Midterm Review

Introduction to Computer Systems, Fall 2024

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Midterm Review: Which Topic Next?

- Binary & 2C
- Binary C Programming
- C: Memory Diagrams
- C Programming: Strings & Output Parameters
- C Programming: Malloc & Double Pointers
- CMOS, PLA, Gates
- Gate Delay
- Combinatorial Logic: Mux

Logistics

- Midterm Exam: **This Thursday "in lecture"**
  - Details released on the course website
- Midterm Review in recitation
  - @4pm tomorrow (DRL 3C6)
  - Extra Recitation offering at 7:30 tomorrow (Towne 100)
- HW04 Sample solutions and grades posted yesterday
- HW05 Sample Solutions (and grades probably) posted tonight

Binary & 2C

- There are about 236 students in the class and 27 staff. If we wanted to assign each of these individuals a unique numerical ID, how many bits would each ID need to be?

- Translate:
  - -1 into 4-bit 2C
  - 7 into 4-bit 2c
  - 7 into 8-bit 2c
  - 5 into 3bit unsigned

Binary & 2C

- There are about 195 students in the class and 22 staff. If we wanted to assign each of these individuals a unique numerical ID, how many bits would each ID need to be?
  - 236 + 27 = 263. smallest power of 2 that is greater than 263 is 512 2^9. So 9 bits needed. (N bits can represent 2^N different values)
- Translate:
  - -1 into 4-bit 2C
    - 1111 // -8 + 4 + 2 + 1 = -1 (and -1 is always the all 1 bit pattern)
  - 7 into 4-bit 2c
    - 0111 // $(-1 * 0 * 2^3) + 1 * 2^2 + 1 * 2^1 + 1*2^0 = 0 + 4 + 2 + 1 = 7$
  - 7 into 8-bit 2c:
    - 0000 0111 already, had 7 from above with 4 bits. Add leading zeros to leave the numerical value unchanged.
  - 5 into 3bit unsigned 101 // $1 * 2^2 + 0 * 2^1 + 1*2^0 = 4 + 0 + 1 = 5$

Binary C Programming

- Write the function `reverse_bits()` which takes an unsigned integer and returns a new unsigned integer but with the bits reversed
  - Assume `unsigned int` is 32 bits long
  - Input: `0000 … 0001` returns `1000 … 0000` (only 1 bit is a 1)
  - Input : `1111 … 1111` returns `1111 … 1111` (all bits are 1)

```
unsigned int reverse_bits(unsigned int num) {









}
```

Binary C Programming

- Write the function `reverse_bits()` which takes an unsigned integer and returns a new unsigned integer but with the bits reversed
  - Assume `unsigned int` is 32 bits long

```c
unsigned int reverse_bits(unsigned int num) {
  unsigned int result = 0;
  for (int i = 0; i < 32 ; i++) {
    result = result << 1;  // shift result to make room
                           // for next bit

    unsigned int lsb = num & 1; // get lsb of num
    result = result | lsb;  // add the lsb to result

    num = num >> 1;  // shift num to right to get next bit
  }
  return result;
}
```

C: Memory Diagrams

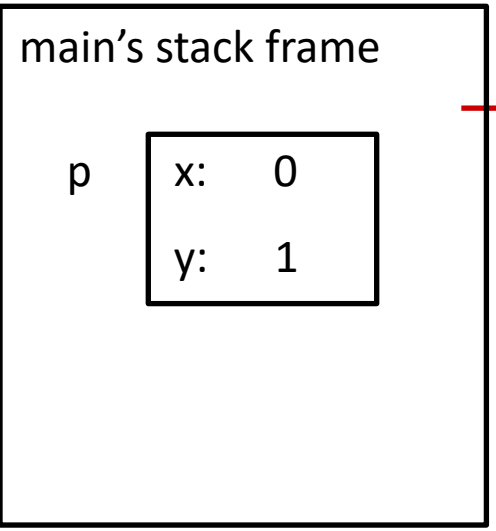
```c
typedef struct {
  int x;
  int y;
} pair;

typedef struct {
  pair* data;
  size_t len;
} pair_arr;
```

```c
pair_arr make_pair_arr(size_t len, pair p) {
  pair_arr result;
  result.len = len;
  result.data = malloc(sizeof(pair) * len);
  for (size_t i = 0; i < len; i++) {
    p.x += i;
    p.y += i;
    result.data[i] = p;
  }
  return result;
}
```

```c
int main() {
  pair p = (pair) {0, 1};
  pair_arr a = make_pair_arr(3, p);
  printf("%d %d\n", p.x, p.y);
  for (size_t i = 0; i < a.len; i++) {
    p = a.data[i];
    printf("%d %d\n", p.x, p.y);
  }
}
```

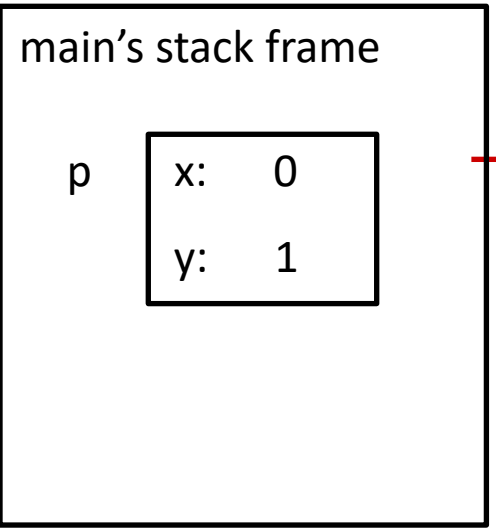
What does this print?
What memory errors are there?
How do we fix them?

C: Memory Diagrams




```c
int main() {
  pair p = (pair) {0, 1};
  pair_arr a = make_pair_arr(3, p);
  printf("%d %d\n", p.x, p.y);
  for (size_t i = 0; i < a.len; i++) {
    p = a.data[i];
    printf("%d %d\n", p.x, p.y);
  }
}
```

C: Memory Diagrams




```c
int main() {
  pair p = (pair) {0, 1};
  pair_arr a = make_pair_arr(3, p);
  printf("%d %d\n", p.x, p.y);
  for (size_t i = 0; i < a.len; i++) {
    p = a.data[i];
    printf("%d %d\n", p.x, p.y);
  }
}
```

C: Memory Diagrams

main's stack frame

p

x:	0
y:	1

m_p_a's stack frame

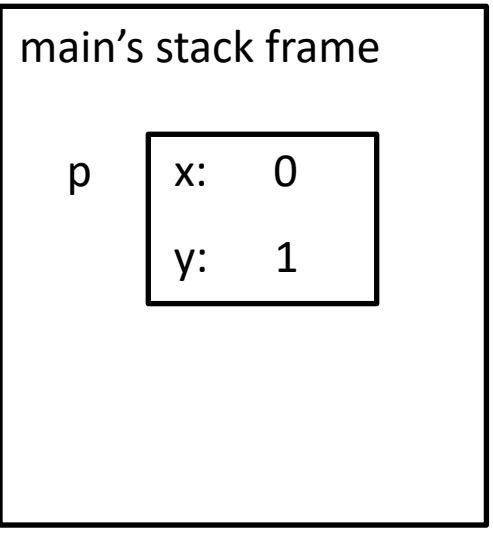
p

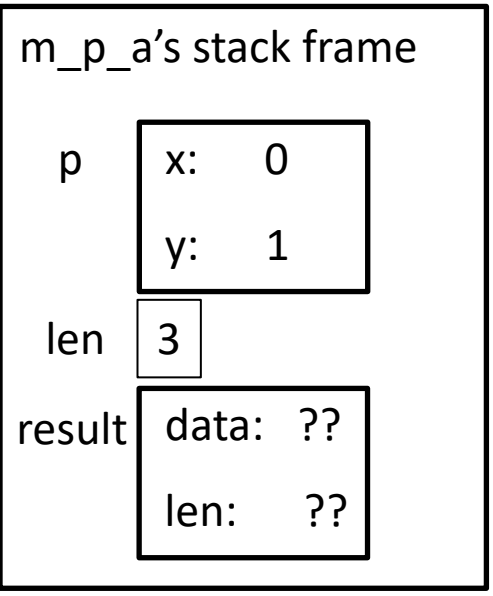
x:	0
y:	1

len | 3 |

```
pair_arr make_pair_arr(size_t len, pair p) {
  pair_arr result;
  result.len = len;
  result.data = malloc(sizeof(pair) * len);
  for (size_t i = 0; i < len; i++) {
    p.x += i;
    p.y += i;
    result.data[i] = p;
  }
  return result;
}
```

