Exam 2 Review

COSC 208, Introduction to Computer Systems, 2022-04-05

Announcements

- Exam 2 (this week; study guide posted on Moodle)
- No lab this week
- Project 3 due Thurs, Apr 14

Outline

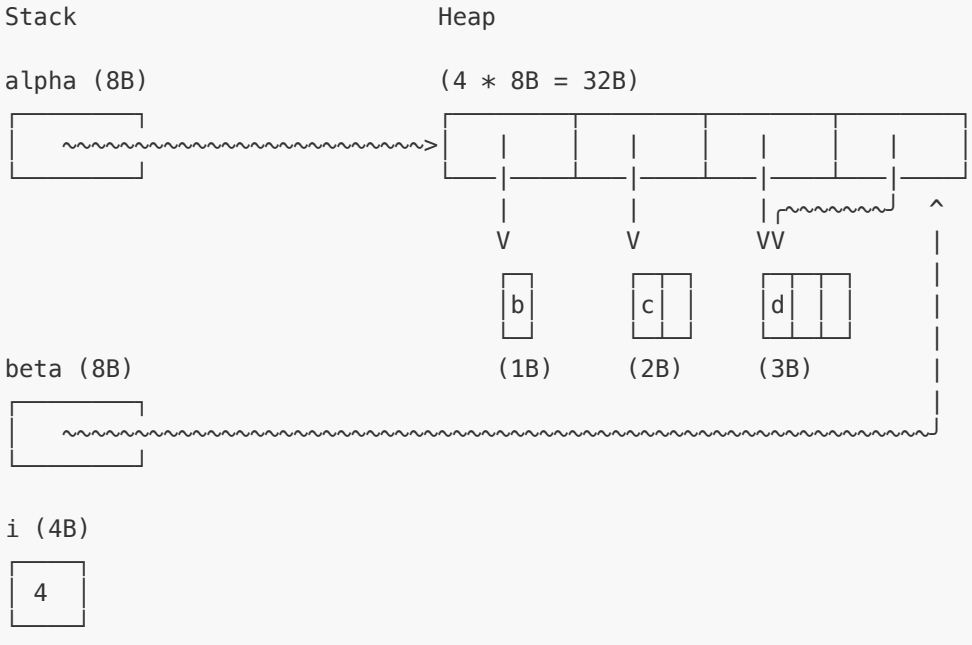
- Exam 2 review

No warm-up — happy Monday!

Dynamic memory allocation

Q1: *The function below allocates several regions of memory on the heap. Draw a diagram that depicts the contents of the stack and heap at the end of main. Label each memory region with its size in bytes.)*

```c
#include <stdlib.h>
int main() {
    char **alpha = malloc(sizeof(char *) * 4);
    char **beta = alpha;
    for (int i = 1; i < 4; i++) {
        alpha[i] = malloc(i);
        *alpha[i] = i + 'a';
        *beta = alpha[i];
        beta++;
    }
}
```

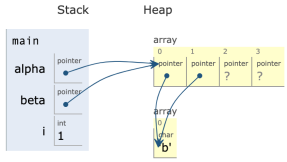


C (gcc 9.3, C17 + GNU extensions)
(known limitations)

```
1  #include <stdlib.h>
2  int main() {
3      char **alpha = malloc(sizeof(char *) * 4);
4      char **beta = alpha;
5      for (int i = 1; i < 4; i++) {
6          alpha[i] = malloc(sizeof(char) * i);
7          *alpha[i] = i + 'a';
8          *beta = alpha[i];
9          beta++;
10     }
11 }
```

Edit this code

line that just executed
next line to execute

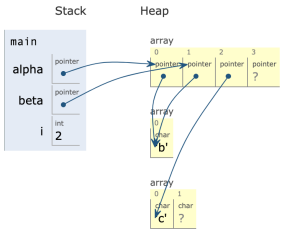


C (gcc 9.3, C17 + GNU extensions)
(known limitations)

```
1  #include <stdlib.h>
2  int main() {
3      char **alpha = malloc(sizeof(char *) * 4);
4      char **beta = alpha;
5      for (int i = 1; i < 4; i++) {
6          alpha[i] = malloc(sizeof(char) * i);
7          *alpha[i] = i + 'a';
8          *beta = alpha[i];
9          beta++;
10     }
11 }
```

