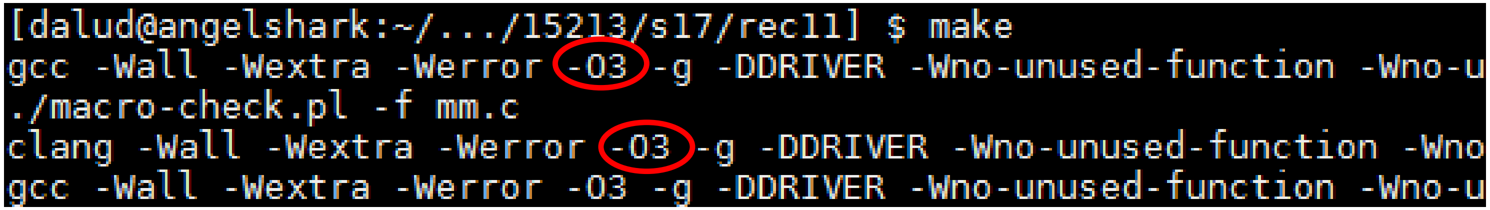
- **Using GDB well in malloclab can save you HOURS[*] of debugging time**
  - Average 20 hours using GDB for “B” on malloclab
  - Average 23 hours not using GDB for “B” on malloclab

- **Form pairs**
  - Login to a shark machine
  - wget http://www.cs.cmu.edu/~213/activities/rec11.tar
  - tar xf rec11.tar
  - cd rec11
  - make
- **Two buggy mdrivers**

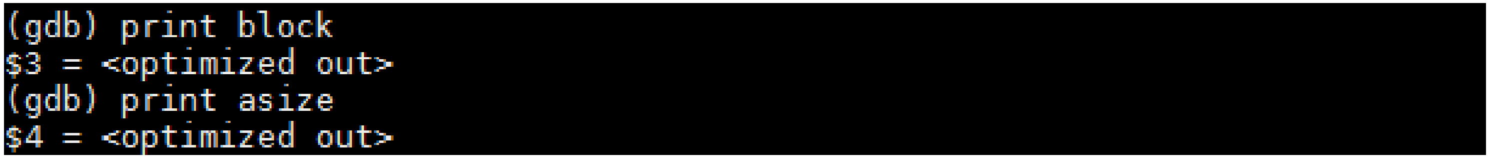
***Average time is based on Summer 2016 survey results**

First things first

- Try running $ **`make`**
  - If you look closely, our code compiles your `malloc` implementation with the `-O3` flag.
  - This is an optimization flag. `-O3` makes your code run as efficiently as the compiler can manage, but also makes it horrible for debugging (almost everything is “optimized out”).



```
[dalud@angelshark:~/.../15213/s17/rec11] $ make
gcc -Wall -Wextra -Werror -O3 -g -DDRIVER -Wno-unused-function -Wno-u
./macro-check.pl -f mm.c
clang -Wall -Wextra -Werror -O3 -g -DDRIVER -Wno-unused-function -Wno
gcc -Wall -Wextra -Werror -O3 -g -DDRIVER -Wno-unused-function -Wno-u
```



```
(gdb) print block
$3 = <optimized out>
(gdb) print asize
$4 = <optimized out>
```

Debugging mdriver

```
$ gdb --args ./mdriver -c traces/syn-mix-short.rep
(gdb) run
(gdb) backtrace
(gdb) list
```

Optional: Type Ctrl-X Ctrl-A to see the source code. Don’t linger there for long, since this visual mode is buggy. Type that key combination again to go back to console mode.

1) What function is listed on the top of backtrace?

2) What line of code crashed?

3) How did that line cause the crash?

Debugging mdriver

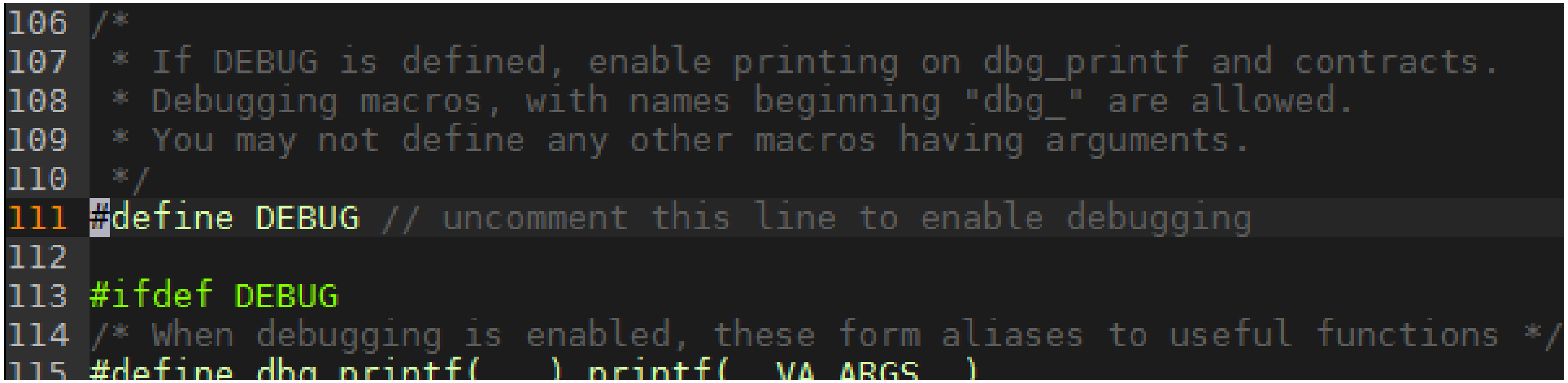
- (gdb) `x /10gx block`
  - Shows the memory contents within the block
  - In particular, look for the header.
- **Remember the output from** (gdb) `bt?`
- (gdb) `frame 1`
  - Jumps to the function one level down the call stack (aka the function that called `write_footer`)
  - Ctrl-X, Ctrl-A again if you want to see visuals
- **What was the caller function? What is its purpose?**
  - Was it writing to `block` or `block_next` when it crashed?