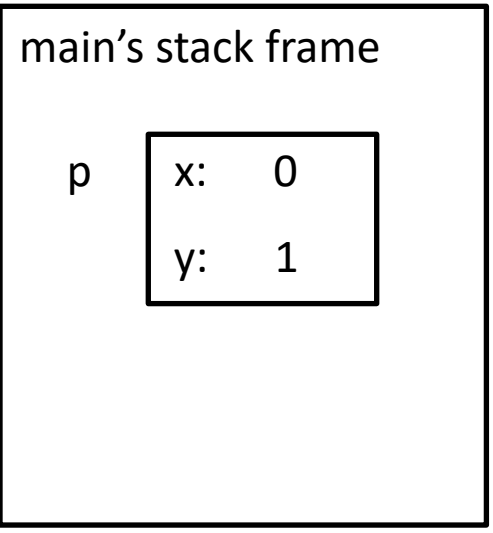
C: Memory Diagrams

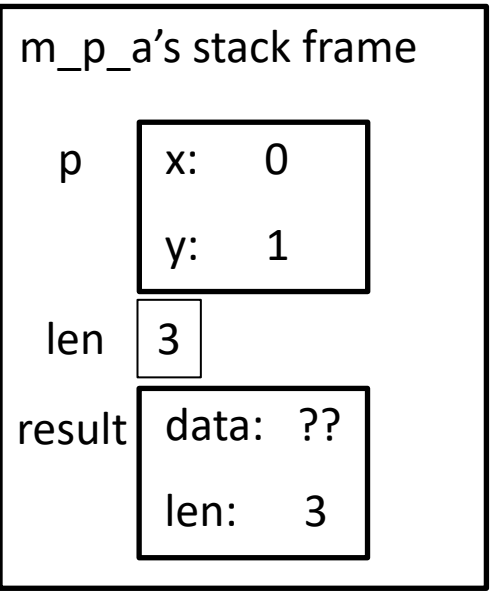





```c
pair_arr make_pair_arr(size_t len, pair p) {
  pair_arr result;
  result.len = len;
  result.data = malloc(sizeof(pair) * len);
  for (size_t i = 0; i < len; i++) {
    p.x += i;
    p.y += i;
    result.data[i] = p;
  }
  return result;
}
```

C: Memory Diagrams






```
pair_arr make_pair_arr(size_t len, pair p) {
  pair_arr result;
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  for (size_t i = 0; i < len; i++) {
    p.x += i;
    p.y += i;
    result.data[i] = p;
  }
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}
```
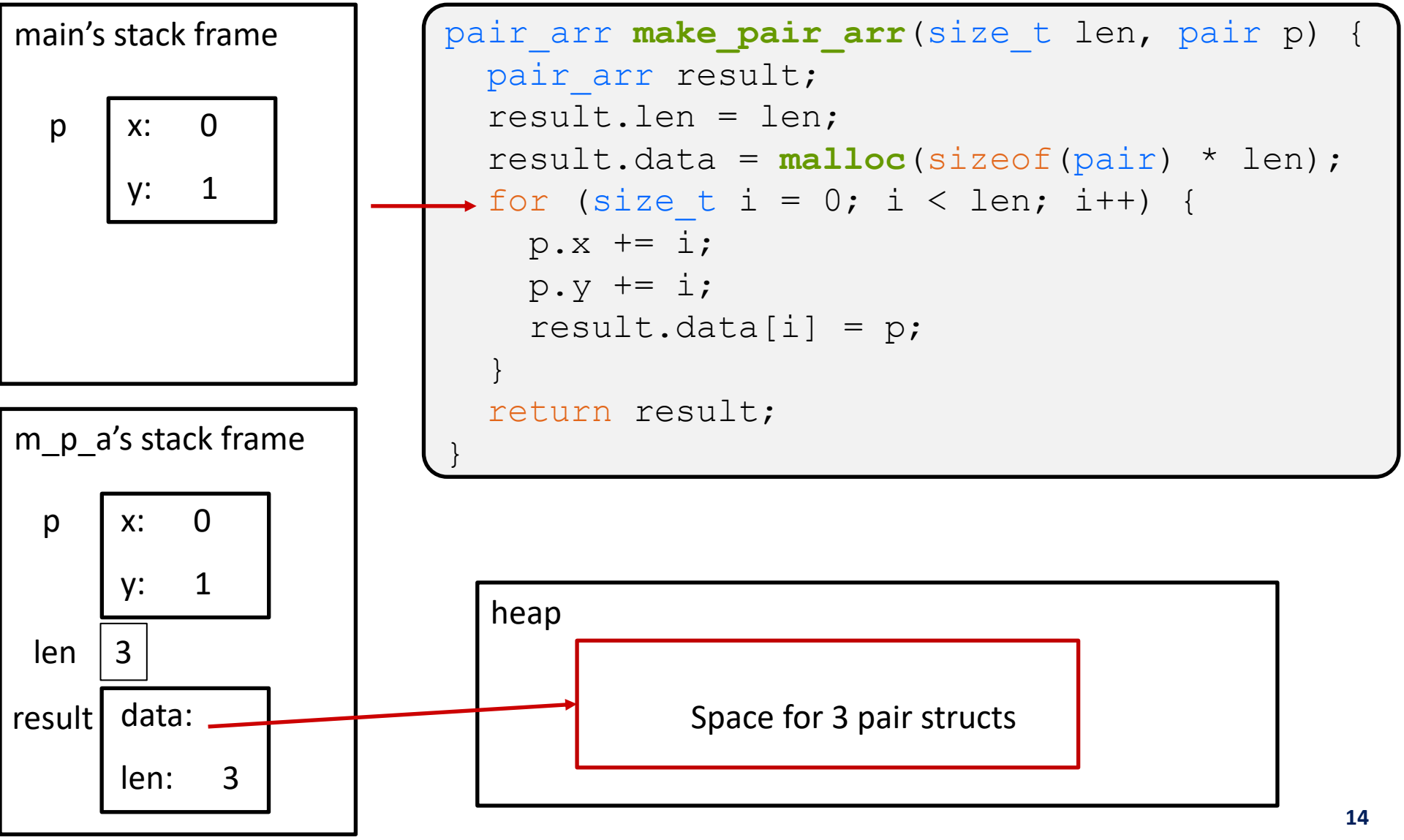
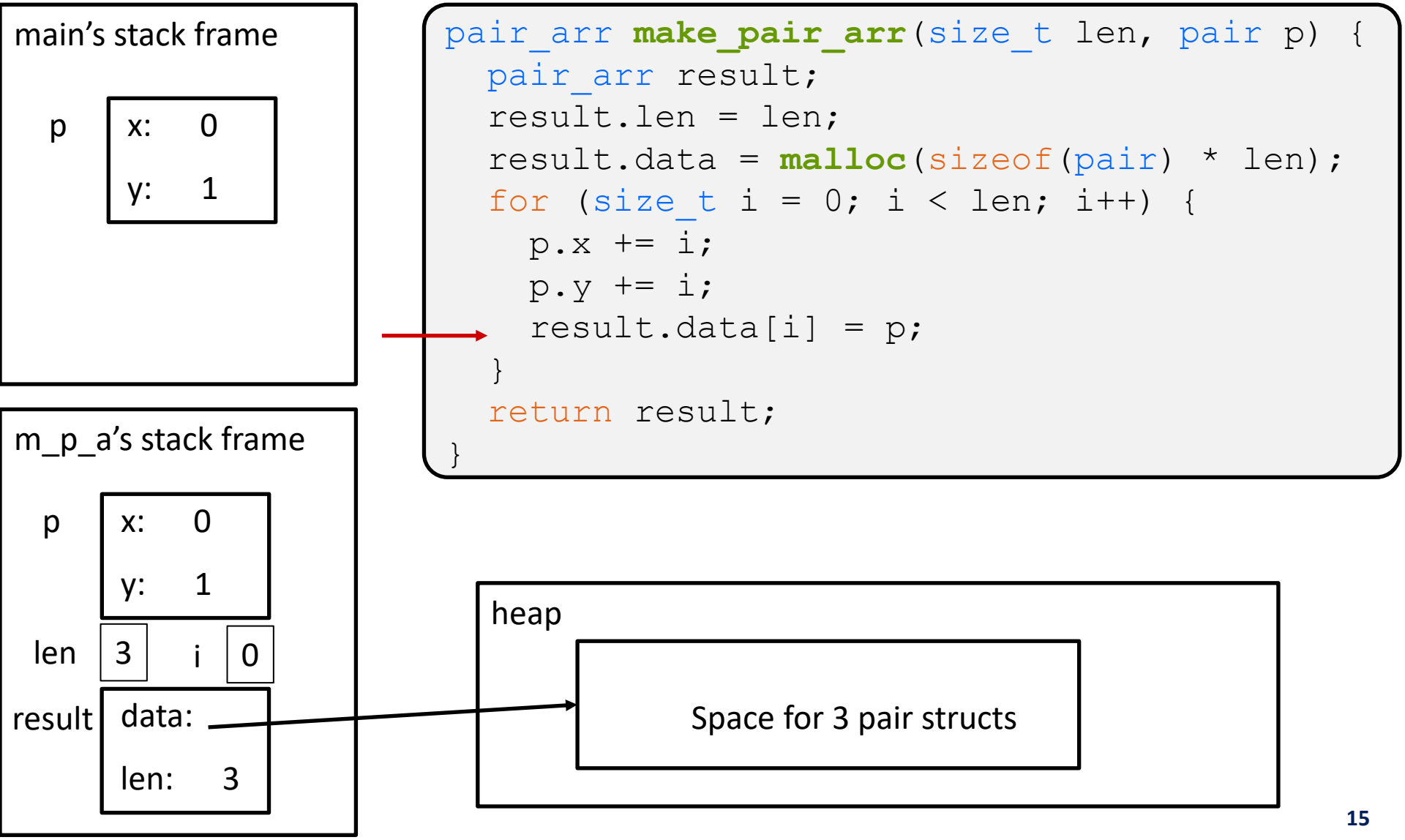