Edit this code

line that just executed
next line to execute

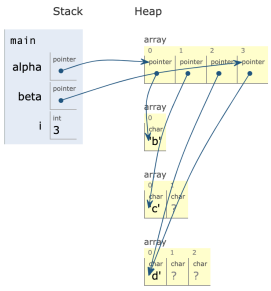


C (gcc 9.3, C17 + GNU extensions)
(known limitations)

```
1  #include <stdlib.h>
2  int main() {
3      char **alpha = malloc(sizeof(char *) * 4);
4      char **beta = alpha;
5      for (int i = 1; i < 4; i++) {
6          alpha[i] = malloc(sizeof(char) * i);
7          *alpha[i] = i + 'a';
8          *beta = alpha[i];
9          beta++;
10     }
11 }
```

Edit this code

line that just executed
next line to execute



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Step 19 of 20

Customize visualization

Data structures using dynamic memory allocation

Q2: *The following code provides a function to add an integer value to the end of a queue:*

```
#include <stdlib.h>
struct item {
    int value;
    struct item *next;
}
struct item *enqueue(struct item *head, int value) {
    // Allocate new item and populate
    struct item *new = malloc(sizeof(struct item));
    new->value = value;
    new->next = NULL;

    // Item becomes new head if queue is empty
    if (NULL == head) {
        return next;
    }

    // Item goes at the end of the queue
    while (head->next != NULL) {
        head = head->next;
    }
    head->next = new;
    return new;
}
```

Write a corresponding `dequeue` function that removes the head of the queue, stores its value in the memory location pointed to by the `result` argument, and returns the new head (which may be `NULL`). If the queue is empty, return `NULL` and leave the contents of result untouched. Your function should be written such that there are no memory leaks.

```
struct item *dequeue(struct item *head, int *result) {
    // Do nothing if queue is empty
    if (NULL == head) {
        return NULL;
    }

    *result = head->value;
    struct item *new_head = head->next;
    free(head);
    return new_head;
}
```

Assembly

C code

```c
int interest_due(int outstanding, int rate) {
    int divisor = 12 * 100;
    int annual = outstanding * rate;
    int monthly = annual / divisor;
    return monthly;
}

int make_payment(int outstanding, int payment, int rate) {
    int interest = interest_due(outstanding, rate);
    int principal = payment - interest;
    if (principal > outstanding) {
        outstanding = 0;
    } else {
        outstanding -= principal;
    }
    return outstanding;
}

int months_remain(int outstanding, int payment, int rate) {
    int months = 0;
    while (outstanding > 0) {
        months++;
        outstanding = make_payment(outstanding, payment, rate);
    }
    return months;
}

int main() {
    int outstanding = 0, payment = 0, rate = 0;
    printf("Outstanding principal: $");
    scanf("%d", &outstanding);
    printf("Monthly payment: $");
    scanf("%d", &payment);
    printf("Interest rate: ");
    scanf("%d", &rate);
    int remain = months_remain(outstanding, payment, rate);
    printf("Your loan will be paid off in %d months\n", remain);
}
```