Thought process while debugging

- **`write_footer` crashed because it got the wrong address for the footer…**
- **The address was wrong because the header of the block was some garbage value**
  - Since `write_footer` uses `get_size(block)` after all
- **But why in the world does the header contain garbage??**
  - The crash happened in `place`, which basically splits a free block into two and uses the first one to store things.
  - Hm, `block_next` would be the new block created after the split? The one on the right?
  - The header would be in the middle of the original free block actually. Wait, but I wrote a new header before I wrote the footer!
    - Right? …Oh, I didn't. Darn.

Heap consistency checker

- mm-2.c activates debug mode, and so mm_checkheap runs at the beginning and end of many of its functions.



```
/*
 * If DEBUG is defined, enable printing on dbg_printf and contracts.
 * Debugging macros, with names beginning "dbg_" are allowed.
 * You may not define any other macros having arguments.
 */
#define DEBUG // uncomment this line to enable debugging

#ifdef DEBUG
/* When debugging is enabled, these form aliases to useful functions */
#define dbg_printf(...) printf(__VA_ARGS__)
```

- The next bug will be a total nightmare to find without this heap consistency checker*.

*Even though the checker in mm-2.c is short and buggy

Now you try debugging this

```
$ gdb --args ./mdriver-2 -c traces/syn-array-short.rep
```

`mm_checkheap` will fail. What reason does it cite?

Where's the footer? Use `x  /gx` and some arithmetic

Track changes in the header and the footer:

```
(gdb) watch *[header address]
(gdb) watch *[footer address]
```

When does the footer's value turn inconsistent? What function was running at the time? Which part of that function was wrong? Use `backtrace` and `frame`.

MallocLab Checkpoint

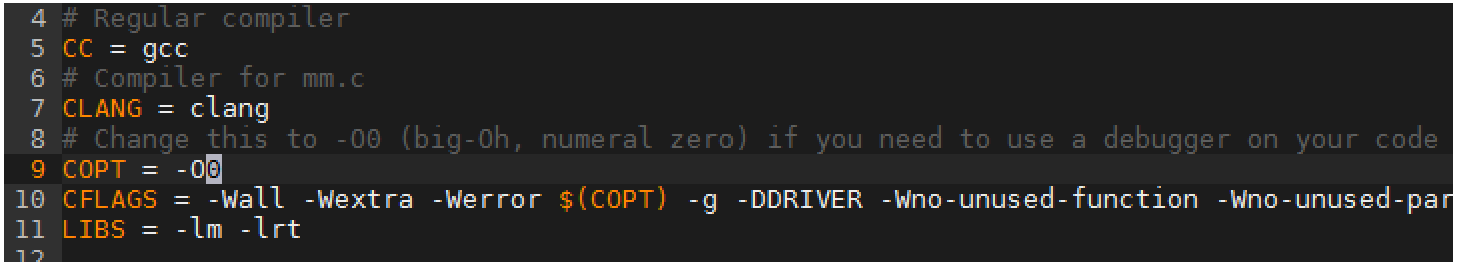
- Due ***Thursday***
- Checkpoint should take a bit less than half of the time
- Read the writeup. Slowly. Carefully.
- Use GDB
- Ask us for debugging help
  - Only after you implement mm_checkheap though

Appendix: Advanced GDB Usage

- **`backtrace`: Shows the call stack**
- **`frame`: Lets you go to one of the levels in the call stack**
- **`list`: Shows source code**
- **`print <expression>`:**
  - Runs any valid C command, even something with side effects like mm_malloc(10) or mm_checkheap(1337)
- **`watch <expression>`:**
  - Breaks when the value of the expression changes
- **`break <function / line> if <expression>`:**
  - Only stops execution when the expression holds true
- **Ctrl-X Ctrl-A for visualization**

Appendix: Building O0

- **Edit the file named `Makefile` and make it use `-O0`**



```
# Regular compiler
CC = gcc
# Compiler for mm.c
CLANG = clang
# Change this to -O0 (big-Oh, numeral zero) if you need to use a debugger on your code
COPT = -O0
CFLAGS = -Wall -Wextra -Werror $(COPT) -g -DDRIVER -Wno-unused-function -Wno-unused-par
LIBS = -lm -lrt
```

- **Then run `$ make -B`**
  - Alternative: `$ make clean` `$ make`
  - Just running `make` won't work because it'll say nothing new needs to be compiled. So we force it to recompile.
- **Remember to set it back to `–O3` when you're done to test throughput, since `-O0` makes your code much slower.**