C: Memory Diagrams



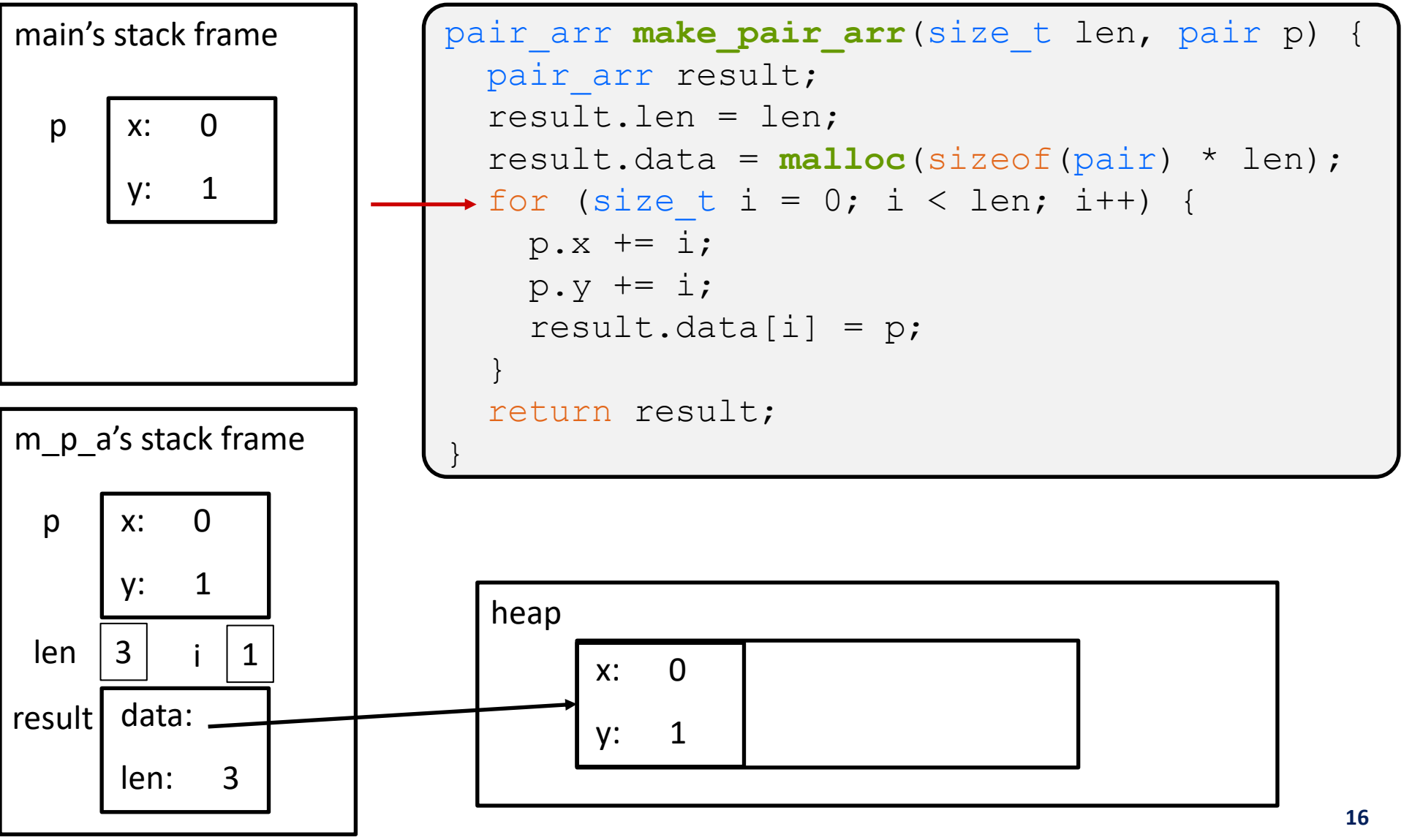

```
pair_arr make_pair_arr(size_t len, pair p) {
  pair_arr result;
  result.len = len;
  result.data = malloc(sizeof(pair) * len);
  for (size_t i = 0; i < len; i++) {
    p.x += i;
    p.y += i;
    result.data[i] = p;
  }
  return result;
}
```

C: Memory Diagrams

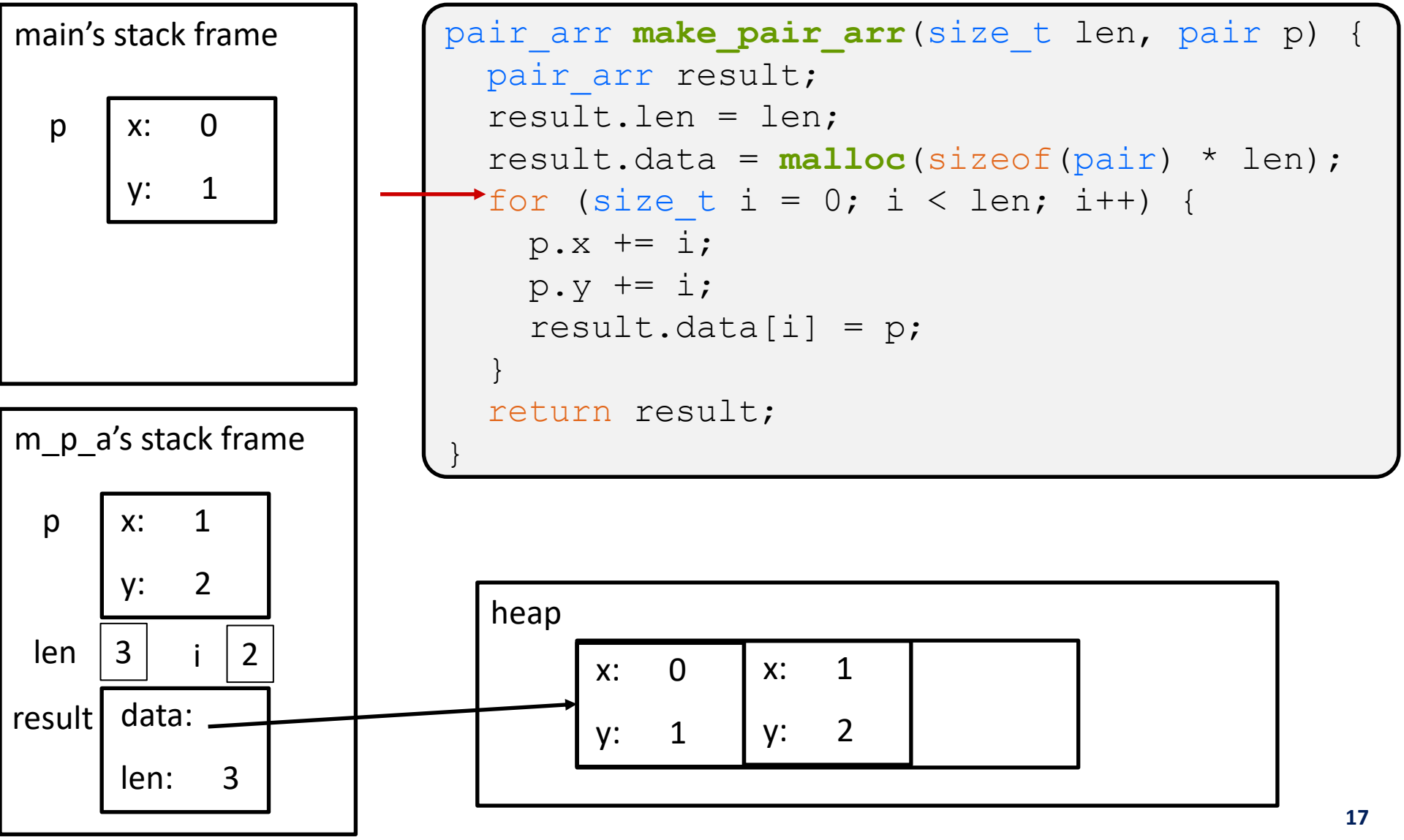



```
pair_arr make_pair_arr(size_t len, pair p) {
  pair_arr result;
  result.len = len;
  result.data = malloc(sizeof(pair) * len);
  for (size_t i = 0; i < len; i++) {
    p.x += i;
    p.y += i;
    result.data[i] = p;
  }
  return result;
}
```