Assembly code

```
00000000004005d4 <interest_due>:
  4005d4:    d10083ff     sub    sp, sp, #0x20
  4005d8:    b9001fe0     str    w0, [sp, #28]
  4005dc:    b9001be1     str    w1, [sp, #24]
  4005e0:    52809608     mov    w8, #0x4b0
  4005e4:    b90017e8     str    w8, [sp, #20]
  4005e8:    b9401fe8     ldr    w8, [sp, #28]
  4005ec:    b9401be9     ldr    w9, [sp, #24]
  4005f0:    1b097d08     mul    w8, w8, w9
  4005f4:    b90013e8     str    w8, [sp, #16]
  4005f8:    b94013e8     ldr    w8, [sp, #16]
  4005fc:    b94017e9     ldr    w9, [sp, #20]
  400600:    1ac90d08     sdiv   w8, w8, w9
  400604:    b9000fe8     str    w8, [sp, #12]
  400608:    b9400fe0     ldr    w0, [sp, #12]
  40060c:    910083ff     add    sp, sp, #0x20
  400610:    d65f03c0     ret

0000000000400614 <make_payment>:
  400614:    d100c3ff     sub    sp, sp, #0x30
  400618:    f90013fe     str    x30, [sp, #32]
  40061c:    b9001fe0     str    w0, [sp, #28]
  400620:    b9001be1     str    w1, [sp, #24]
  400624:    b90017e2     str    w2, [sp, #20]
  400628:    b9401fe0     ldr    w0, [sp, #28]
  40062c:    b94017e1     ldr    w1, [sp, #20]
  400630:    97fffe9      bl     4005d4 <interest_due>
  400634:    b90013e0     str    w0, [sp, #16]
  400638:    b9401be8     ldr    w8, [sp, #24]
  40063c:    b94013e9     ldr    w9, [sp, #16]
  400640:    6b090108     subs   w8, w8, w9
  400644:    b9000fe8     str    w8, [sp, #12]
  400648:    b9400fe8     ldr    w8, [sp, #12]
  40064c:    b9401fe9     ldr    w9, [sp, #28]
  400650:    6b09011f     cmp    w8, w9
  400654:    5400006d     b.le   400660 <make_payment+0x4c>
  400658:    b9001fff     str    wzr, [sp, #28]
  40065c:    14000005     b      400670 <make_payment+0x5c>
  400660:    b9400fe8     ldr    w8, [sp, #12]
  400664:    b9401fe9     ldr    w9, [sp, #28]
  400668:    6b080128     subs   w8, w9, w8
  40066c:    b9001fe8     str    w8, [sp, #28]
  400670:    b9401fe0     ldr    w0, [sp, #28]
  400674:    f94013fe     ldr    x30, [sp, #32]
  400678:    9100c3ff     add    sp, sp, #0x30
  40067c:    d65f03c0     ret
```

```
0000000000400680 <months_remain>:
  400680:    d10083ff     sub    sp, sp, #0x20
  400684:    f9000bfe     str    x30, [sp, #16]
  400688:    b9000fe0     str    w0, [sp, #12]
  40068c:    b9000be1     str    w1, [sp, #8]
  400690:    b90007e2     str    w2, [sp, #4]
  400694:    b90003ff     str    wzr, [sp]
  400698:    b9400fe8     ldr    w8, [sp, #12]
  40069c:    7100011f     cmp    w8, #0x0
  4006a0:    37000148     b.le   4006c8 <months_remain+0x4c>
  4006a4:    b94003e8     ldr    w8, [sp]
  4006a8:    11000508     add    w8, w8, #0x1
  4006ac:    b90003e8     str    w8, [sp]
  4006b0:    b9400fe0     ldr    w0, [sp, #12]
  4006b4:    b9400be1     ldr    w1, [sp, #8]
  4006b8:    b94007e2     ldr    w2, [sp, #4]
  4006bc:    97ffffd5     bl     400614 <make_payment>
  4006c0:    b9000fe0     str    w0, [sp, #12]
  4006c4:    17fffff4     b      400698 <months_remain+0x18>
  4006c8:    b94003e0     ldr    w0, [sp]
  4006cc:    f9400bfe     ldr    x30, [sp, #16]
  4006d0:    910083ff     add    sp, sp, #0x20
  4006d4:    d65f03c0     ret
```

Mapping assembly code to C source code

Q1: *For each line of assembly code, indicate which line of C code was used to generate that line of assembly code.*

```
00000000004005d4 <interest_due>:
  4005d4:    d10083ff     sub    sp, sp, #0x20   // 1
  4005d8:    52809608     mov    w8, #0x4b0      // 2
  4005dc:    b9001fe0     str    w0, [sp, #28]   // 1
  4005e0:    b9001be1     str    w1, [sp, #24]   // 1
  4005e4:    b90017e8     str    w8, [sp, #20]   // 2
  4005e8:    b9401fe8     ldr    w8, [sp, #28]   // 3
  4005ec:    b9401be9     ldr    w9, [sp, #24]   // 3
  4005f0:    1b097d08     mul    w8, w8, w9      // 3
  4005f4:    b90013e8     str    w8, [sp, #16]   // 3
  4005f8:    b94013e8     ldr    w8, [sp, #16]   // 4
  4005fc:    b94017e9     ldr    w9, [sp, #20]   // 4
  400600:    1ac90d08     sdiv   w8, w8, w9      // 4
  400604:    b9000fe8     str    w8, [sp, #12]   // 4
  400608:    b9400fe0     ldr    w0, [sp, #12]   // 5
  40060c:    910083ff     add    sp, sp, #0x20   // 5
  400610:    d65f03c0     ret                    // 5
```

Q2: *For each line of assembly code, indicate which line of C code was used to generate that line of assembly code.*

```
0000000000400614 <make_payment>:
  400614:    d100c3ff     sub    sp, sp, #0x30   // 8
  400618:    f90013fe     str    x30, [sp, #32]  // 8
  40061c:    b9001fe0     str    w0, [sp, #28]   // 8
  400620:    b9001be1     str    w1, [sp, #24]   // 8
  400624:    b90017e2     str    w2, [sp, #20]   // 8
  400628:    b9401fe0     ldr    w0, [sp, #28]   // 9
  40062c:    b94017e1     ldr    w1, [sp, #20]   // 9
  400630:    97ffffe9     bl     4005d4 <interest_due> // 9
  400634:    b90013e0     str    w0, [sp, #16]   // 9
  400638:    b9401be8     ldr    w8, [sp, #24]   // 10
  40063c:    b94013e9     ldr    w9, [sp, #16]   // 10
  400640:    6b090108     subs   w8, w8, w9      // 10
  400644:    b9000fe8     str    w8, [sp, #12]   // 10
  400648:    b9400fe8     ldr    w8, [sp, #12]   // 11
  40064c:    b9401fe9     ldr    w9, [sp, #28]   // 11
  400650:    6b09011f     cmp    w8, w9          // 11
  400654:    5400006d     b.le   400660 <make_payment+0x4c>  // 11
  400658:    b9001fff     str    wzr, [sp, #28]  // 12
  40065c:    14000005     b      400670 <make_payment+0x5c>  // 13
  400660:    b9400fe8     ldr    w8, [sp, #12]   // 14
  400664:    b9401fe9     ldr    w9, [sp, #28]   // 14
  400668:    6b080128     subs   w8, w9, w8      // 14
  40066c:    b9001fe8     str    w8, [sp, #28]   // 14
  400670:    b9401fe0     ldr    w0, [sp, #28]   // 16
  400674:    f94013fe     ldr    x30, [sp, #32]  // 16
  400678:    9100c3ff     add    sp, sp, #0x30   // 16
  40067c:    d65f03c0     ret                    // 16
```