C: Memory Diagrams



C: Memory Diagrams




```
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  pair_arr result;
  result.len = len;
  result.data = malloc(sizeof(pair) * len);
  for (size_t i = 0; i < len; i++) {
    p.x += i;
    p.y += i;
    result.data[i] = p;
  }
  return result;
}
```
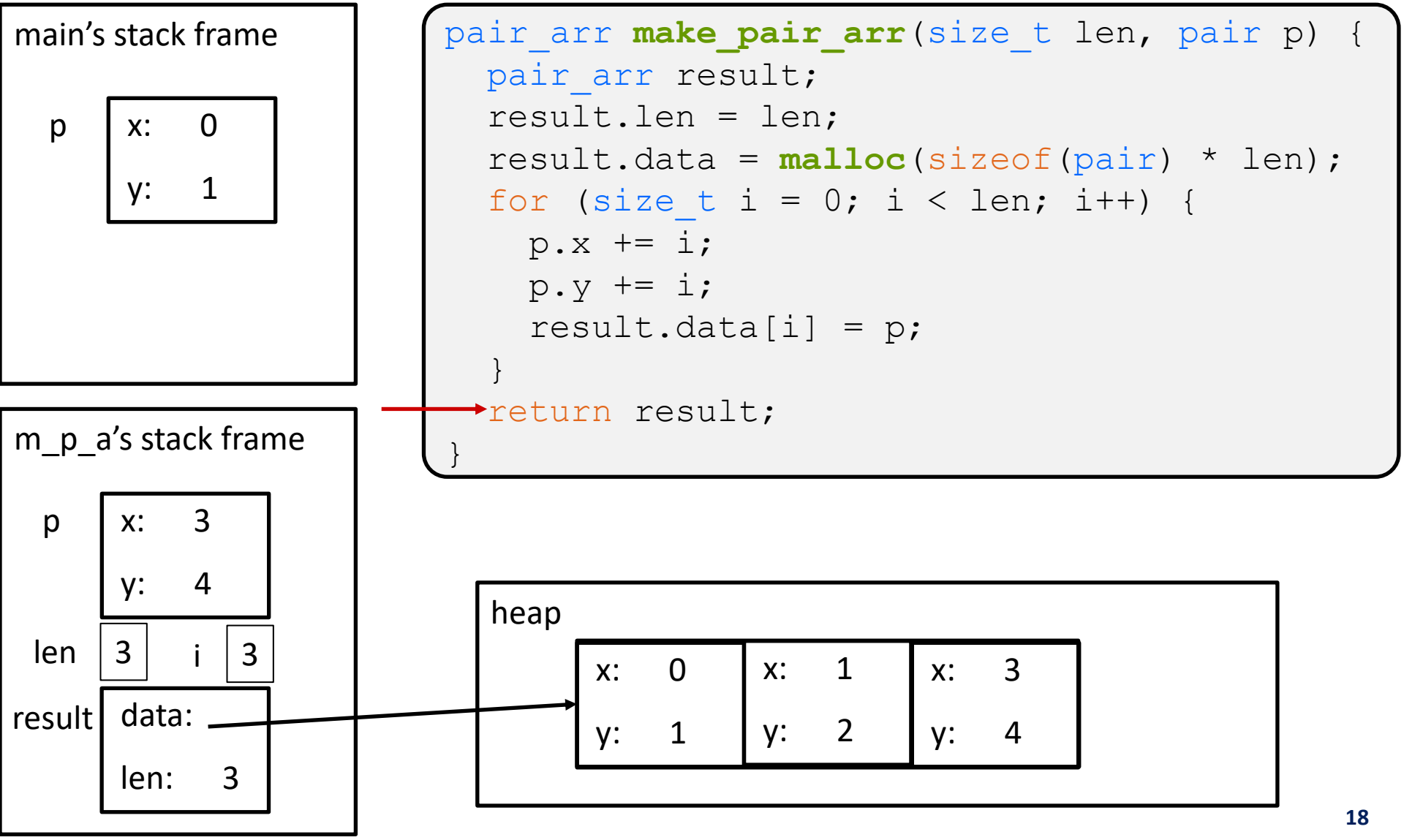

C: Memory Diagrams




```c
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  pair_arr result;
  result.len = len;
  result.data = malloc(sizeof(pair) * len);
  for (size_t i = 0; i < len; i++) {
    p.x += i;
    p.y += i;
    result.data[i] = p;
  }
  return result;
}
```
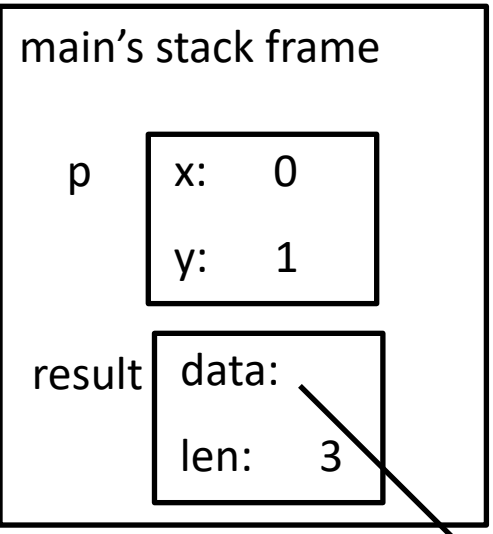
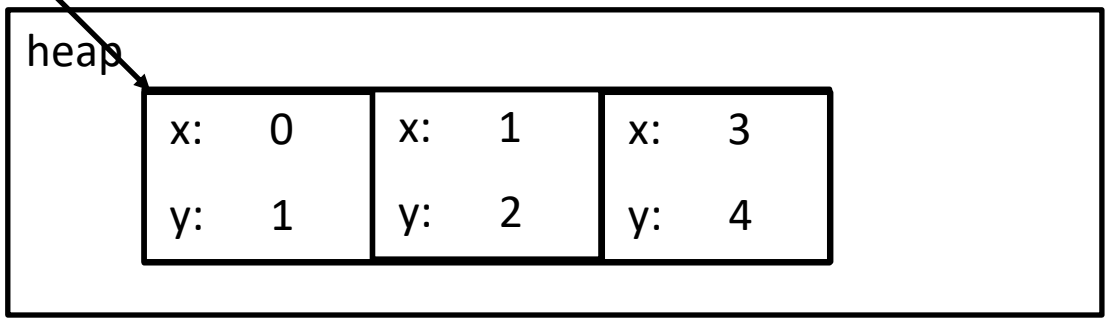

C: Memory Diagrams




```c
int main() {
  pair p = (pair) {0, 1};
  pair_arr a = make_pair_arr(3, p);
  printf("%d %d\n", p.x, p.y);
  for (size_t i = 0; i < a.len; i++) {
    p = a.data[i];
    printf("%d %d\n", p.x, p.y);
  }
}
```



C Strings & Output Params

- Complete the following function (on Codio)

```
// given a string, allocates and creates a new duplicate
// of it and returns it through the output parameter "out".
// Returns false on error, returns true otherwise

bool str_duplicate(char* str, char** out) {









}
```

C Strings & Output Params

NOTE: There are other possible solutions

- Complete the following function

```
// given a string, allocates and creates a new duplicate
// of it and returns it through the output parameter "out".
// Returns false on error, returns true otherwise

bool str_duplicate(char* str, char** out) {
  char* res = malloc((strlen(str) + 1) * sizeof(char));
  *out = res;
  while(*str) {
    *res = *str
    str++;
    res++;
  }
  *res = *str;  // null terminator
  return true;
}
```

C Strings & Output Params

- Complete the main function

```
// given a string, duplicates it and returns it through
// the output parameter "out". Returns false on error
// returns true otherwise
bool str_duplicate(char* str, char** out);

// duplicates a string literal,
// prints the duplicate, and runs without errors
int main(int argc, char** argv) {
  char* sample = "Hello World!";




}
```

C Strings & Output Params

NOTE: There are other possible solutions

- Complete the main function

```c
// given a string, duplicates it and returns it through
// the output parameter "out". Returns false on error
// returns true otherwise
bool str_duplicate(char* str, char** out);

// duplicates a string literal,
// prints the duplicate, and runs without errors
int main(int argc, char** argv) {
  char* sample = "Hello World!";

  char* dup;
  str_duplicate(sample, &dup);
  printf("%s", dup);
  free(dup);
  return EXIT_SUCCESS;
}
```

This problem may be on the harder side.

If space would have given you a memory diagram of the output

C Programming: Malloc & Double Pointers

- We want to make a module that implements 2d matrices in C. We define the following struct which holds a dynamically allocated 2-dimensional array.

```
typedef struct {
  int** data;
  int rows;
  int cols;
} matrix;
```

- Implement the `create_matrix` function which creates a matrix on the heap with the specified rows and cols. Assume malloc does not fail. Zero out all data in the matrix.
- Example: create_matrix(2, 3) should create a 2x3 matrix. data points to 2 `int*`, each of those point to 3 `int`s.

```
matrix* create_matrix(int rows, int cols) {
  // Implement this function. You need more than 1 line.
}
```

This problem may be on the harder side.

If space would have given you a memory diagram of the output

C Programming: Malloc & Double Pointers

```
matrix* create_matrix(int rows, int cols) {
  matrix *m  = malloc(sizeof(matrix));
  m->rows = rows;
  m->cols = cols;

  m->data = malloc(rows * sizeof(int*));

  for (int i = 0; i < rows; i++) {
    m->data[i] = malloc(cols * sizeof(int));
    for (int j = 0; j < cols; j++) {
      m->data[i][j] = 0;
    }
  }
  return m;
}
```

C Programming: Malloc & Double Pointers

- We want to make a module that implements 2d matrices in C. We define the following struct which holds a dynamically allocated 2-dimensional array.

```
typedef struct {
  int** data;
  int rows;
  int cols;
} matrix;
```

- Implement the `free_matrix()` function which deallocates the matrix allocated in `create_matrix()`
- Example: create_matrix(2, 3) should create a 2x3 matrix. data points to 2 `int*`, each of those point to 3 `int`s.

```
void free_matrix(matrix* m) {
  // Implement this function.



}
```

C Programming: Malloc & Double Pointers

```c
matrix* create_matrix(int rows, int cols) {
  matrix *m  = malloc(sizeof(matrix));
  m->rows = rows;
  m->cols = cols;

  m->data = malloc(rows * sizeof(int*));

  for (int i = 0; i < rows; i++) {
    m->data[i] = malloc(cols * sizeof(int));
    for (int j = 0; j < cols; j++) {
      m->data[i][j] = 0;
    }
  }
  return m;
}
```

```c
void free_matrix(matrix* m) {
  // Implement this function.


}
```

C Programming: Malloc & Double Pointers

```
void free_matrix(matrix* m) {
  for (int i = 0; i < m->rows; i++) {
    free(m->data[i]);
  }
  free(m->data);
  free(m);
}
```

CMOS, PLAS, GATES

- Create a circuit that takes in an unsigned 4-bit input I ($I_3I_2I_1I_0$), and outputs a 1 if and only if the 4-bit input is a non-zero multiple of 7
  - List the outputs that result in a 1 for the output
  - Create a corresponding CMOS circuit
    - Can assume you have the inverses of the Input bits
  - Create a corresponding PLA circuit
  - Create a corresponding gate level non-PLA circuit

CMOS, PLAS, GATES

- Create a circuit that takes in an unsigned 4-bit input I ($I_3I_2I_1I_0$), and outputs a 1 if and only if the 4-bit input is a non-zero multiple of 7
  - List the outputs that result in a 1 for the output
  - 7 (0b0111) and 14 (0b1110)

CMOS

- Create a circuit that takes in an unsigned 4-bit input I ($I_3I_2I_1I_0$), and outputs a 1 if and only if the 4-bit input is a non-zero multiple of 7. You can assume you have inverse of the input signals.
  - Overall Expression: $(\sim I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, I_0) \mid (I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, \sim I_0)$

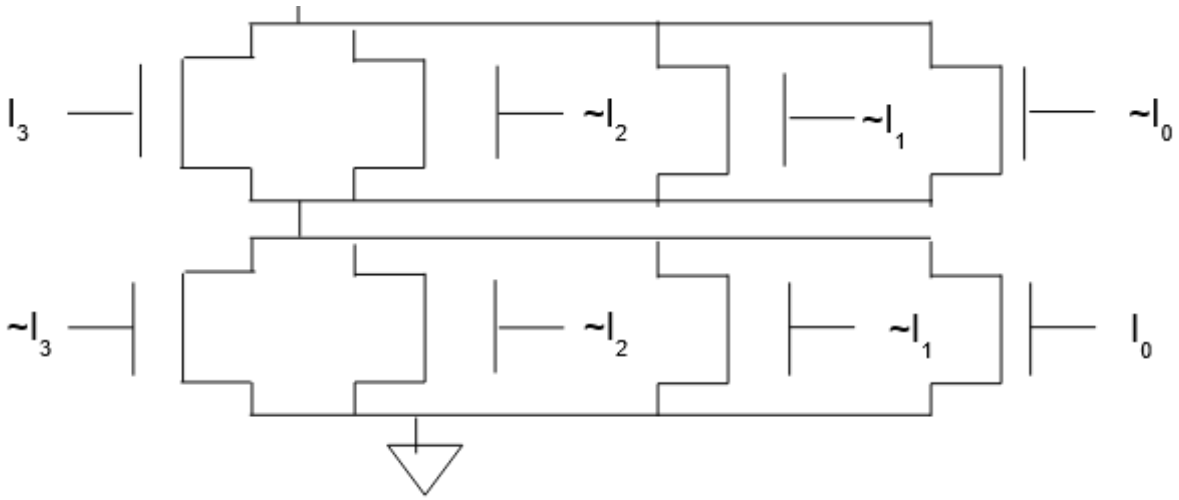
CMOS Strategy 1 (Starting with PDN)

- Overall Expression: $(\sim I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, I_0) \mid (I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, \sim I_0)$
- PDN Expression:
  - $\sim((\sim I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, I_0) \mid (I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, \sim I_0))$
  - $\sim(\sim I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, I_0) \,\&\, \sim(I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, \sim I_0)$
  - $(I_3 \mid \sim I_2 \mid \sim I_1 \mid \sim I_0) \,\&\, (\sim I_3 \mid \sim I_2 \sim I_1 \mid I_0)$

CMOS Strategy 1 (Starting with PDN)

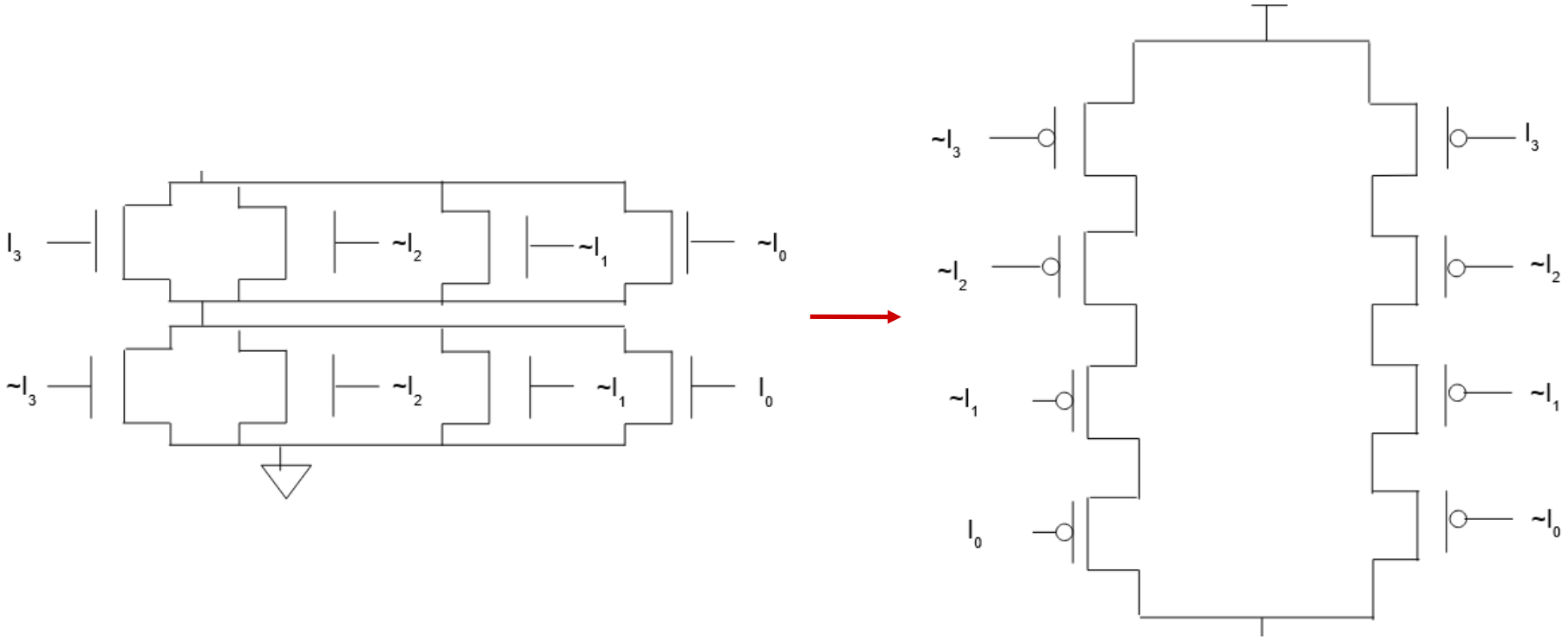
- Overall Expression: $(\sim I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, I_0) \mid (I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, \sim I_0)$
- PDN Expression:
  - $\sim((\sim I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, I_0) \mid (I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, \sim I_0))$ // negate
  - $\sim(\sim I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, I_0) \,\&\, \sim(I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, \sim I_0)$ // De Morgan's
  - $(I_3 \mid \sim I_2 \mid \sim I_1 \mid \sim I_0) \,\&\, (\sim I_3 \mid \sim I_2 \sim I_1 \mid I_0)$ // De Morgan's

- Translated to PDN:



CMOS Strategy 1 (Starting with PDN)

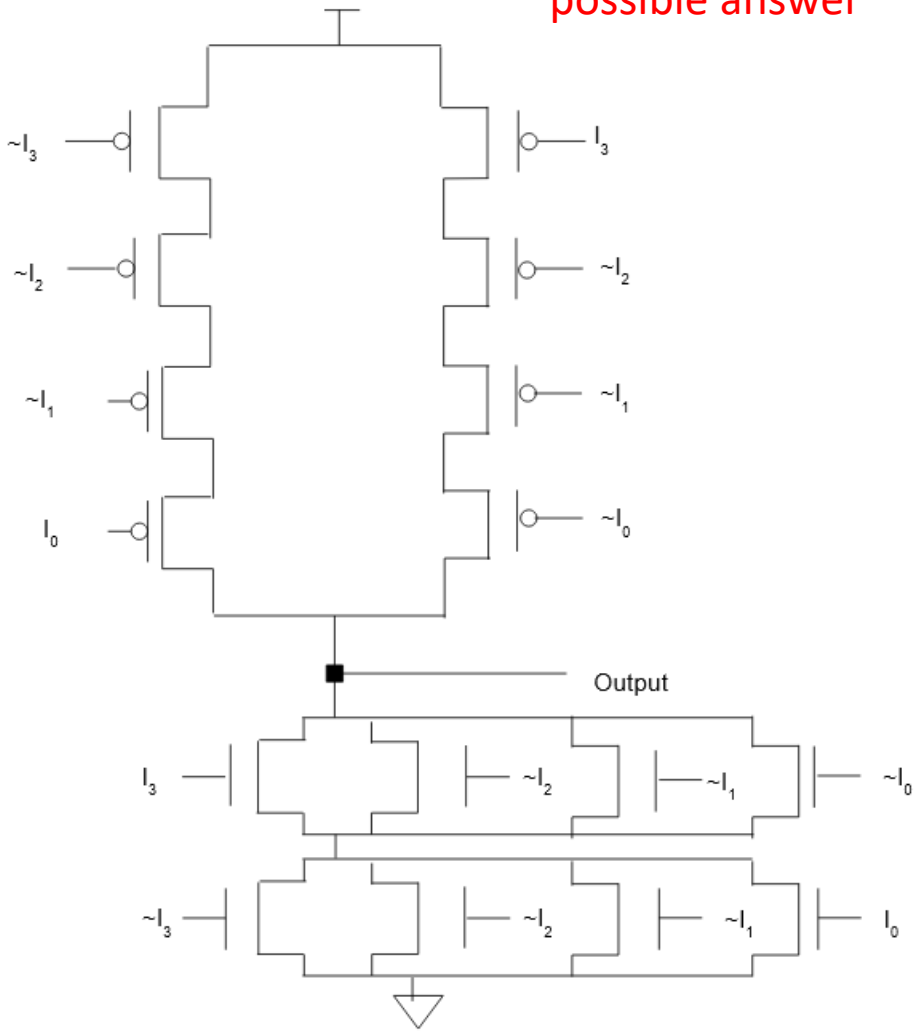
- Flip PDN into PUN:



CMOS Strategy 1 (Starting with PDN)

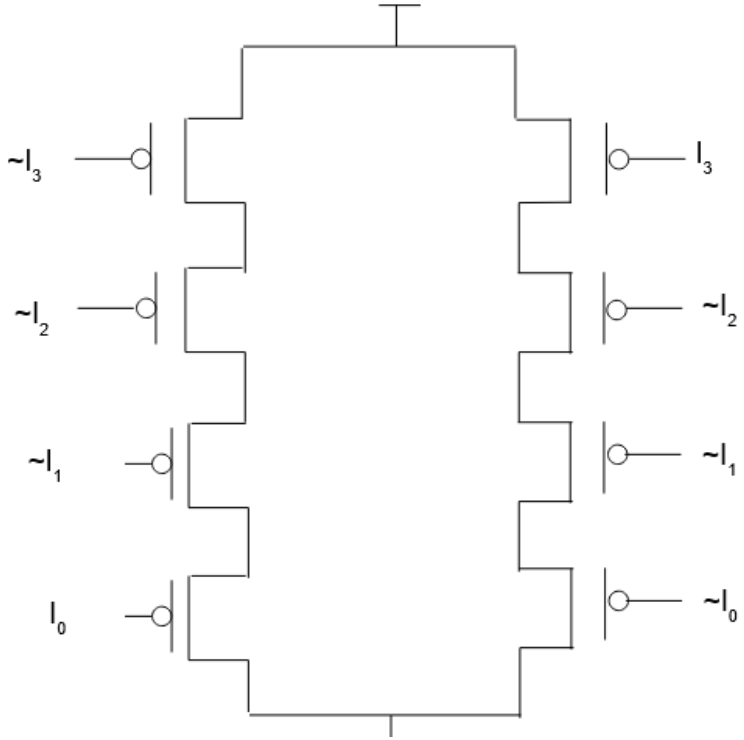
- Connect PDN and PUN:

Not the only possible answer



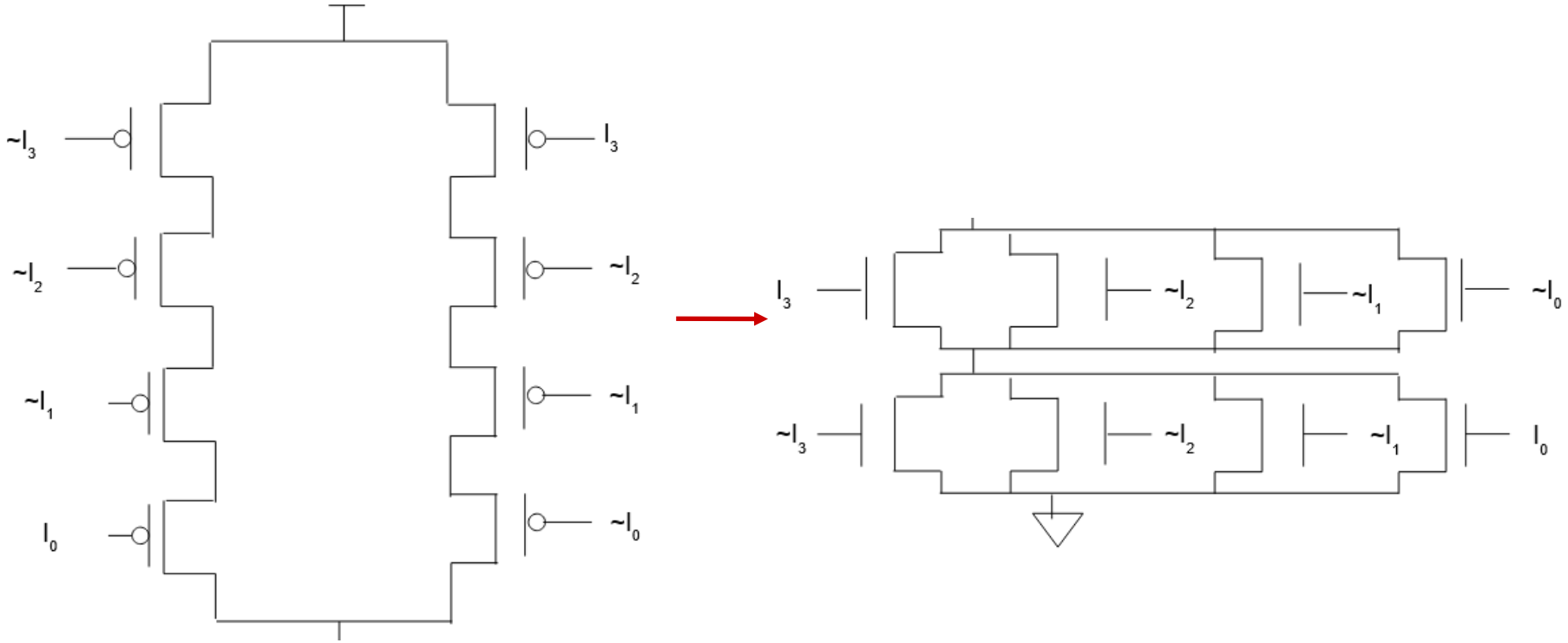
CMOS Strategy 2 (Starting with PUN)

- Take the original expression:
  - $(I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, \sim I_0) \mid (\sim I_3 \,\&\, I_2 \,\&\, I_1 \,\&\, I_0)$
- Translate it directly into PDN but add a negation to each input
  - This is because PMOS transistors are "naturally negating"
  - E.g., $\sim I_3$ becomes $\sim\sim I_3 == I_3$



CMOS Strategy 2 (Starting with PUN)

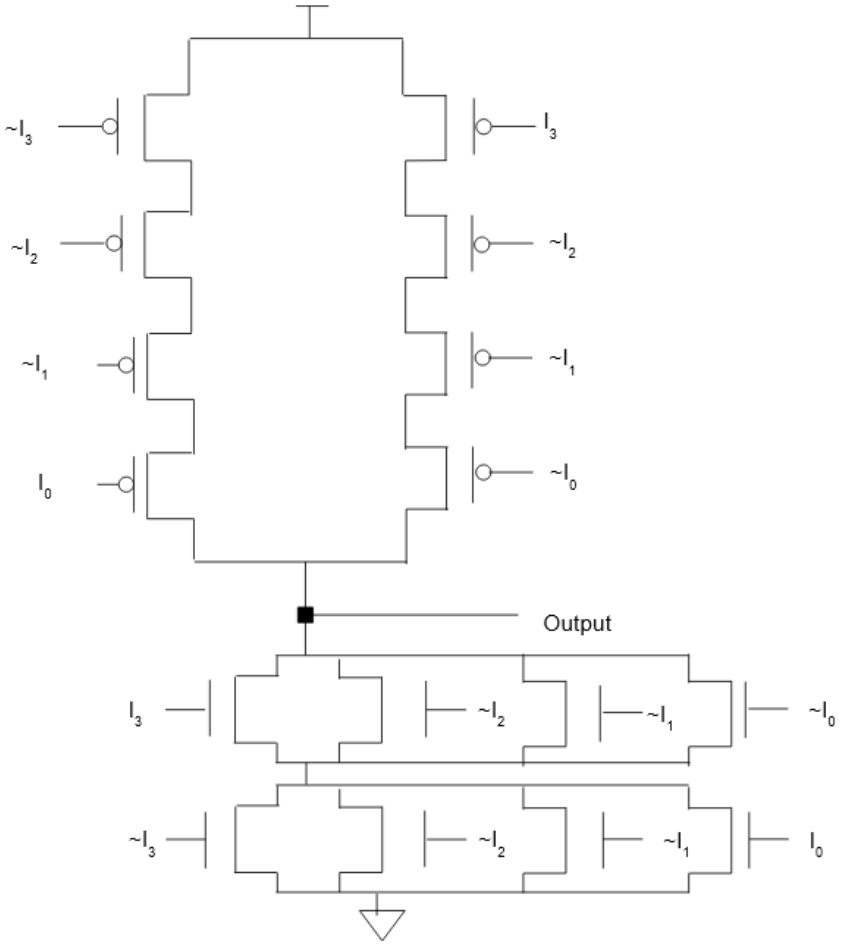
- Flip PUN to get PDN



CMOS Strategy 2 (Starting with PUN)

- Connect the PDN and PUN

Not the only possible answer



PLA

- Create a circuit that takes in an unsigned 4-bit input I ($I_3I_2I_1I_0$), and outputs a 1 if and only if the 4-bit input is a non-zero multiple of 7

PLA

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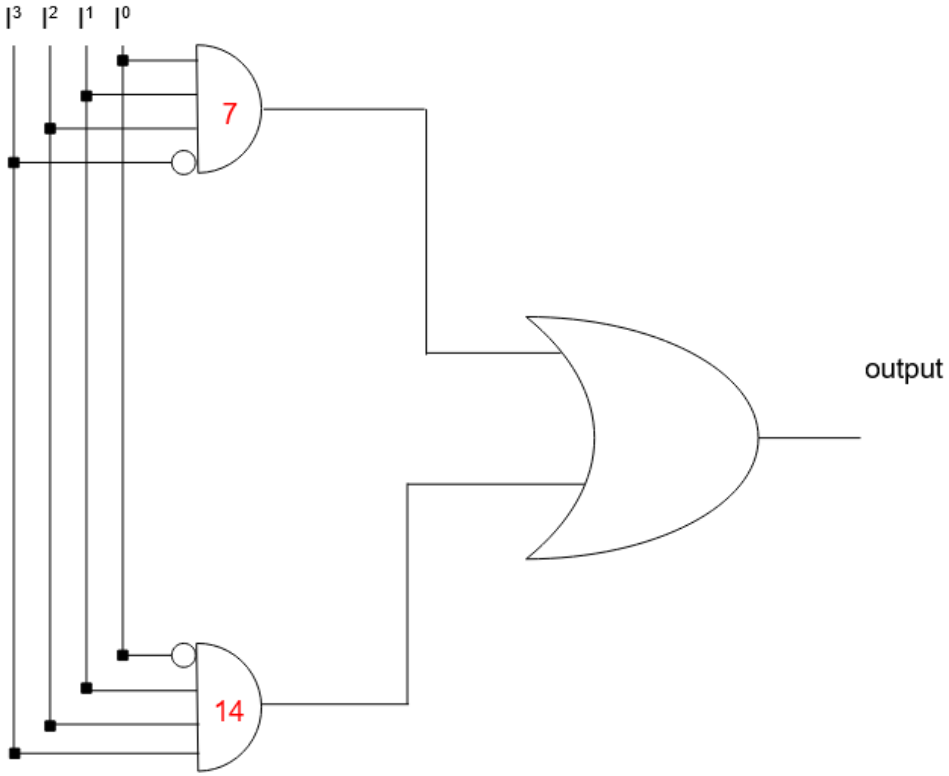


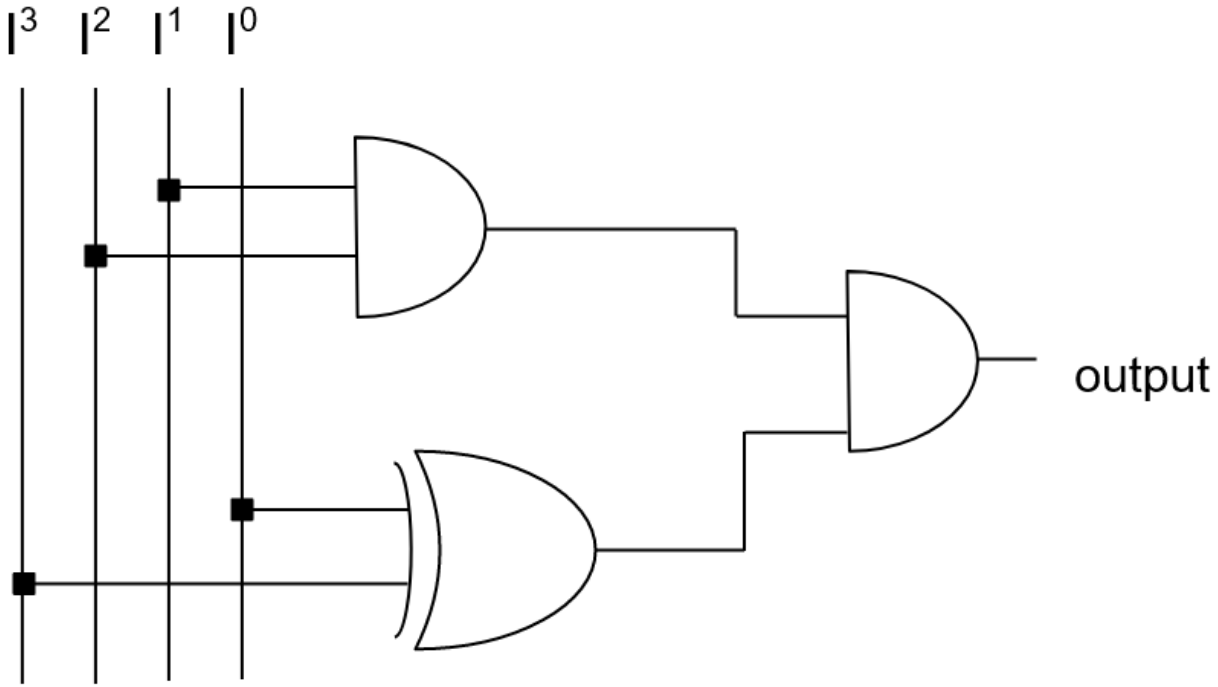
Non-PLA

- Create a circuit that takes in an unsigned 4-bit input I ($I_3I_2I_1I_0$), and outputs a 1 if and only if the 4-bit input is a non-zero multiple of 7

Non-PLA

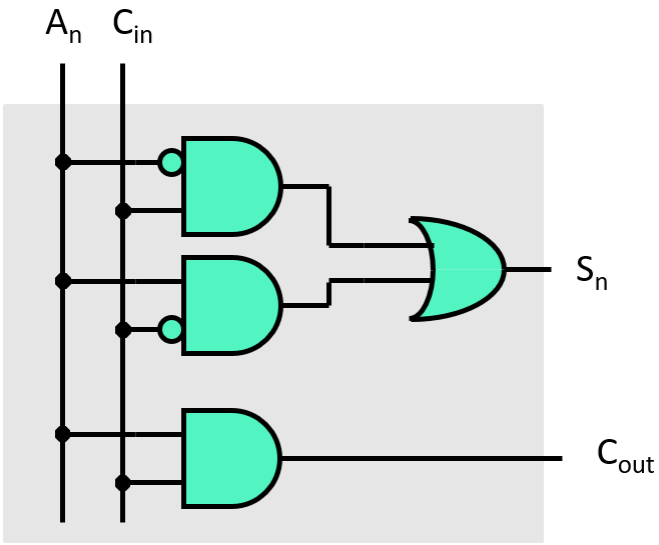
Not the only possible answer

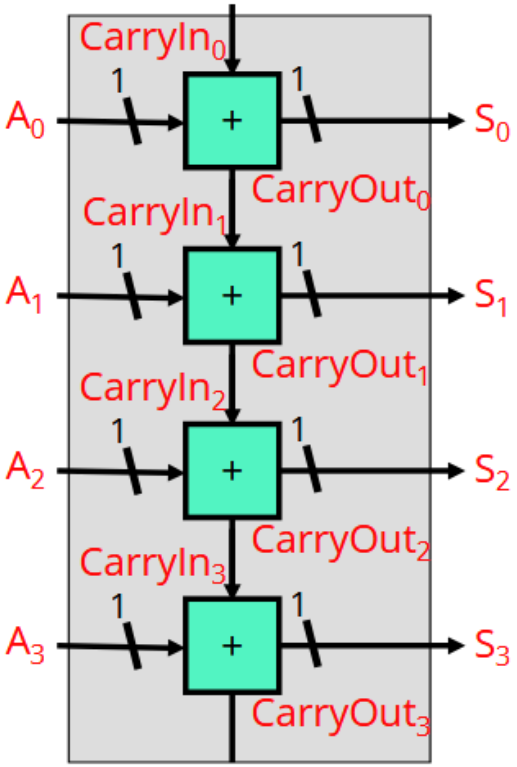
- Create a circuit that takes in an unsigned 4-bit input I ($I_3I_2I_1I_0$), and outputs a 1 if and only if the 4-bit input is a non-zero multiple of 7



Gate delay pt.1

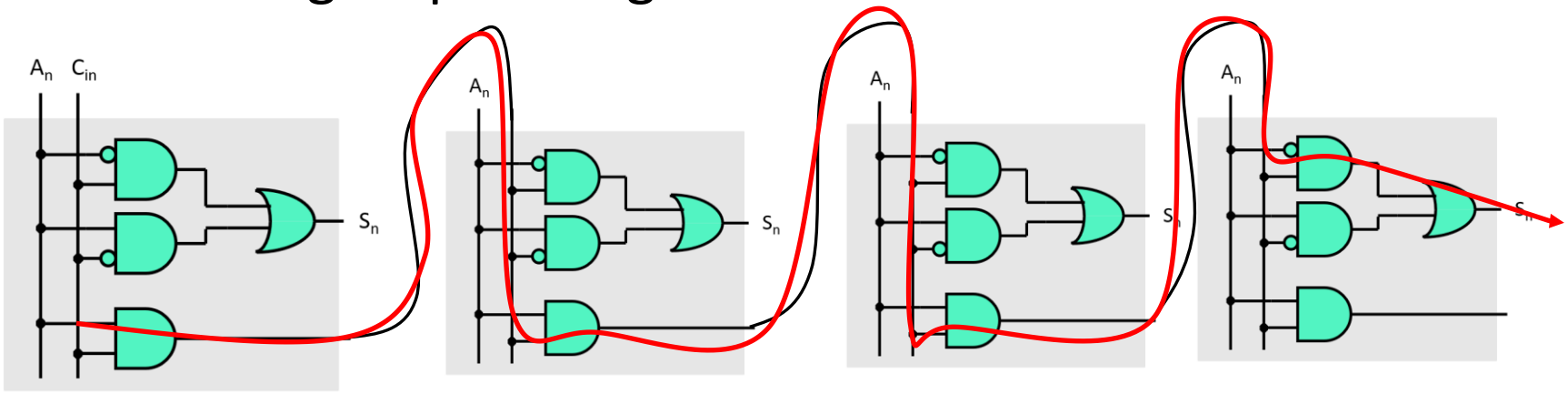
- Given the 4-bit incrementor that we created in lecture, how long do we have to wait to make sure that the output of the incrementor matches the input?
  - Assume that each gate has a 1ns delay
  - You can ignore delay from inverters





Gate delay pt.1 Answer

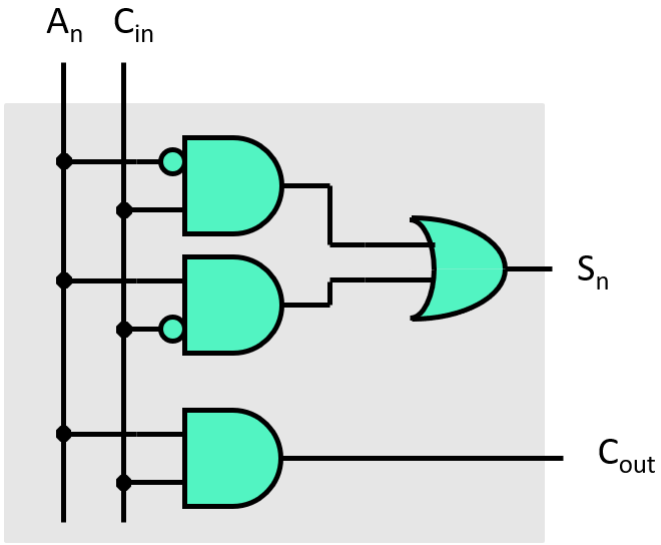
- Find the longest path of gates in the circuit

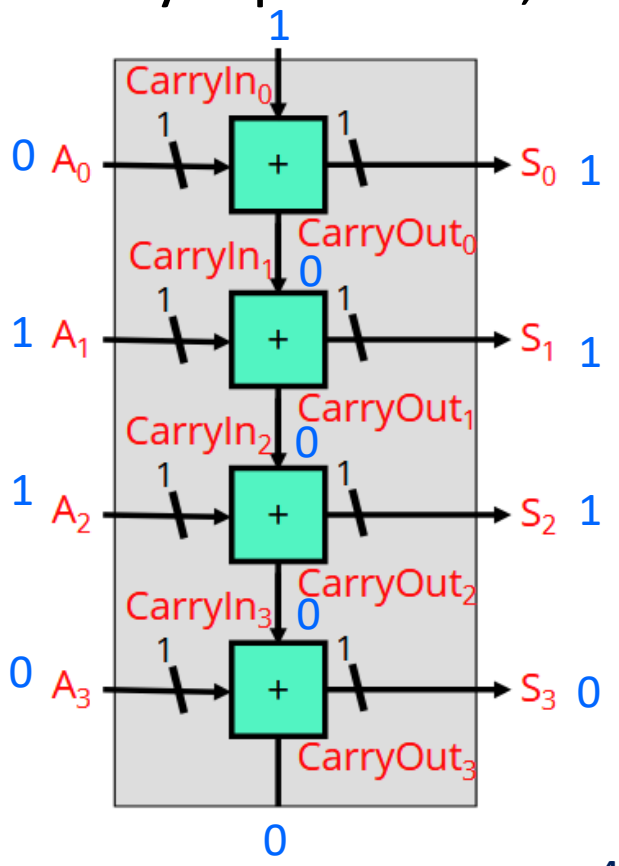


  - Longest path goes through 5 gates, so we must wait 5ns for the whole circuit to stabilize and produce the correct output

Gate delay pt.2

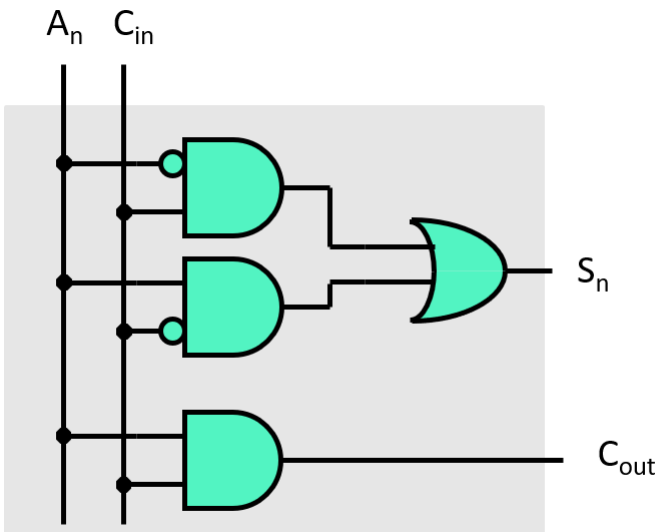
- The 4-bit incrementor that we created in lecture is currently in a stable state showing the output of 1 + 0110. If the A input signals were to simultaneously flip to 0111, what would all signals be after 2ns
  - Assume that each gate has a 1ns delay
  - Ignore delays from inverters
  - $CarryIn_n$ stays the same

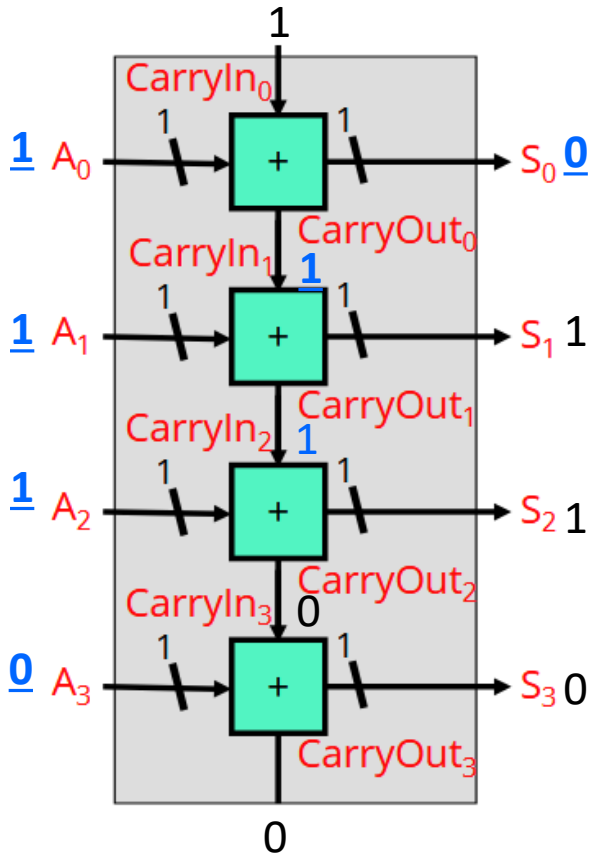




Gate delay pt.2

- To see what changes after 2ns, see which outputs have all paths that are 2 gate or less.
- Answer:
  - S_0 would update
  - $Cout_0$ would update
  - $Cout_1$ would update
  - S_1 would be partially computed, but not fully updated





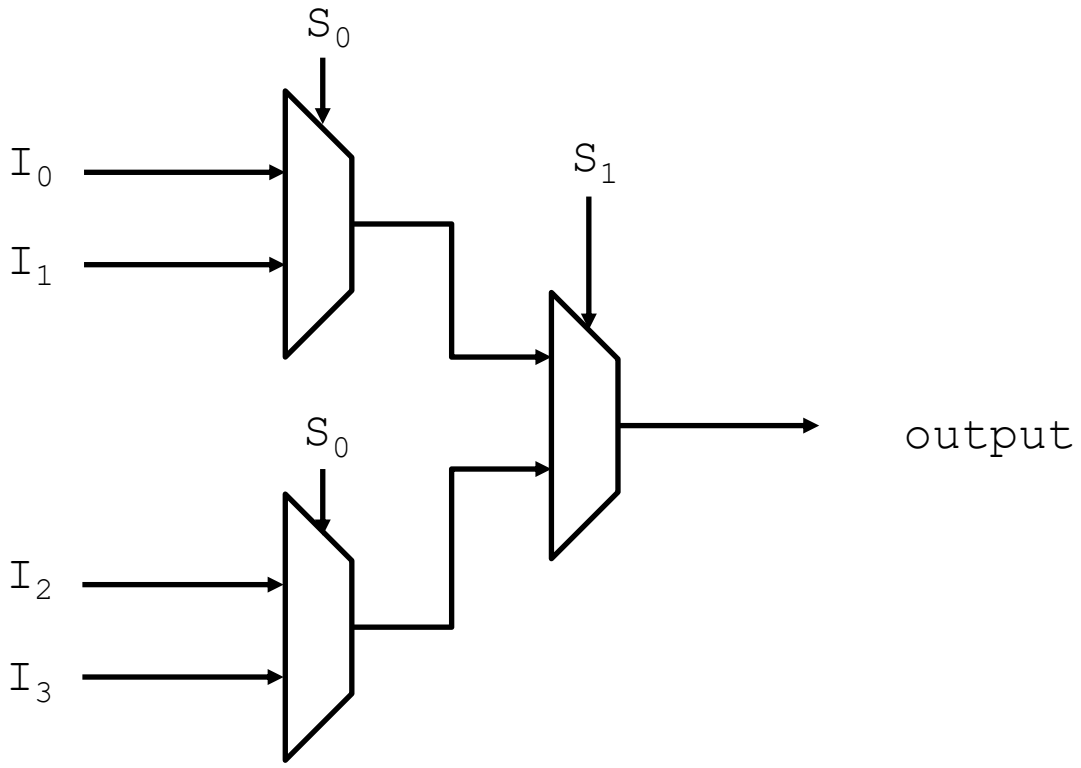
Combinatorial Logic: Mux

- Given inputs I_0 I_1 I_2 I_3 and selector bits S_1 and S_0 draw a logic circuit using 2-to-1 muxes to implement the 4-to-1 MUX. You can assume you have access to each bit/wire.

- Requirements:
  - If S_1S_0 == 00, the output should be I_0
  - If S_1S_0 == 01, the output should be I_1
  - If S_1S_0 == 10, the output should be I_2
  - If S_1S_0 == 11, the output should be I_3
  - Clearly label the inputs, select lines, and output
- Yes, you are allowed to use more than one 2-to-1 mux

Combinatorial Logic: Mux

- 4-to-1 Mux out of 2-to-1 muxes
- (one possible solution)



General Questions & Answers

- Take questions/requests from students