Translating assembly into low-level C code

Q3: *For each of the following lines of assembly, write one or more lines of low-level C code that express the semantics (i.e., meaning) of the assembly code. Your C code should use register names as variable names.*

```
0000000000400614 <make_payment>:
  400614:    d100c3ff     sub    sp, sp, #0x30   // sp = sp - 0x30
  400618:    f90013fe     str    x30, [sp, #32]  // *(sp + 32) = x30
  40061c:    b9001fe0     str    w0, [sp, #28]   // *(sp + 28) = w0
  400620:    b9001be1     str    w1, [sp, #24]   // *(sp + 24) = w1
  400624:    b90017e2     str    w2, [sp, #20]   // *(sp + 20) = w2
  400628:    b9401fe0     ldr    w0, [sp, #28]   // w0 = *(sp + 28)
  40062c:    b94017e1     ldr    w1, [sp, #20]   // w1 = *(sp + 20)
  400630:    97ffffe9     bl     4005d4 <interest_due> // x30 = pc (0x634); pc =
0x5d4
  400634:    b90013e0     str    w0, [sp, #16]   // *(sp + 16) = w0
  400638:    b9401be8     ldr    w8, [sp, #24]   // w8 = *(sp + 24)
  40063c:    b94013e9     ldr    w9, [sp, #16]   // w8 = *(sp + 16)
  400640:    6b090108     subs    w8, w8, w9    // w8 = w8 - w9
  400644:    b9000fe8     str    w8, [sp, #12]   // *(sp + 12) = w8
  400648:    b9400fe8     ldr    w8, [sp, #12]   // w8 = *(sp + 12)
  40064c:    b9401fe9     ldr    w9, [sp, #28]   // w9 = *(sp + 28)
  400650:    6b09011f     cmp    w8, w9          // if (w8 <= w9)
  400654:    5400006d     b.le   400660 <make_payment+0x4c>  // pc = 0x660
  400658:    b9001fff     str    wzr, [sp, #28]  // *(sp + 28) = 0
  40065c:    14000005     b      400670 <make_payment+0x5c>  // pc = 0x670
  400660:    b9400fe8     ldr    w8, [sp, #12]   // w8 = *(sp + 12)
  400664:    b9401fe9     ldr    w9, [sp, #28]   // w9 = *(sp + 28)
  400668:    6b080128     subs   w8, w9, w8      // w8 = w9 - w8
  40066c:    b9001fe8     str    w8, [sp, #28]   // *(sp + 28) = w8
  400670:    b9401fe0     ldr    w0, [sp, #28]   // w0 = *(sp + 28)
  400674:    f94013fe     ldr    x30, [sp, #32]  // x30 = *(sp + 32)
  400678:    9100c3ff     add    sp, sp, #0x30   // sp = sp + 0x30
  40067c:    d65f03c0     ret                    // pc = x30
```

Transforming C code to use goto

Q4: *Create a `make_payment_goto` function that behaves the same as the `make_payment` function but uses `goto` statements, just as a compiler would do when generating assembly code.*

```c
void make_payment_goto(int outstanding, int payment, int rate) {
  int interest = interest_due(outstanding, rate);
  int principal = payment - interest);
  if (principal <= outstanding)
    goto ELSE;
  outstanding = 0;
  goto END;
ELSE:
  outstanding == principal;
END:
  return outstanding;
}
```

Q5: *Create a `months_remain_goto` function that behaves the same as the `months_remain` function but uses `goto` statements, just as a compiler would do when generating assembly code.*

```c
int months_remain_goto(int outstanding, int pyament, int rate) {
  int months = 0;
LOOP:
  if (oustanding <= 0)
    goto END;
  months++;
  oustanding = make_payment(&outstanding, payment, rate);
  goto LOOP;
END:
  return months;
}
```

Tracing assembly code

Q6: *Assume the code starts executing at the beginning of the `make_payment` function (i.e., `pc = 0x400614`). Draw a diagram that shows the contents of the stack and registers immediately before executing the `ret` instruction in the `interest_due` function (i.e., before executing the assembly instruction at address `0x400610`). Your stack and registers should contain values (e.g., `0x400614`) not variable or register names.*

Assume the initial values of the registers are as follows:

- `pc = 0x4006c0`
- `sp = 0xf80`
- `w0 = 100000`
- `w1 = 500`
- `w2 = 3`
- `x30 = 0x96c`

Final register values:

- `pc = 0x400610`
- `sp = 0xF50`
- `w/x0 = 250`
- `w/x1 = 3`
- `w/x2 = 3`
- `w/x8 = 250`
- `w/x9 = 0x4B0`
- `x30 = 0x400634`

Final stack: