CSE 12: Basic data structures and object-oriented design

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Lecture Seven
16 July 2012

Stacks and queues.

Stacks and queues.

- Let’s now bring in two more fundamental data structures into the course.
- So far we have covered lists -- array-based lists and linked-lists.
  - These are both linear data structures -- each element in the container has at most one *successor* and one *predecessor*.
- Lists are most frequently used when we wish to store objects in a container, and *probably never remove them from it*.
  - E.g., if Amazon uses a list to store its huge collection of customers, it has no intention of “removing” a customer (except at program termination).

Stacks and queues

- Stacks and queues, on the other hand, are examples of *linear* data structures in which every object inserted into it will generally be removed:
  - The stack/queue is intended only as "temporary" storage.
- Both stacks and queues allow the user to add and remove elements.
- Where they differ is the *order* in which elements are removed *relative to when they were added*.

Stacks.

Stacks

- Stacks are *last-in-first-out* (LIFO) data structures.
- The classic analogy for a "stack" is a pile of dishes:
  - Suppose you've already added dishes A, B, and C to the "stack" of dishes.

If you try to remove a middle dish, you get that annoying clanging sound.

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  - Now you add one more, D.

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  - Now you add one more, D.
  - Now you remove one dish -- *you get D back*.

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  - Now you add one more, D.
  - Now you remove one dish -- *you get D back*.
  - If you remove another, you get C, and so on.
- With stacks, you can only add to/remove from the *top* of the stack.

If you try to remove a middle dish, you get that annoying clanging sound.

Usage example of stacks

```
Stack<String> stack = new Stack<String>();
stack.push("a");
stack.push("b");
stack.push("c");
stack.push("d");
...
String s;
s = stack.pop();  // returns "d"
```

push adds an object to the stack

pop both gets and removes the "last" object from the stack

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```

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...
String s;
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s = stack.pop();  // returns "c"
s = stack.pop();  // returns "b"
s = stack.pop();  // returns "a"
```

push adds an object to the stack

pop both gets and removes the "last" object from the stack

Stacks

- Stacks find many uses in computer science, e.g.:
  - Implementing *procedure calls*.
- Consider the following code:

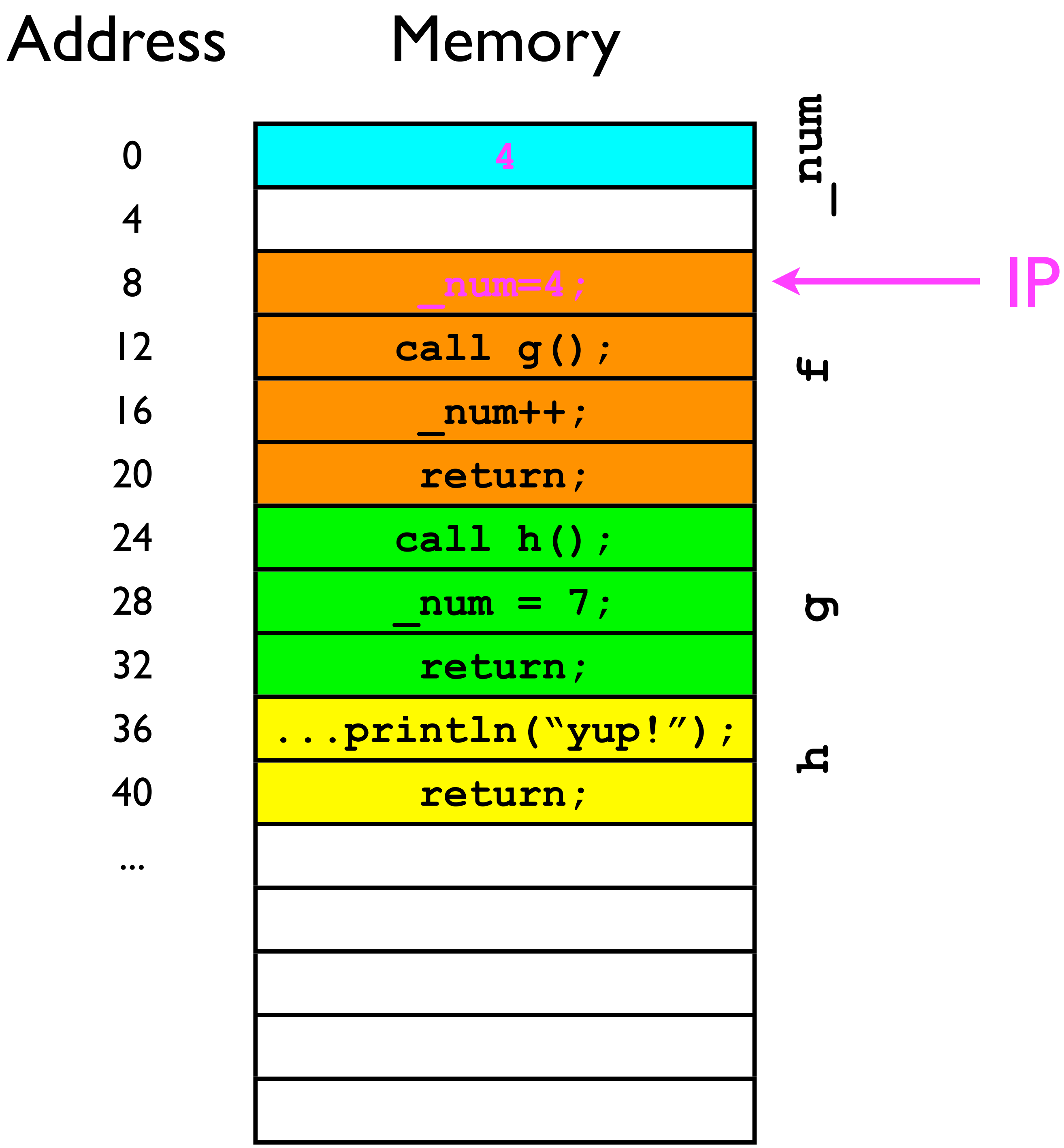
```
void f () {
  _num = 4;
  g();
  _num++;
}
void g () {
  h();
  _num = 7;
}
void h () {
  System.out.println("Yup!");
}
```

How does the CPU know to "jump" from `f` to `g`, `g` to `h`, then `h` back to `g`, and finally `g` back to `f`?

Von Neumann machine

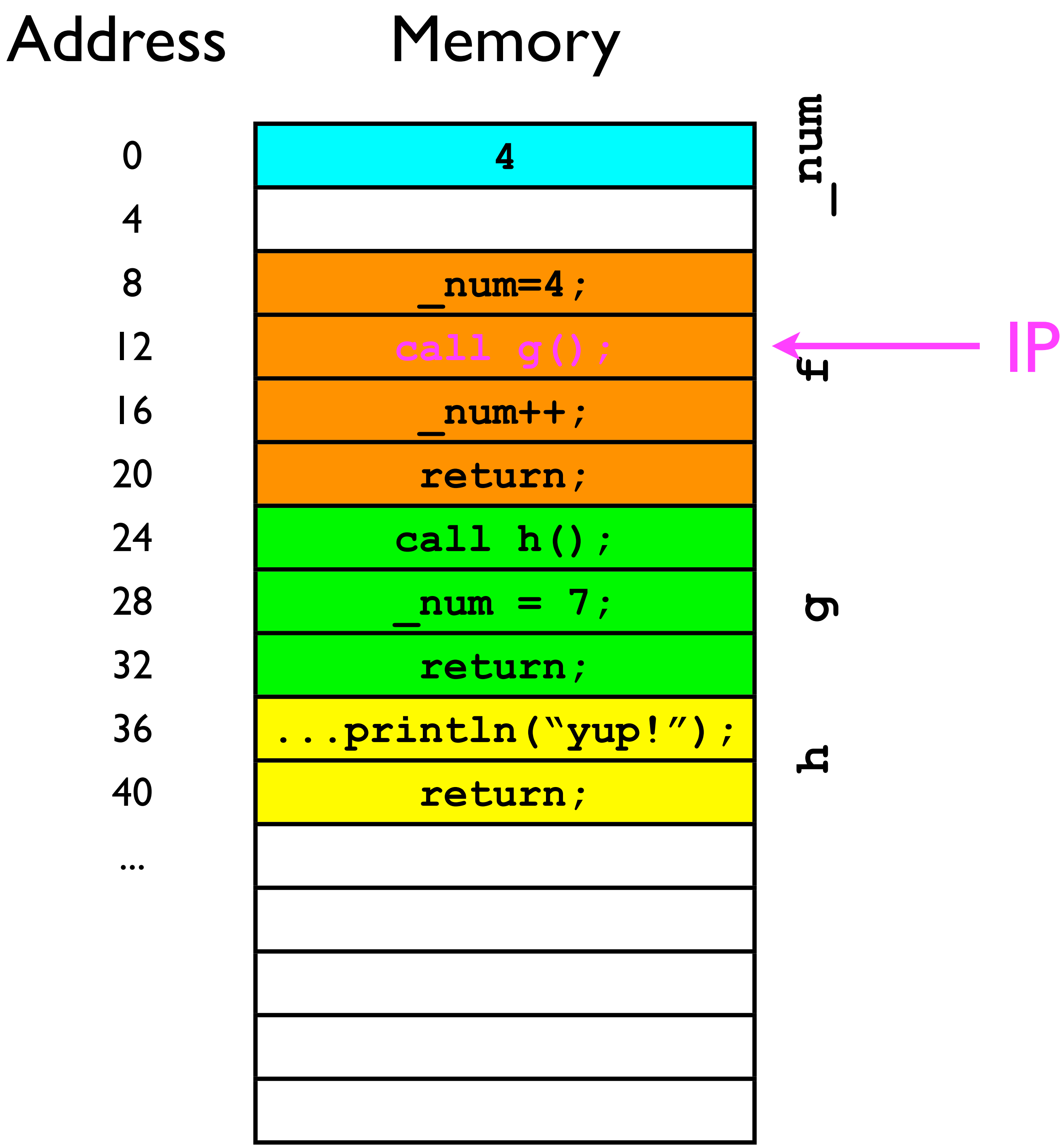
- On all modern machines, a program's *instructions* and its *data* are stored *together* somewhere in the computer's long sequence of bits (Von Neumann architecture).
    - Just by "glancing" at the contents of computer memory, one would have no idea whether a certain byte contains code or data -- it's all just bits.
- To keep track of which instruction in memory is currently being executed, the CPU maintains an Instruction Pointer (IP).

Code execution



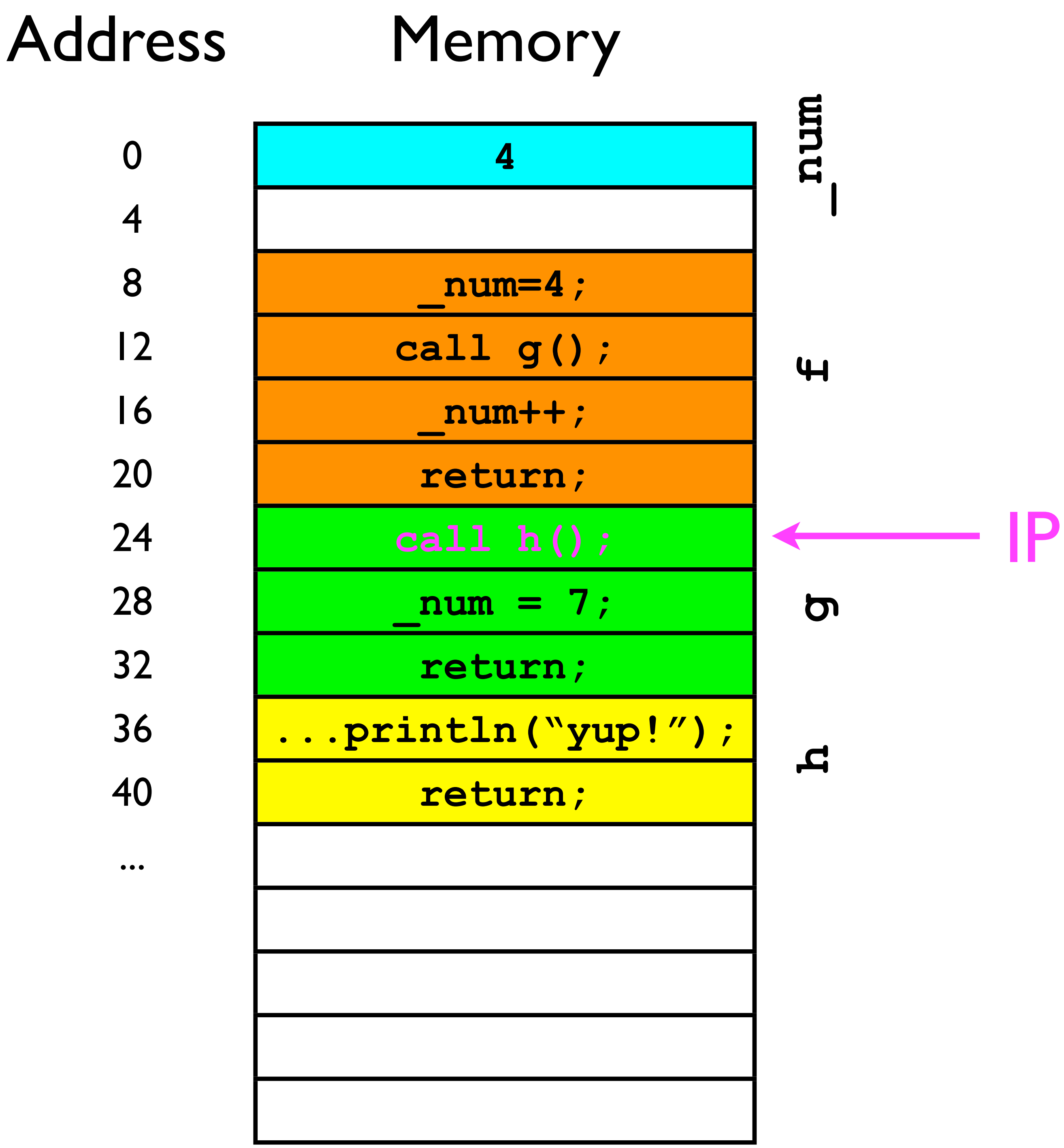
- Suppose the IP is 8:
  - Then the next instruction to execute is **`_num=4`**;
- The CPU then advances the IP to the next instruction (4 bytes later) to 12.

Code execution



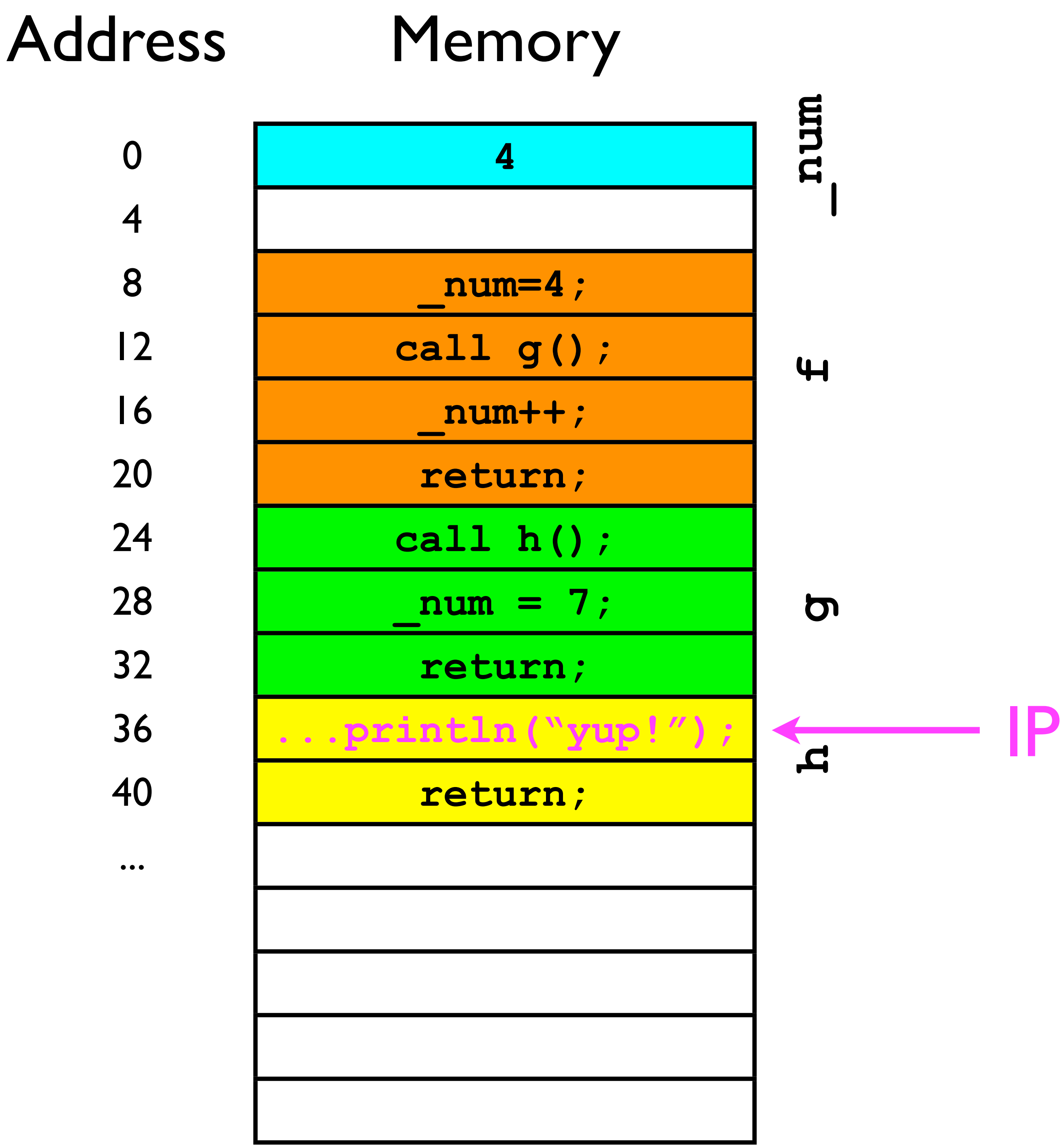
- The next instruction is `call g()`.
- The CPU must now "move" the IP to address 24 (start of g's code) so `g` can start.

Code execution



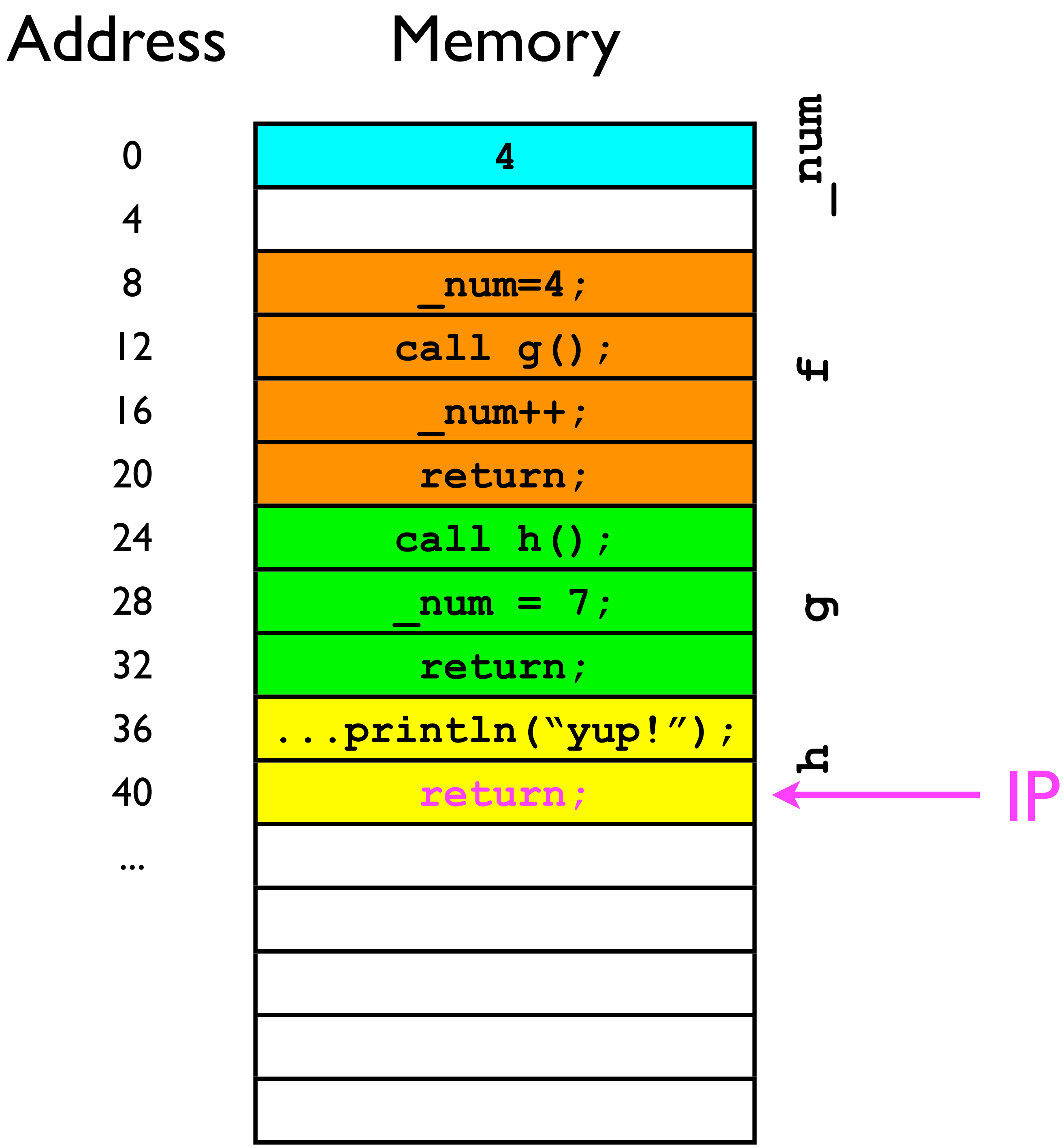
- `g` has now started.
- The first thing `g` does is call `h`.
- We have to move the IP again.

Code execution



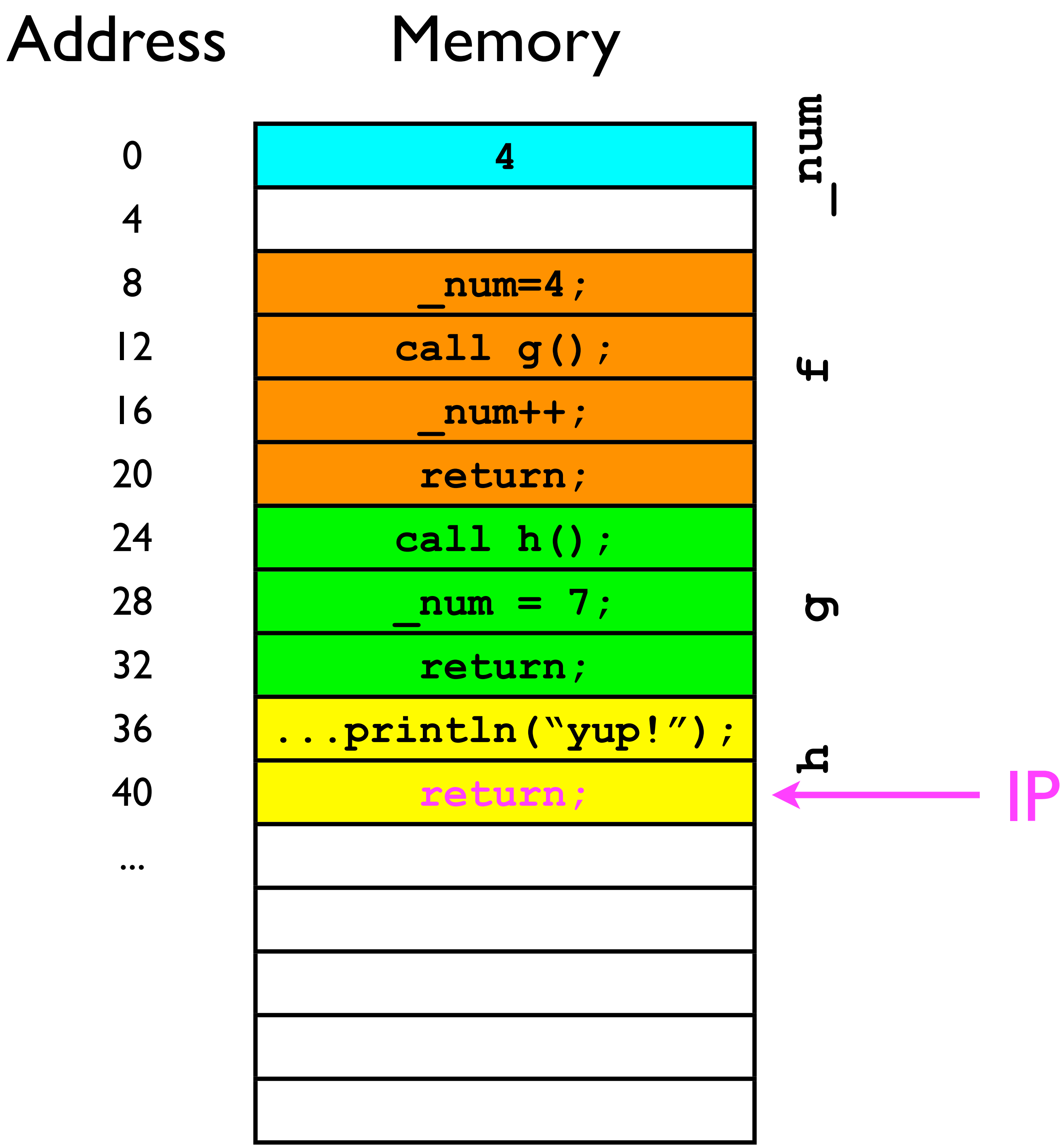
- **h** now prints out "yup!".

Code execution



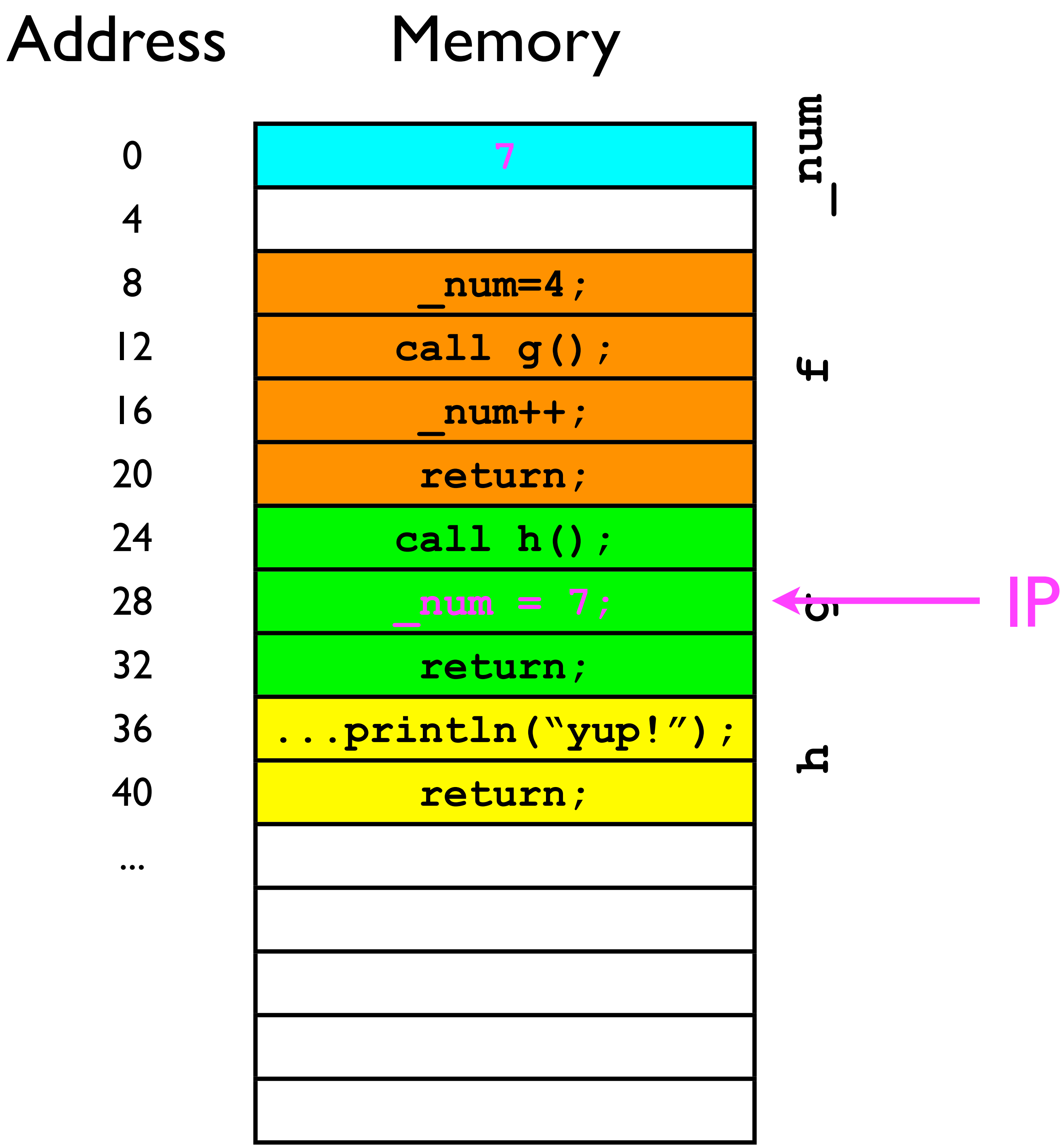
- The return instructions tells the CPU to move the IP back to where it was *before the current method was called.*
- But where is that?

Code execution



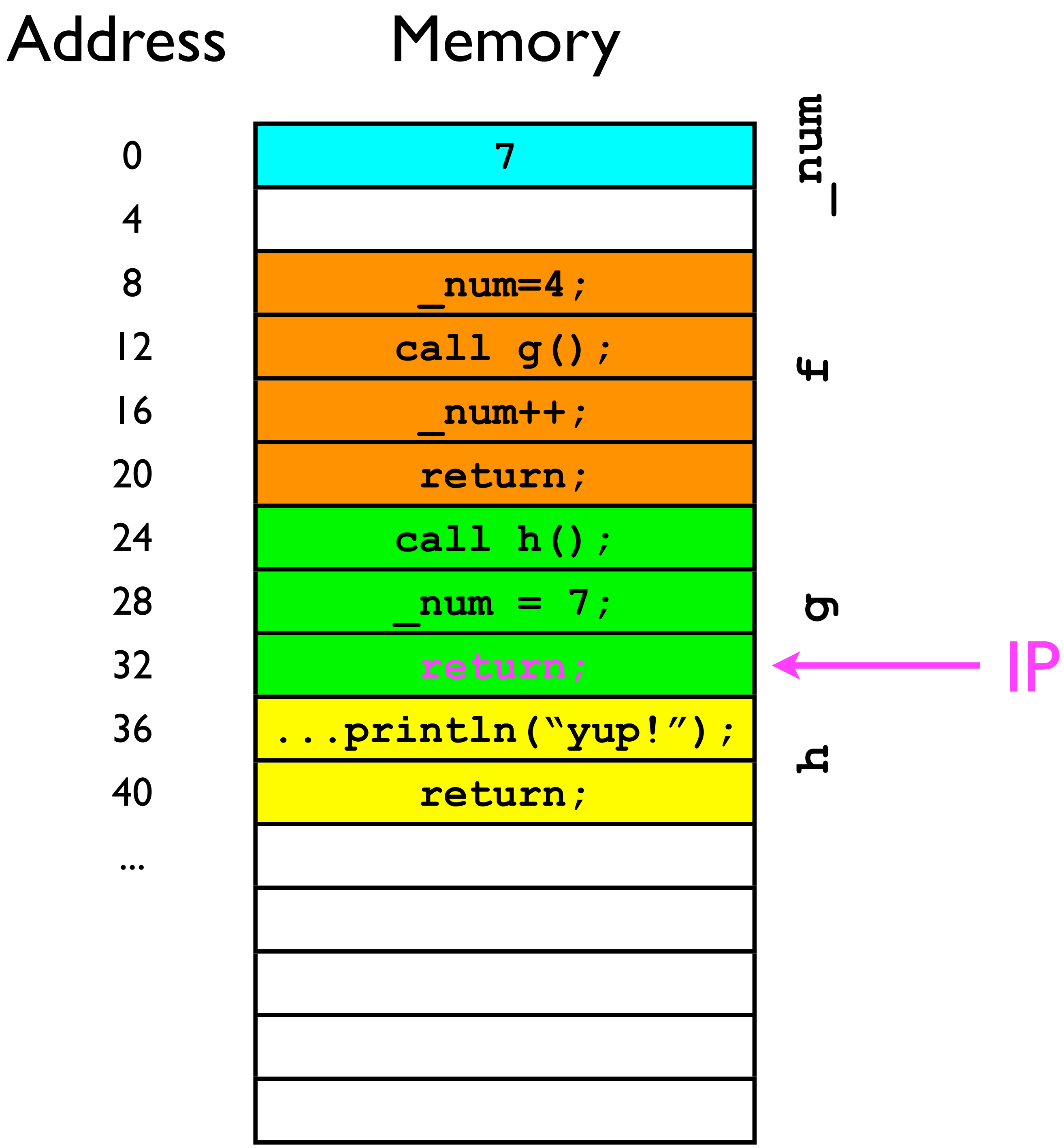
- The return call at address 40 *should* cause the CPU to jump to address 28 -- *the next instruction in* g.

Code execution



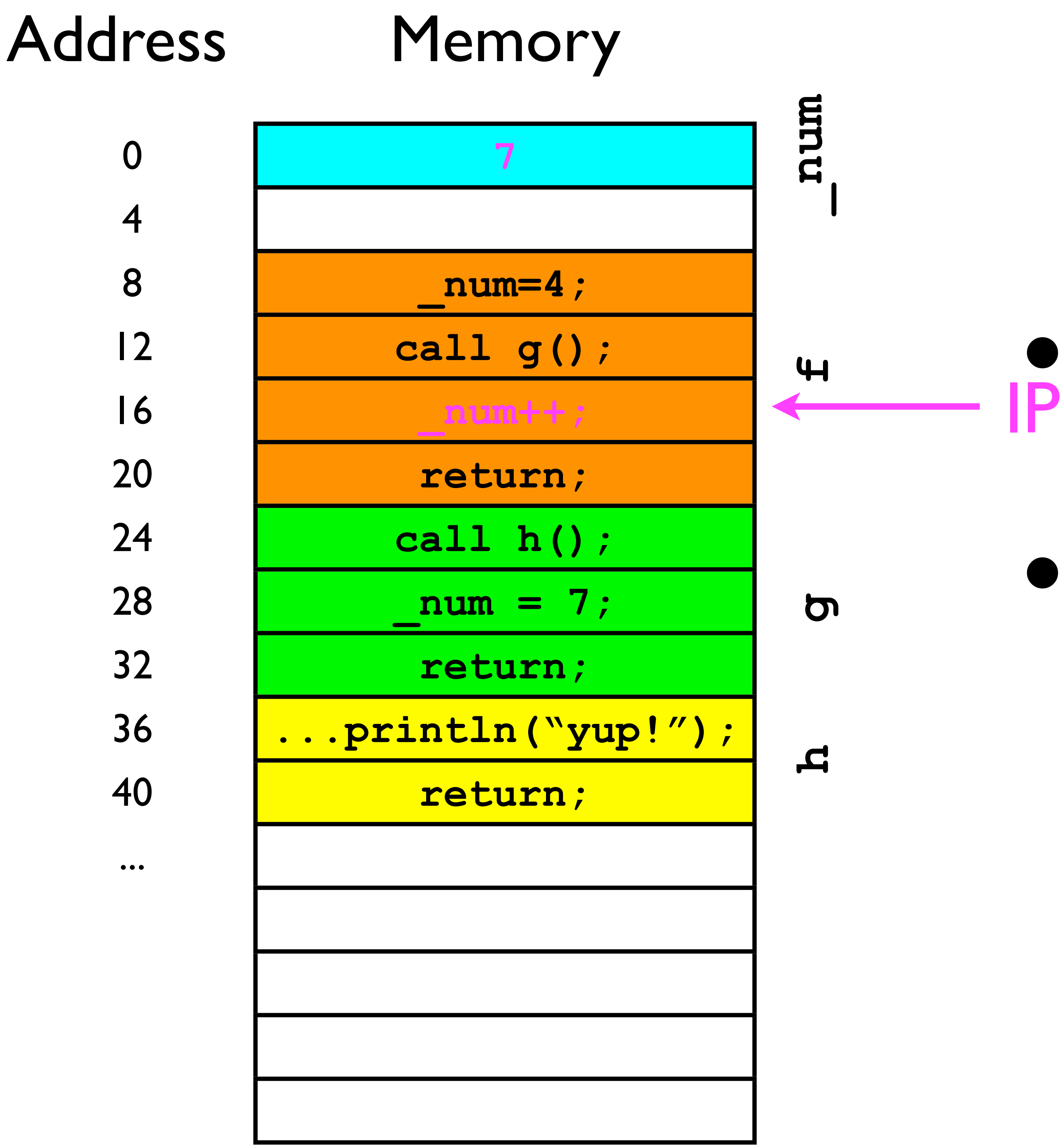
- We then execute `_num=7;`

Code execution



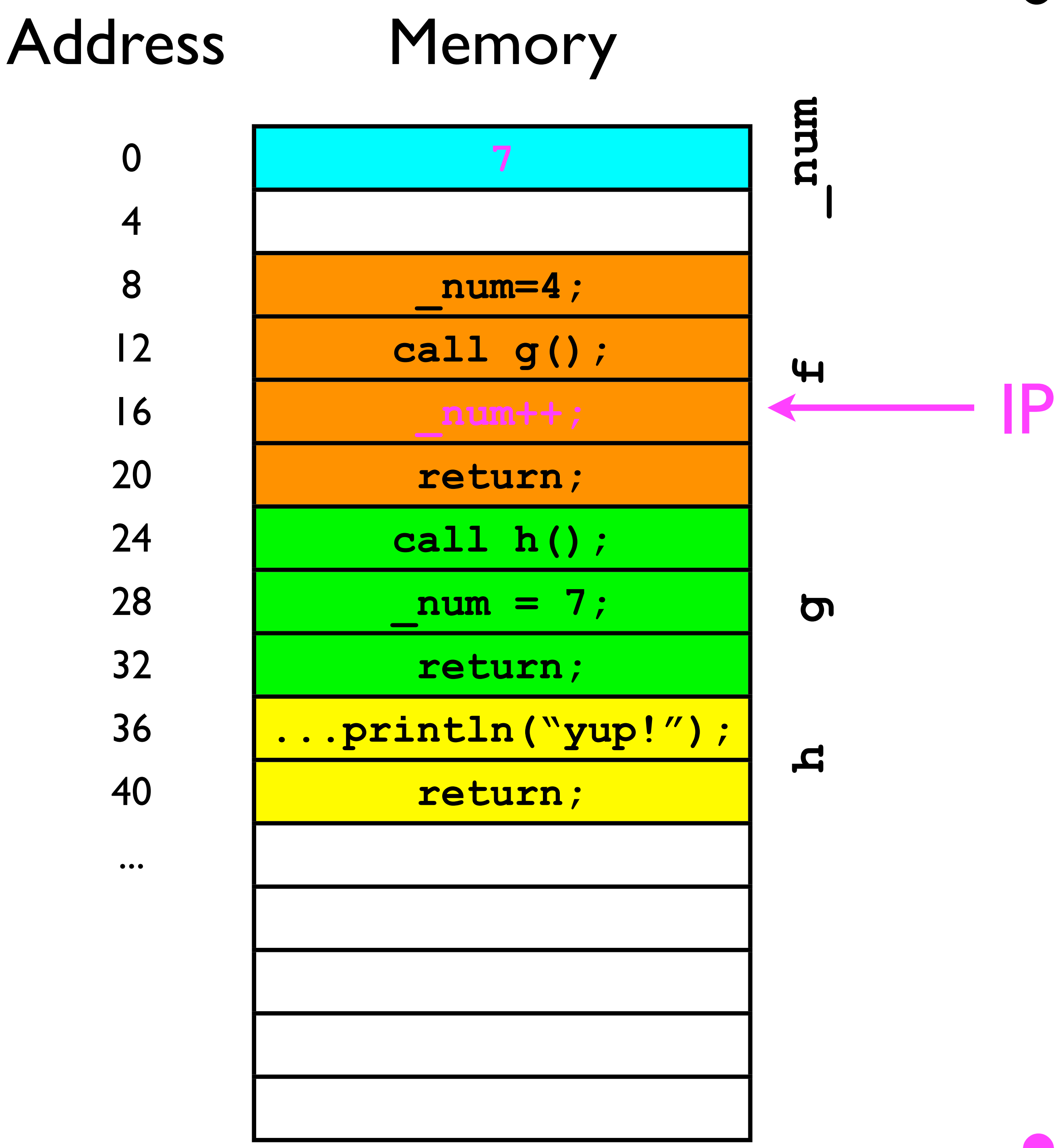
- And now we have to return to where the *caller* of g left off (address 16).

Code execution



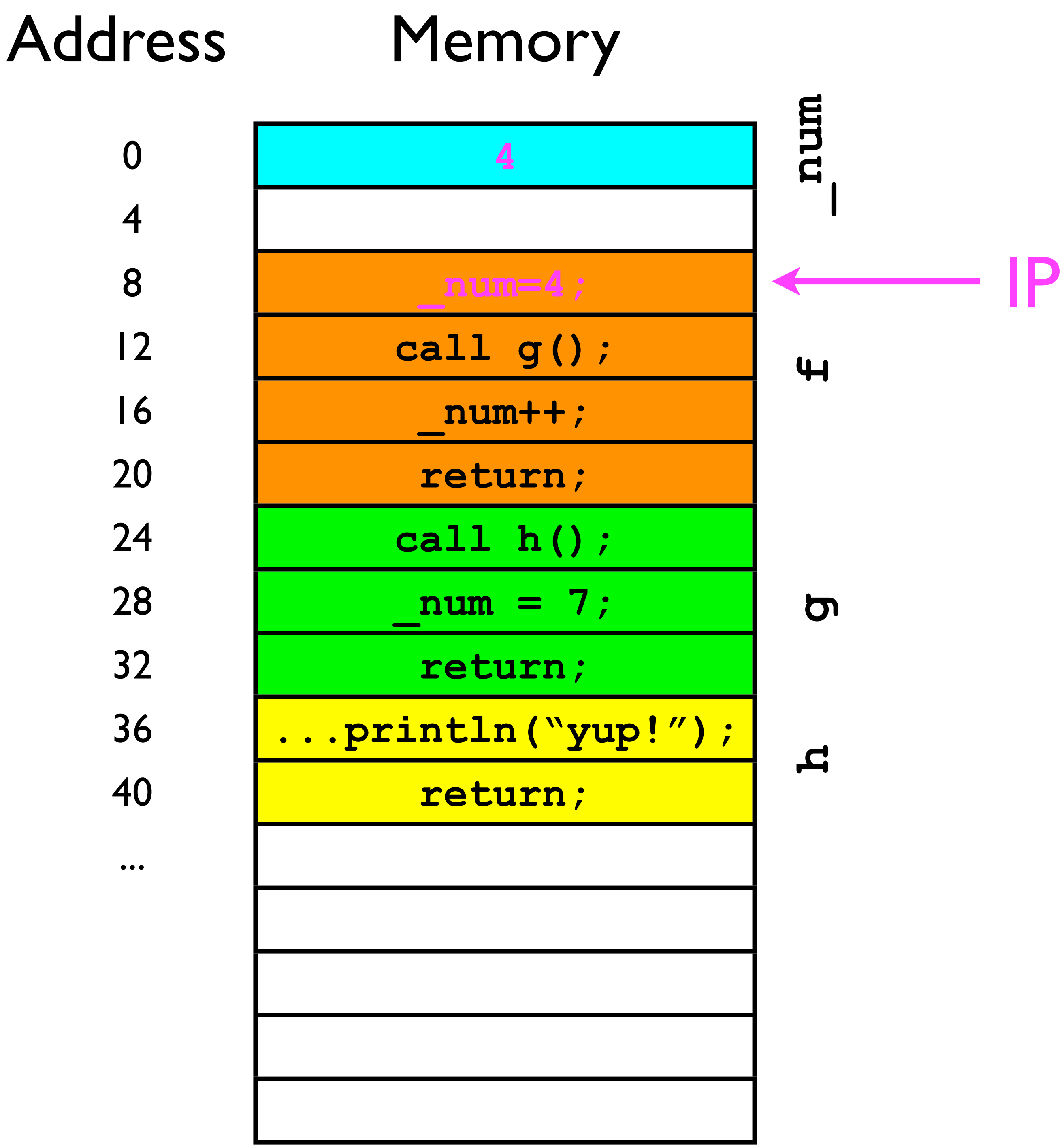
- How does the CPU know which address to "return" to?
- We need some kind of data structure to manage the "return addresses" for us.

Code execution



- What we need is a last-in-first-out data structure ("stack") to remember all the return addresses:
  - *Rule 1*: Before method x calls method y, method x first adds its "return address" to the stack.
  - *Rule 2*: When method y "returns" to its caller, it removes the top of the stack and sets the IP to that address.
- Let's see this work in practice...

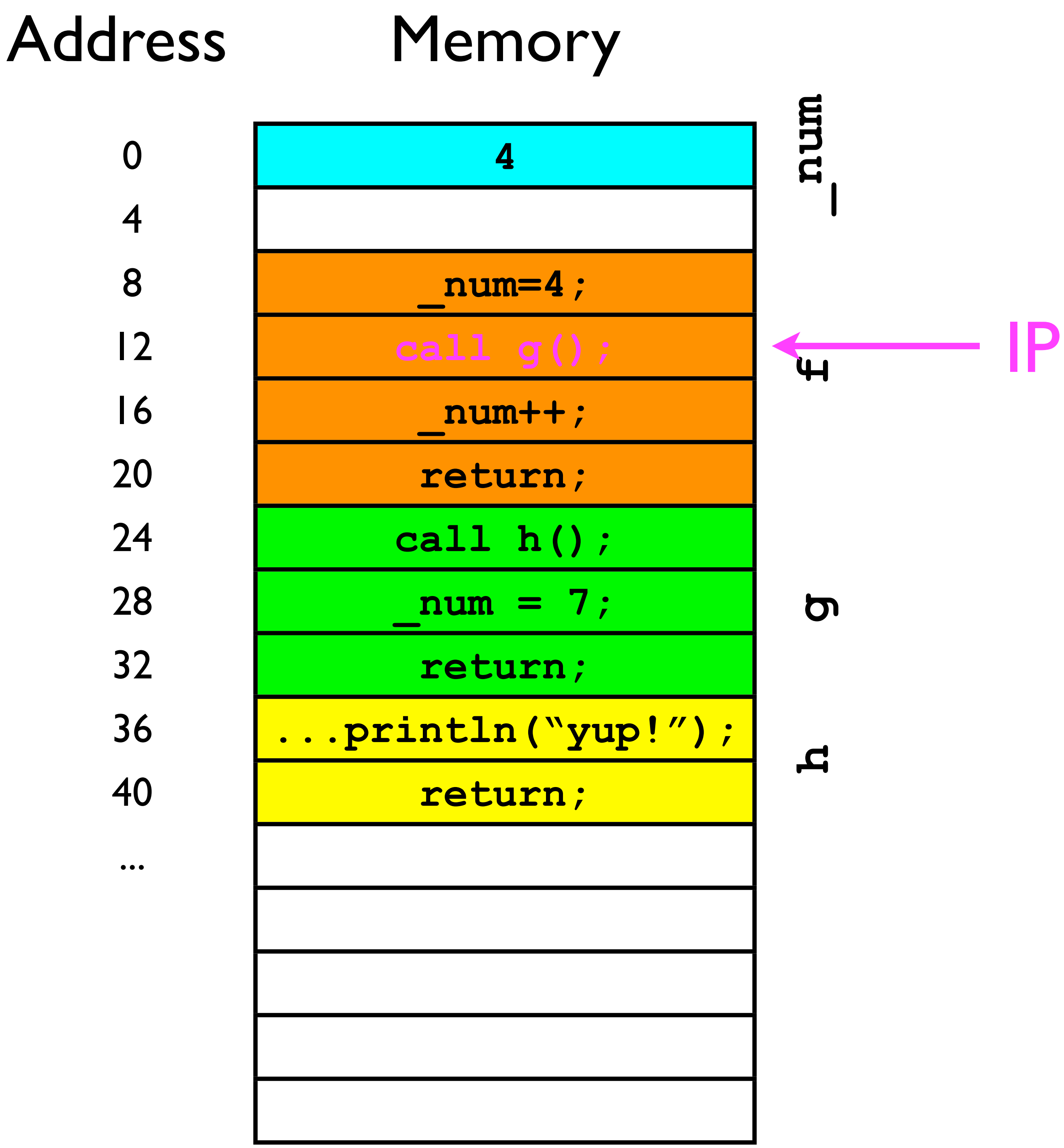
Code execution



- "Return address" stack:

(bottom of stack)

Code execution



- "Return address" stack:

"push" 16 onto stack

16

(bottom of stack)

Code execution

Address	Memory	
0	`4`	`_num`
4		
8	`_num=4;`	`f`
12	`call g();`	`f`
16	`_num++;`	`f`
20	`return;`	`f`
24	`call h();` ← IP	`g`
28	`_num = 7;`	`g`
32	`return;`	`g`
36	`...println("yup!");`	`h`
40	`return;`	`h`
...		

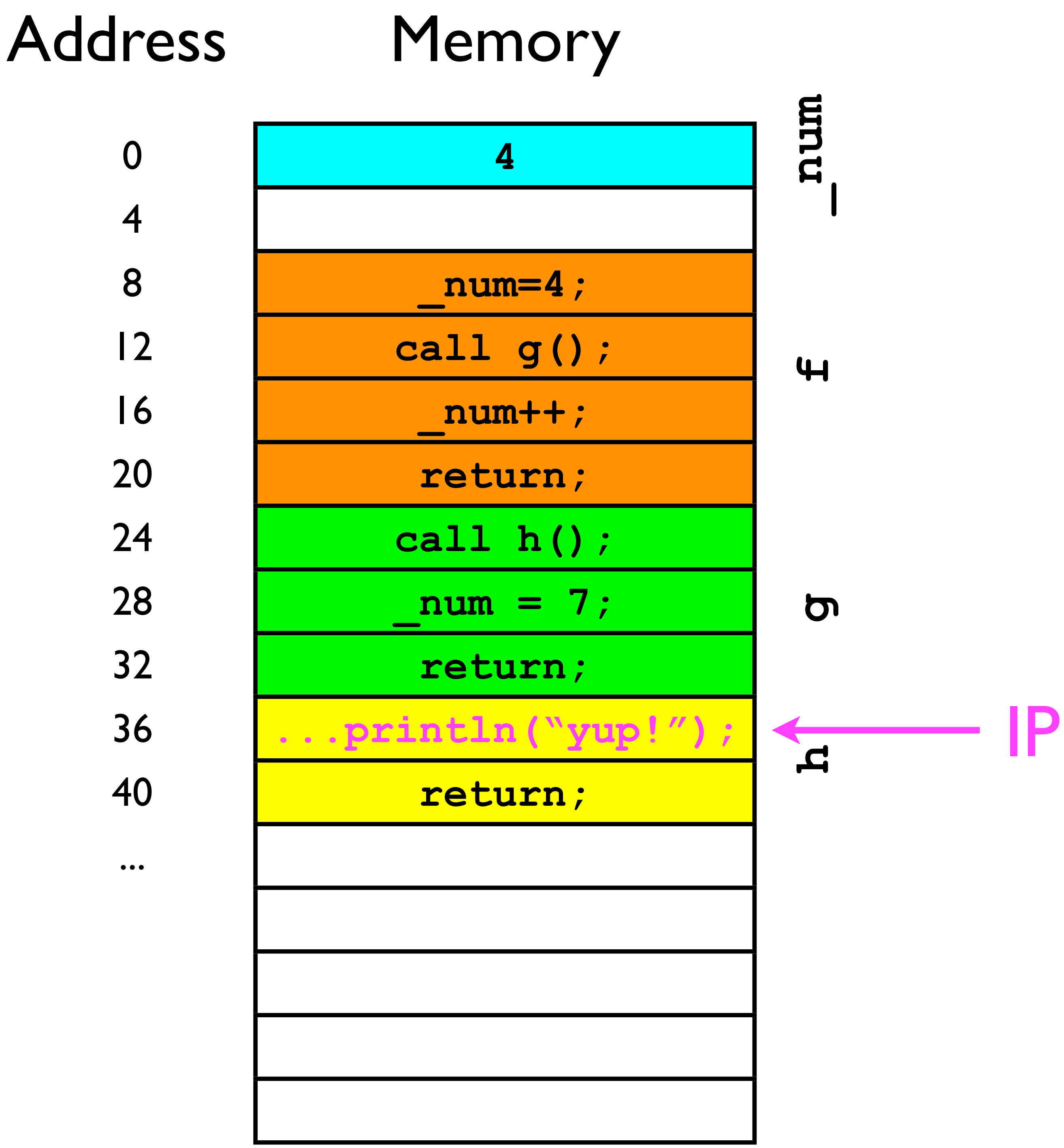
- "Return address" stack:

"push" 28 onto stack

28
16

(bottom of stack)

Code execution

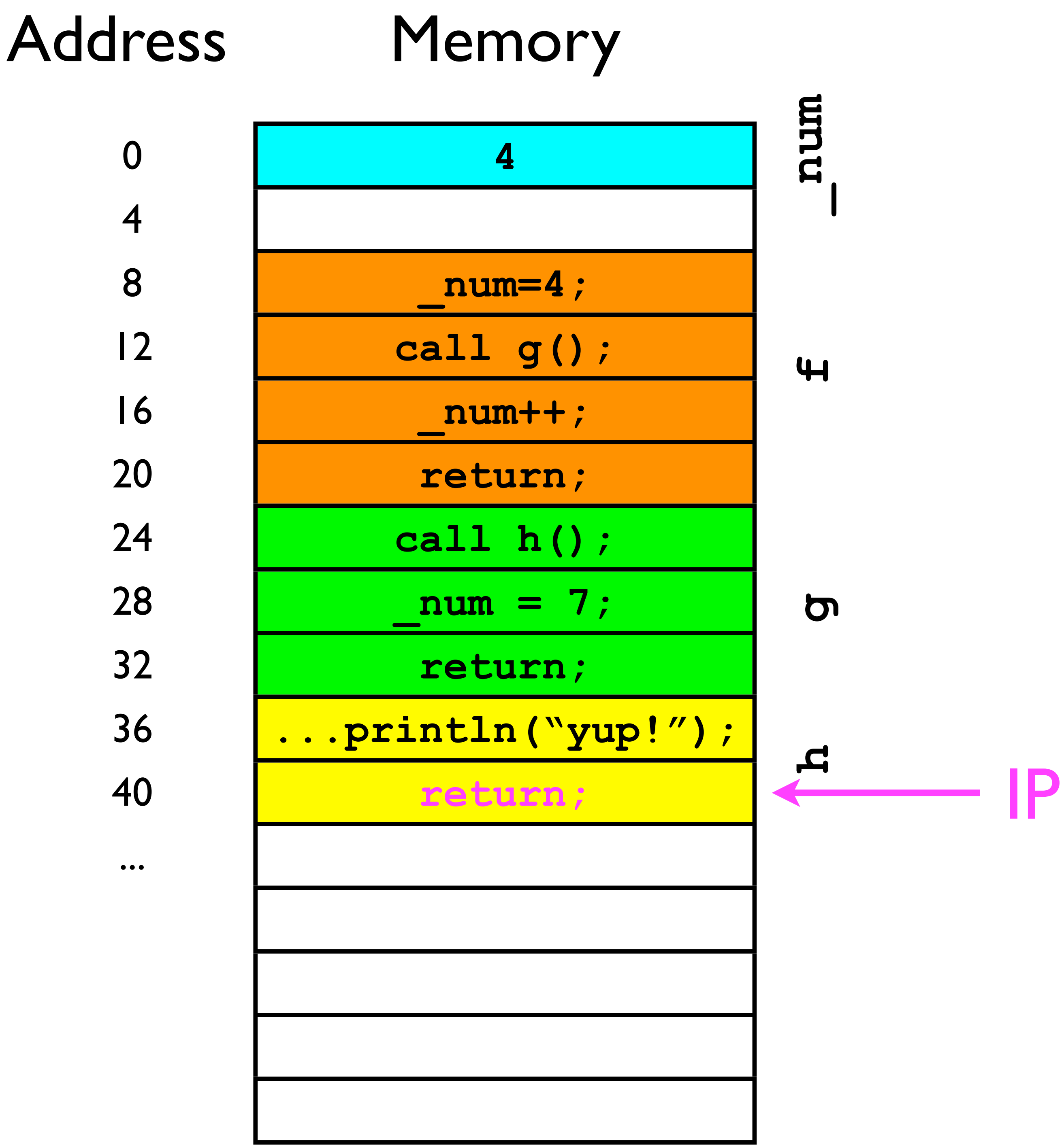


- "Return address" stack:

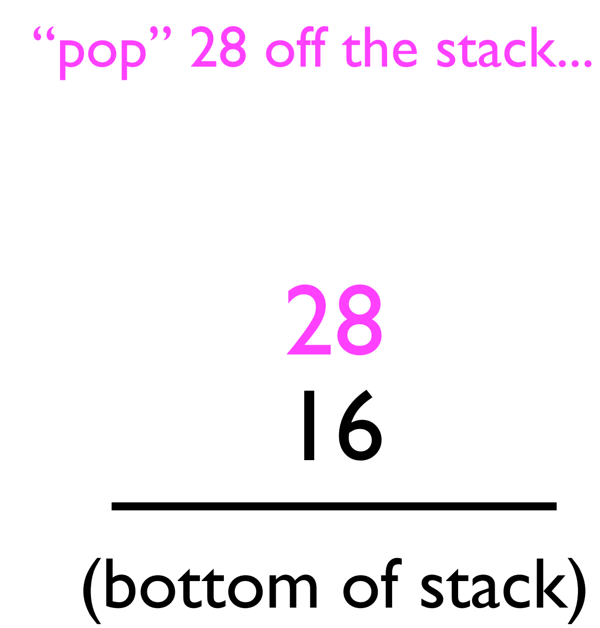
28
16

(bottom of stack)

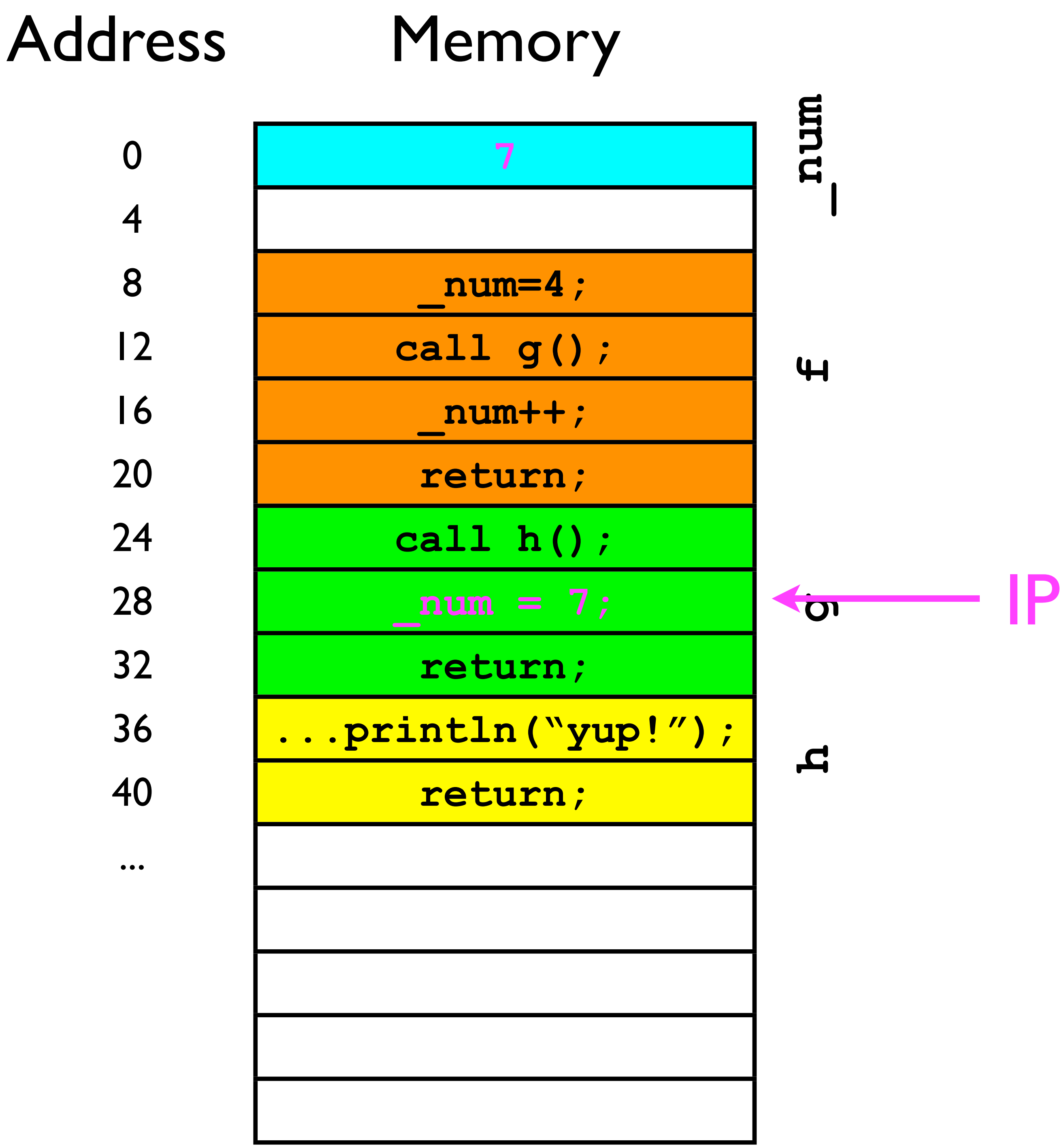
Code execution



- "Return address" stack:



Code execution



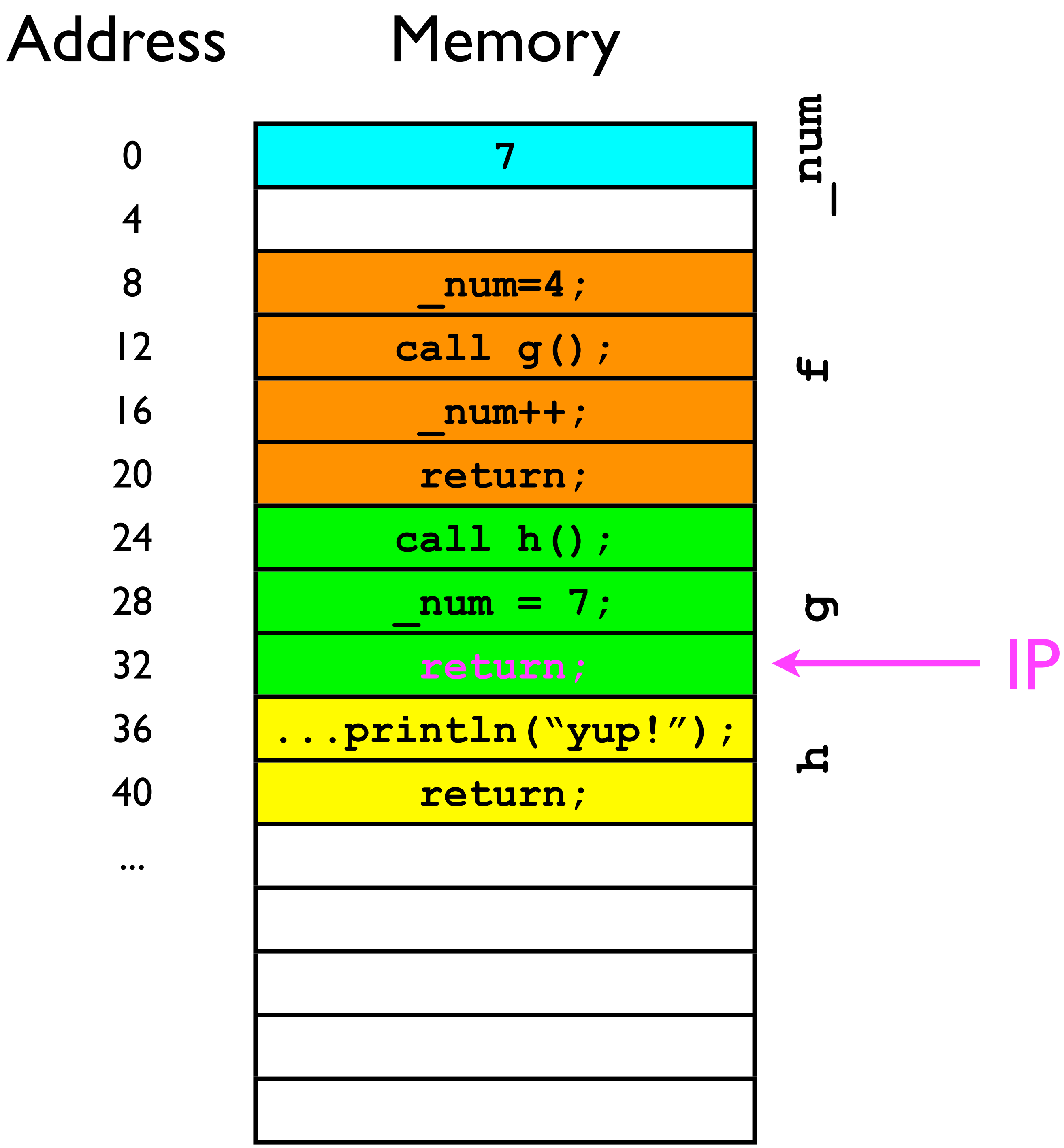
- "Return address" stack:

...and jump to that address.

16

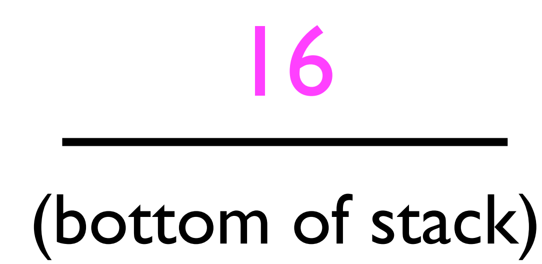
(bottom of stack)

Code execution

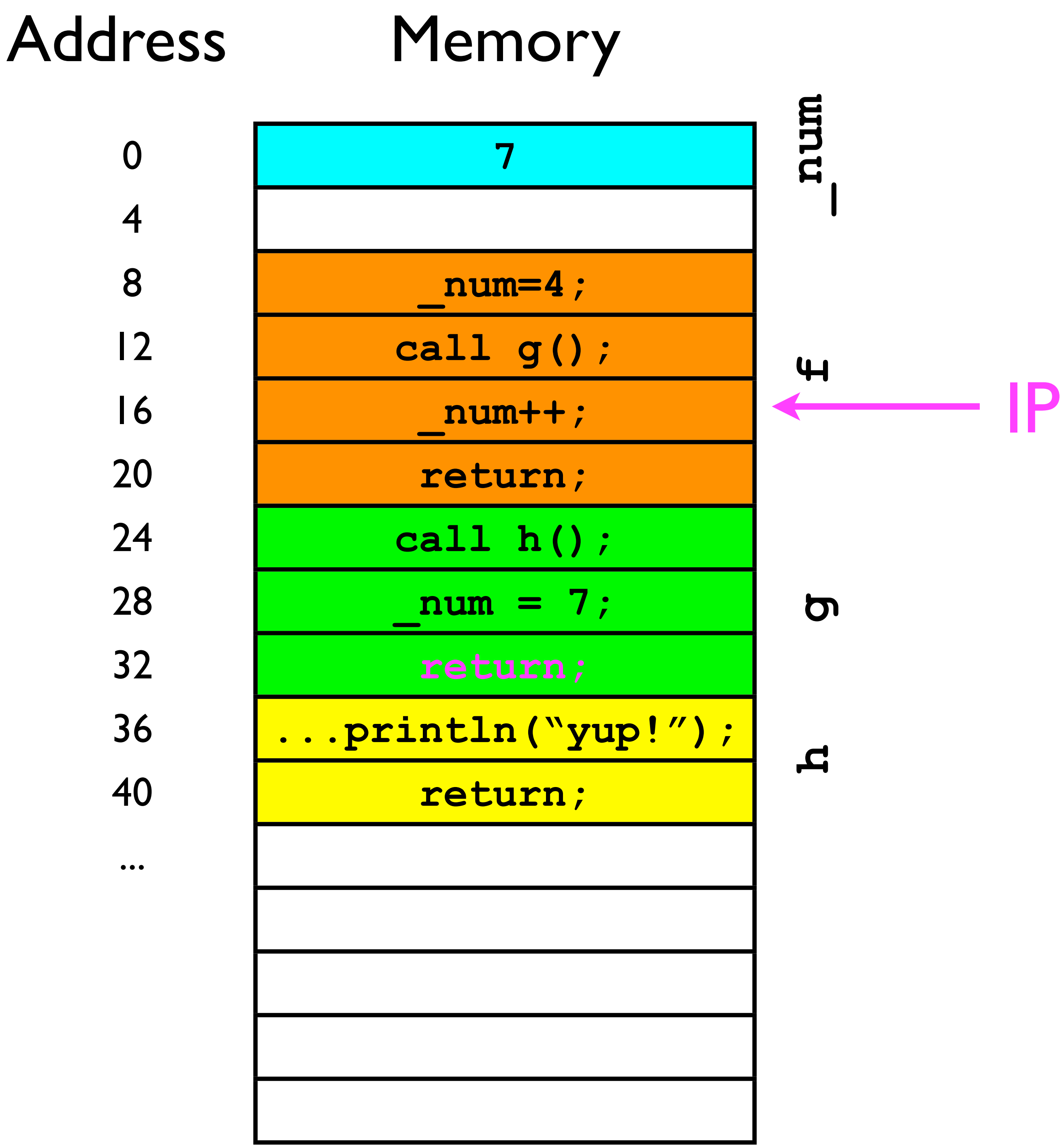


- "Return address" stack:

"pop" 16 off the stack...



Code execution



- "Return address" stack:

...and jump to that address.

(bottom of stack)

Stack ADT

- To support the last-in-first-out adding/removal of elements, a stack must adhere to the following interface:

```
interface Stack<T> {
  // Adds the specified object to the top of the stack.
  void push (T o);

  // Removes the top of the stack and returns it.
  T pop ();

  // Returns the top of the stack without removing it.
  T peek ();
}
```

Review of stacks

- Stacks are a last-in-first-out (LIFO) data structure designed primarily to store data temporarily.
- Data are always added to/removed from the top of the stack.
- Stack ADT interface:

```
interface Stack<T> {
  // Adds the specified object to the top of the stack.
  void push (T o);

  // Removes the top of the stack and returns it.
  T pop () throws NoSuchElementException;

  // Returns the top of the stack without removing it.
  T peek () throws NoSuchElementException;
}
```

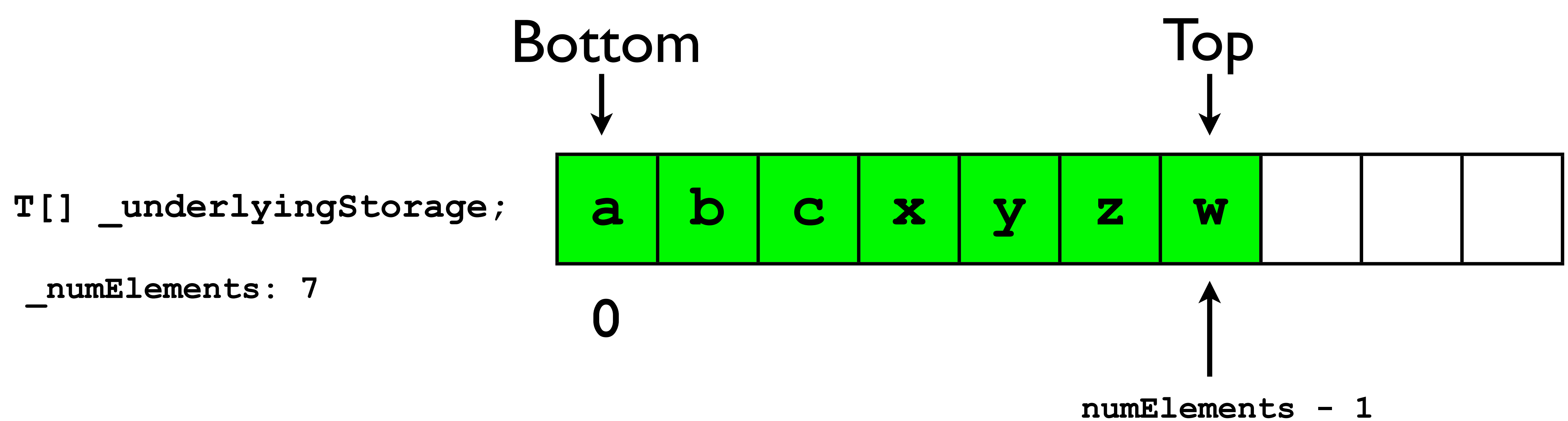
Stack implementations

- A stack can be implemented straightforwardly using two kinds of backing stores/underlying storage.
  - Array
    - More efficient for stacks of a fixed maximum capacity.
  - Linked list
    - More flexible for stacks with a growable capacity.

Array-based stacks

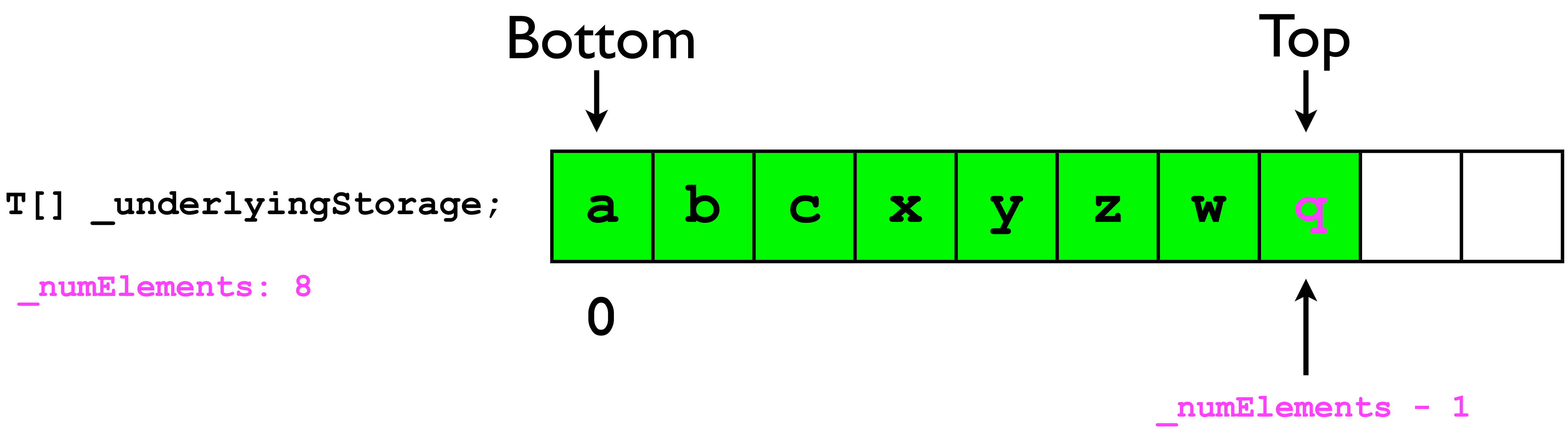
- Arrays offer a natural implementation of stacks:
  - Use `T[] _underlyingStorage` to hold elements added to stack.
    - Maximum capacity is `_underlyingStorage.length`
  - Keep track of "height" of stack using `_numElements` instance variable.

```
...
_stack.push(y);
_stack.push(z);
_stack.push(w);
```



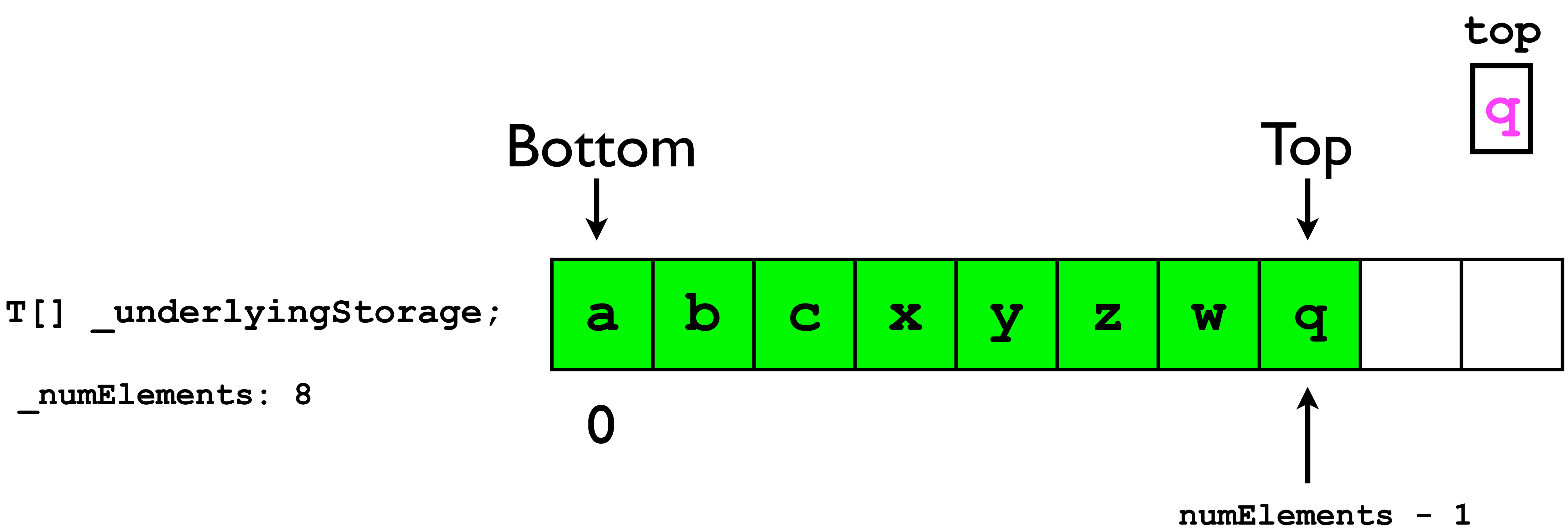
Array-based stacks

- In every call to **push(o)**, e.g., **_stack.push(q);**
    - **_numElements** is incremented.
    - **o** is stored at index **_numElements - 1**.



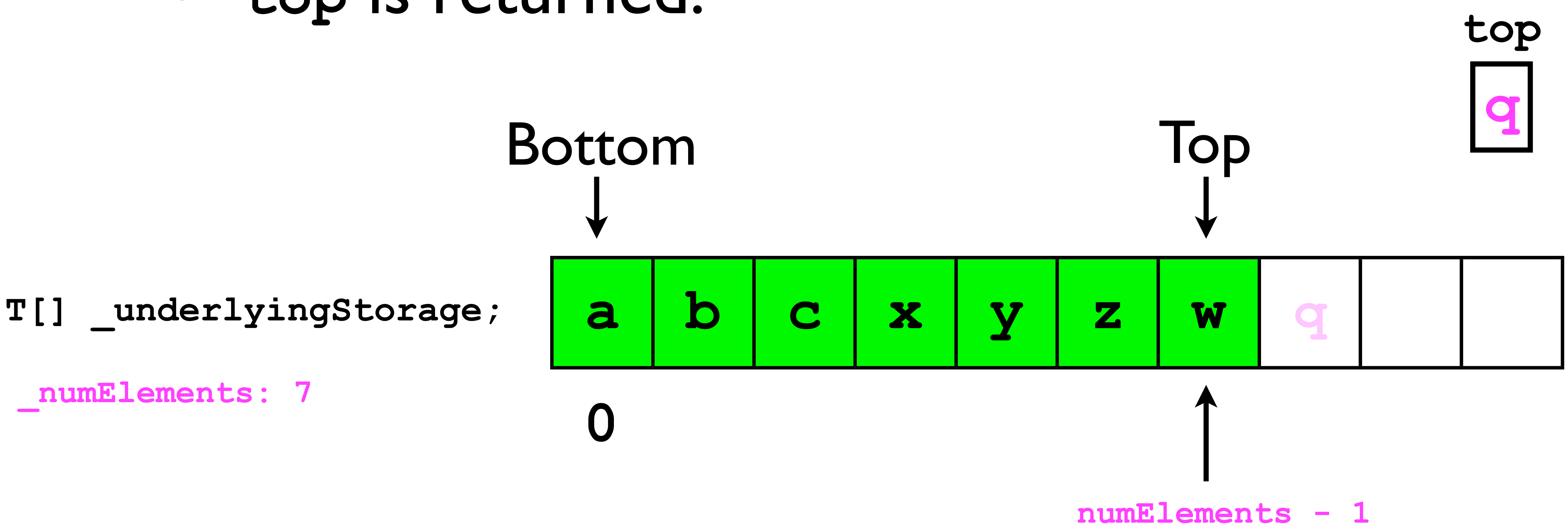
Array-based stacks

- In every call to **`peek()`**:
  - The element stored at index **`_numElements - 1`** is saved to a local variable **`top`**.
  - **`top`** is returned.



Array-based stacks

- In every call to `pop()`:
  - The element stored at index `_numElements - 1` is saved to a local variable `top`.
  - `_numElements` is decremented.
  - `top` is returned.

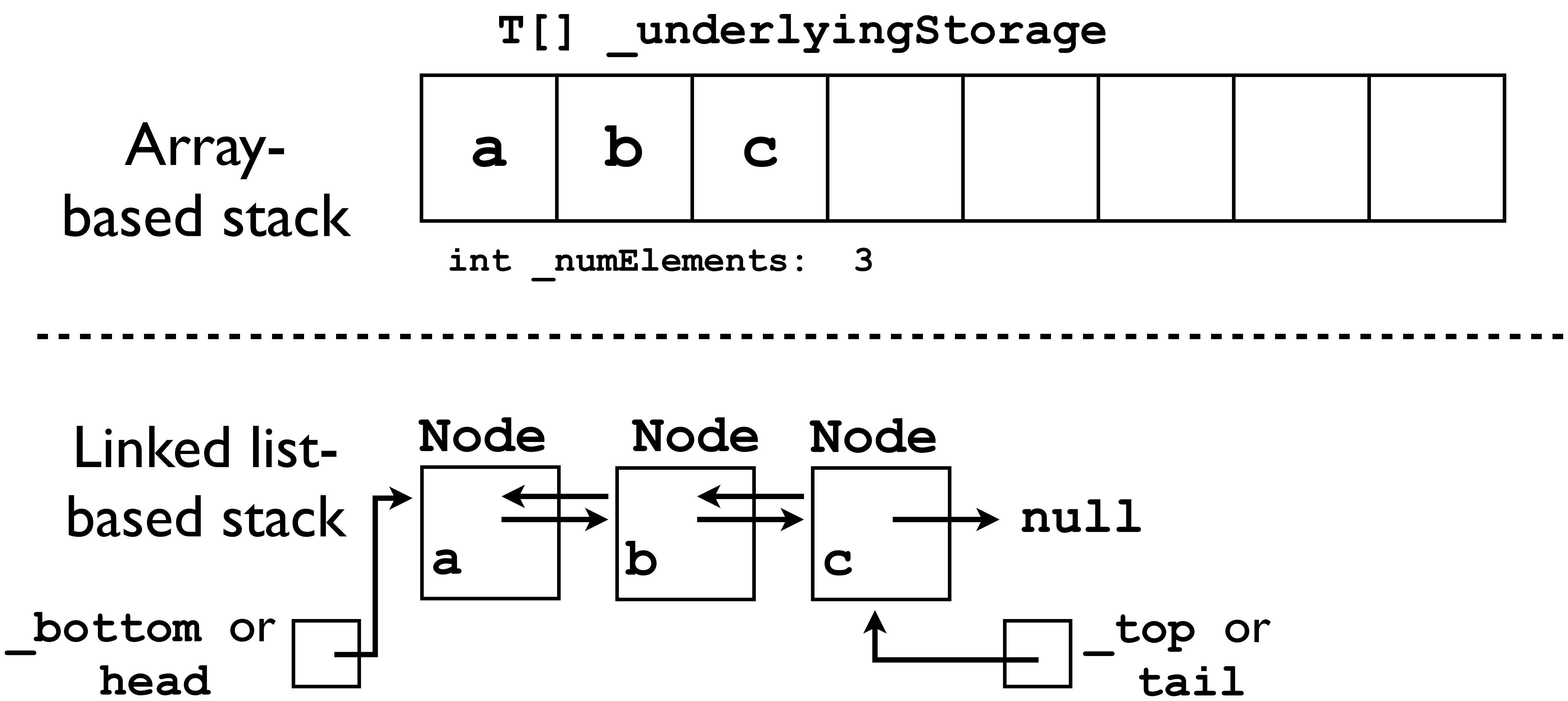


Exceptions

- If a stack has reached its maximum capacity (i.e., `_numElements == _underlyingStorage.length`) and the user calls `push(o)`, then the stack will **overflow**.
- If a stack is empty (`_numElements == 0`) and the user calls `pop()`, then the stack will **underflow**.

Linked list-based stacks

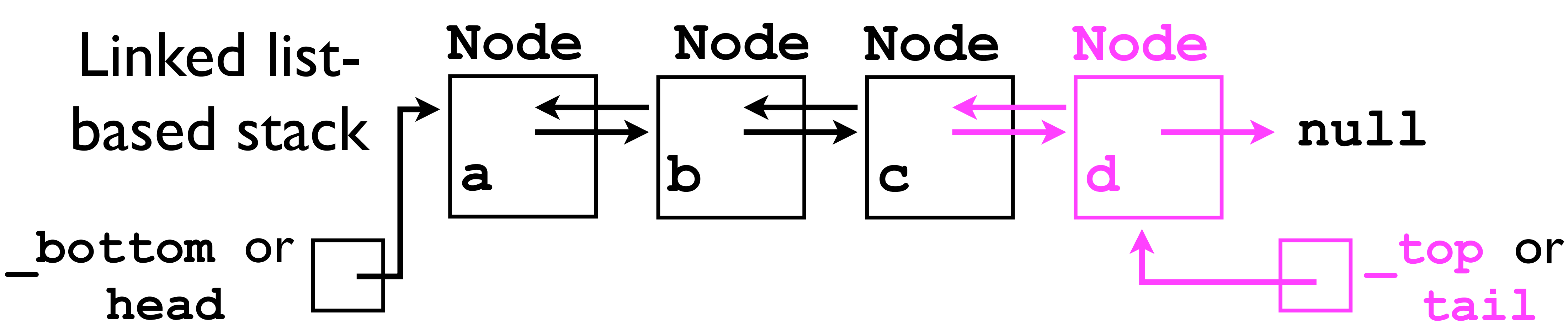
- A stack can also be implemented using a linked-list of nodes:



Linked list-based stacks

- Each call to **`push(o)`** adds a new **`Node`** to the **`_top`** of the stack (or **`_tail`** of the list), e.g.:

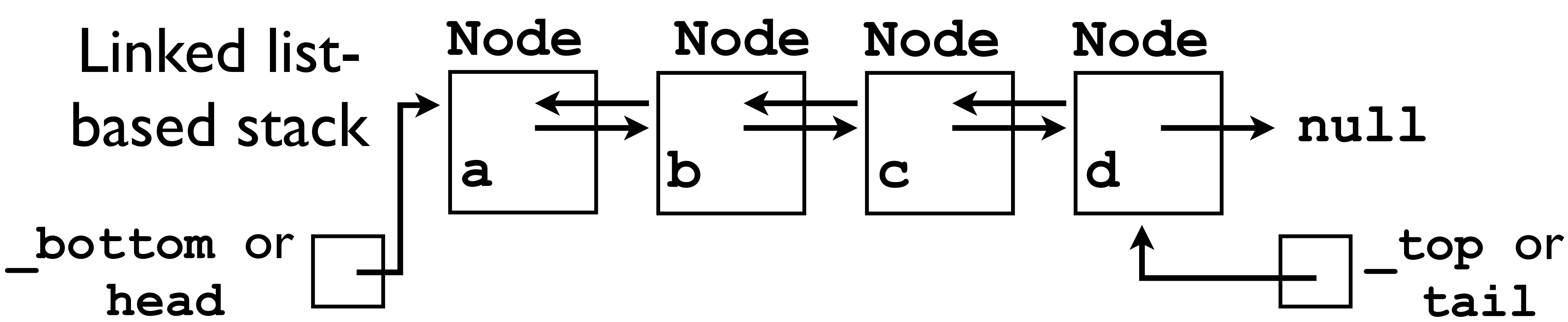
```
_stack.push(d);
```



Linked list-based stacks

- Each call to **`peek()`** simply returns the data referenced by **`_top`** (or **`_tail`**):

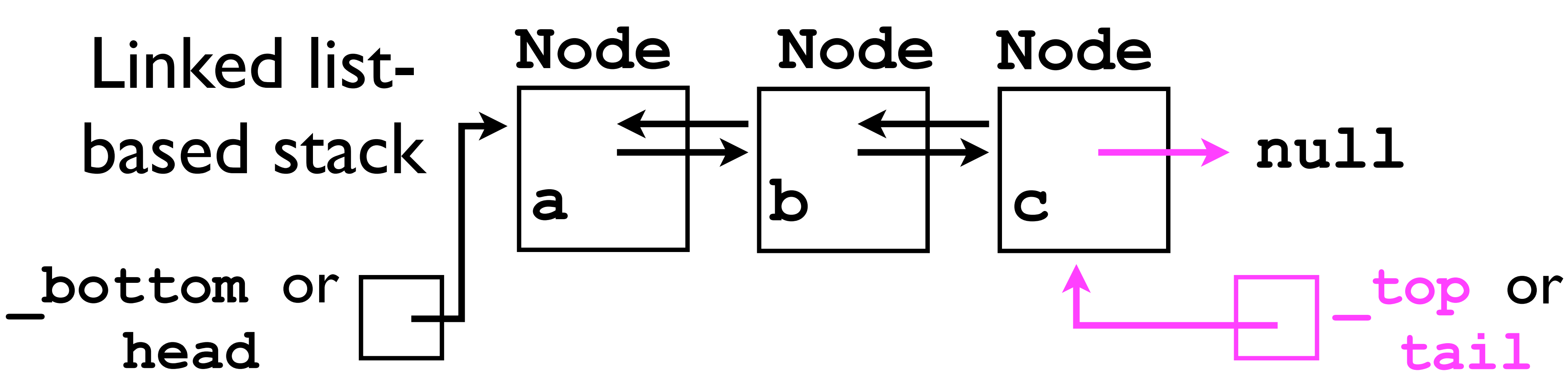
```
final T top = _stack.peek(); // d
```



Linked list-based stacks

- Each call to **`pop()`** removes the **`Node`** at the **`_top`** of the stack (or **`_tail`** of the list) and returns the data it referenced, e.g.:

```
final T top = _stack.pop(); // d
```



Linked list-based stacks

- A linked list-based stack ADT could be implemented by defining a static inner-class **`Node`** and essentially "re-implementing" the **`DoublyLinkedList12`** functionality.
  - But this would be wasteful -- we already have a functioning **`DoublyLinkedList12`** ADT.
  - We can save time and the possibility of human error by "adapting" the **`DoublyLinkedList12`** ADT to a **`Stack`** ADT.

“Adapter” design pattern

- In software engineering, one of the classic “design patterns” is the *adapter*.
  - An *adapter* is a class that “converts” from the interface of one ADT -- the one we’re trying to implement -- to the interface of another ADT *that already exists*.
  - If we adapt an ADT B to implement another ADT A, then every method of A must be “converted” into a related call of B.
  - In particular, we can adapt the `List12` ADT (implemented by `DoublyLinkedList12`) to satisfy the `Stack` ADT interface specification...

Stack as adaptation of linked list

```
class StackImpl<T> implements Stack<T> {
  private DoublyLinkedList _list;
  StackImpl () {
    _list = new DoublyLinkedList();
  }

  void push (T o) {
    _list.addToBack(o);
  }

  T pop () {
    return _list.removeBack();
  }
  ...
}
```

Queues.

Queues

- Queues are a first-in-first-out (FIFO) data structure used typically for temporary data storage.
  - Instead of `add`, `get`, and `remove` methods, queues offer enqueue and dequeue methods.
  - The first object to be `enqueue`d is the first object to be `dequeue`d.
- Similarly to a train entering a tunnel, the first car to enter the tunnel is the first car to exit the tunnel.

Usage example of queues

```
Queue<String> queue = new Queue<String>();
queue.enqueue("a");
queue.enqueue("b");
queue.enqueue("c");
queue.enqueue("d");
...
String s;
s = queue.dequeue();  // returns "a"
s = queue.dequeue();  // returns "b"
...
```

enqueue adds an object to the queue

dequeue both gets and removes the "earliest" object from the queue

Queue example

- Consider enrollment lists for a UCSD course. Suppose max enrollment = 80:

```
class Course {
  private static final int MAX_ENROLLMENT = 80;
  private List<Student> _enrolledStudents;
  private Queue<Student> _waitingList;
  ...
  boolean enroll (Student s) {
    ...
  }
  void addToWaitingList (Student s) {
    ...
  }
  void drop (Student s) {
    ...
  }
}
```

Queue example

- A student can enroll only if course size is less than max enrollment:

```
boolean enroll (Student s) {
  if (_enrolledStudents.size() == MAX_ENROLLMENT) {
    return false;  // course full -- can't enroll!
  }
  _enrolledStudents.add(s);
}
```

Queue example

- If course is full, students can place their name on a waiting list:

```
void addToWaitingList (Student s) {
  _waitingList.enqueue(s);
}
```

Queue example

- If a student drops the course, then we can enroll a student from the waiting list:

```
void drop (Student s) {
  _list.remove(s);
  if (_waitingList.size() > 0) {
    _enrolledStudents.add(_waitingList.dequeue());
  }
}
```

The `Queue` interface ensures that the first `Student` to be dequeued is always the first student who enqueued.

Queue ADT

- The interface for a Queue ADT looks as follows:

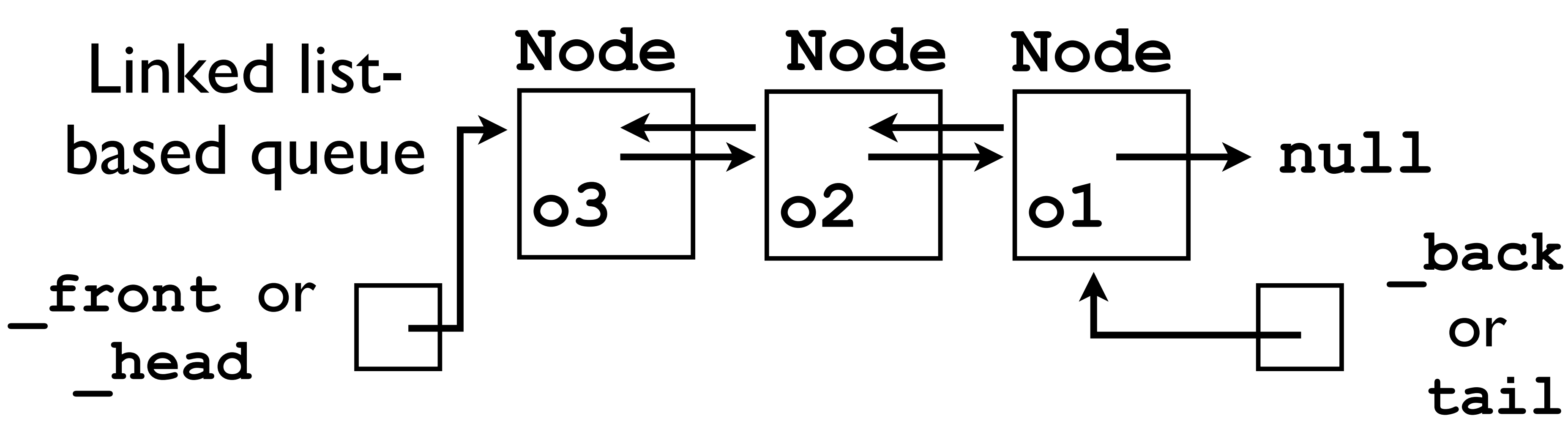
```
interface Queue<T> {
  // Adds o to the back of the queue.
  void enqueue (T o);

  // Removes the object at the front of the
  // queue.
  T dequeue () throws NoSuchElementException;

  // Returns number of elements in queue
  int size ();
}
```

Implementing a queue

- A queue can probably be most easily conceptualized and implemented as a linked list.
- The head of the list is the *front* of the queue.
- The tail is the *back* of the queue.
- Calls to **`enqueue(o)`** add a new **`Node`** to the *back*.
- Calls to **`dequeue()`** remove a **`Node`** (and return its data) from the *front*.



Adapting a DoublyLinkedList12

- As with the **`Stack`** ADT, the **`Queue`** ADT also lends itself to *adapting* the existing **`DoublyLinkedList12`** ADT to suit its needs:
  - Instantiate **`_dll = new DoublyLinkedList12<T>();`**
  - Calls to **`enqueue(o)`**: **`_dll.addToBack(o);`**
  - Calls to **`dequeue()`**: **`return _dll.removeFront();`**

Array-based queue

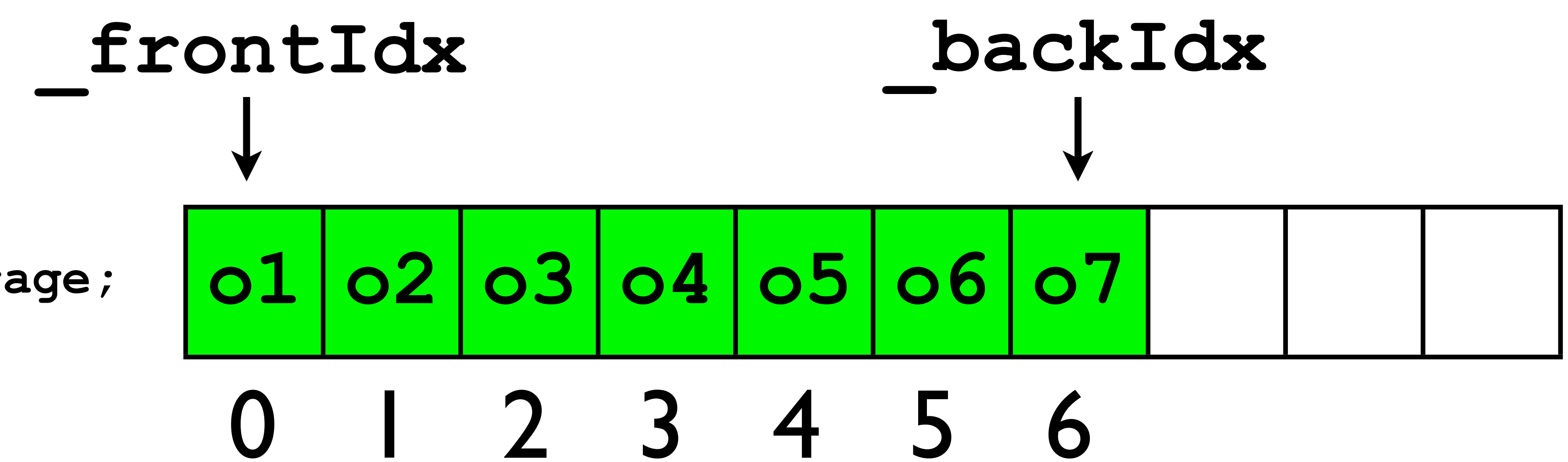
- Like stacks, queues too can be implemented using an array as the underlying storage.
- However, arriving at at an efficient solution is non-trivial.
- Assume following instance variables:
  - **`T[] _underlyingStorage`**
  - **`int _frontIdx, _backIdx`** -- indices into **`_underlyingStorage`** of where the front and back of the queue are located.

Array-based queue

- **`enqueue(o)`**: Append to the *back* of the array:
  - This is easy:

```
_backIdx++;
_underlyingStorage[_backIdx] = o;
```

`T[] _underlyingStorage;`

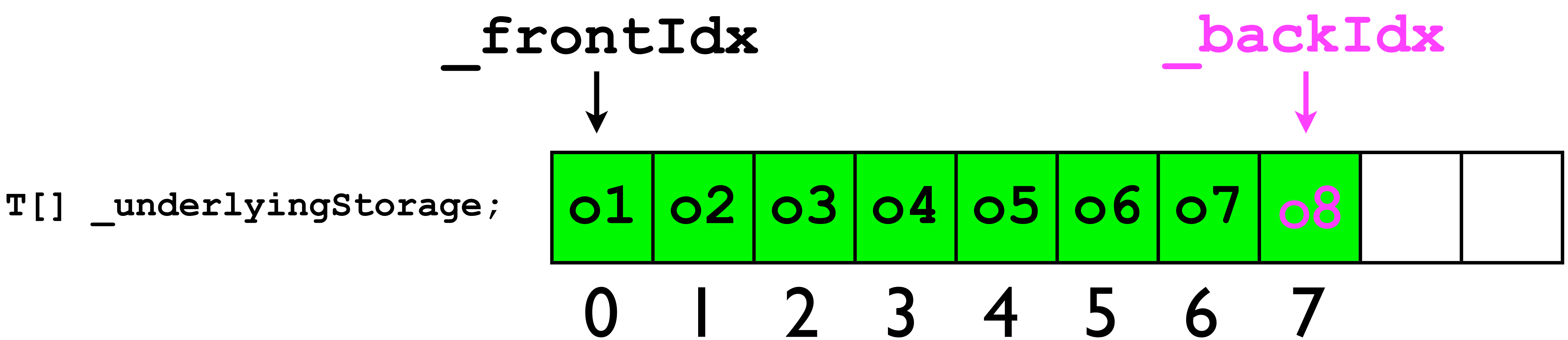


Array-based queue

- `enqueue(o)`: Append to the *back* of the array:
  - This is easy:

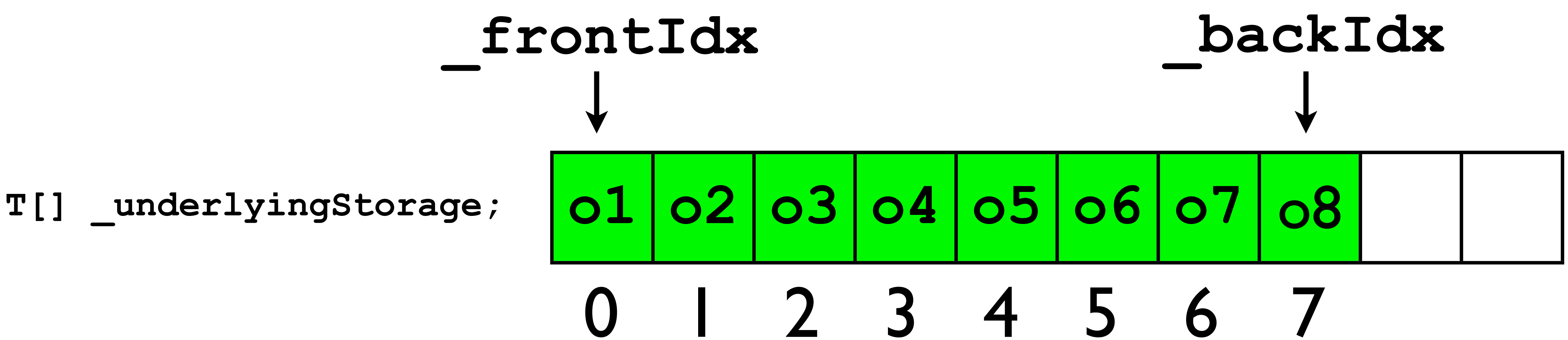
```
_backIdx++;
_underlyingStorage[_backIdx] = o;
```

  - Example: `_queue.enqueue(o8);`



Array-based queue

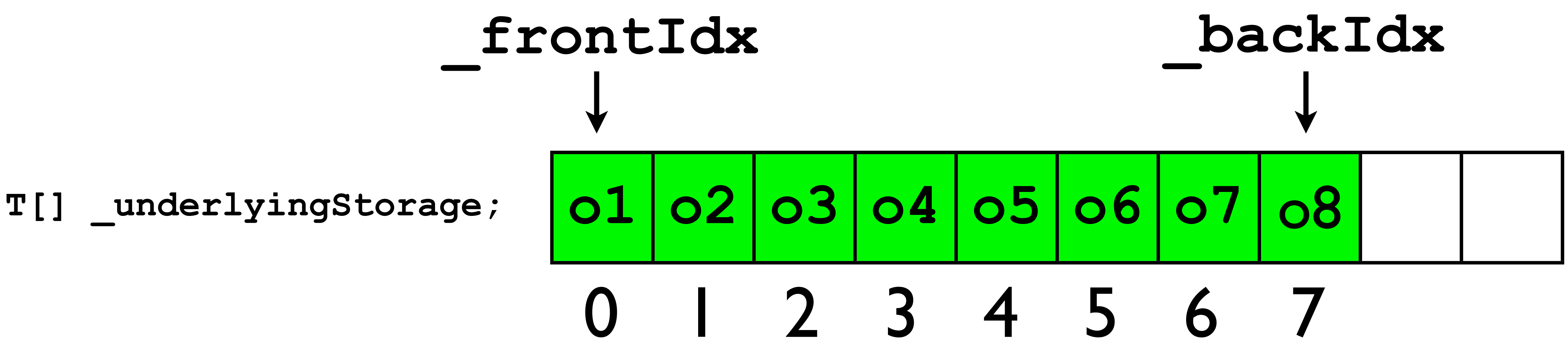
- **`dequeue()`**: Remove from the *front* of the array:
  - This is harder -- what happens when we remove `o1`?
  - There are several ways one can attempt to implement this method...



dequeue() -- Attempt #1

- One possibility is to "shift down" by 1 the entire queue after the front has been removed:

```
final T front = _underlyingStorage[0];
for (int i = _frontIdx+1; i <= _backIdx; i++) {
  _underlyingStorage[i-1] = _underlyingStorage[i];
}
_backIdx--;  // The back has "moved up" by 1
return front;
```



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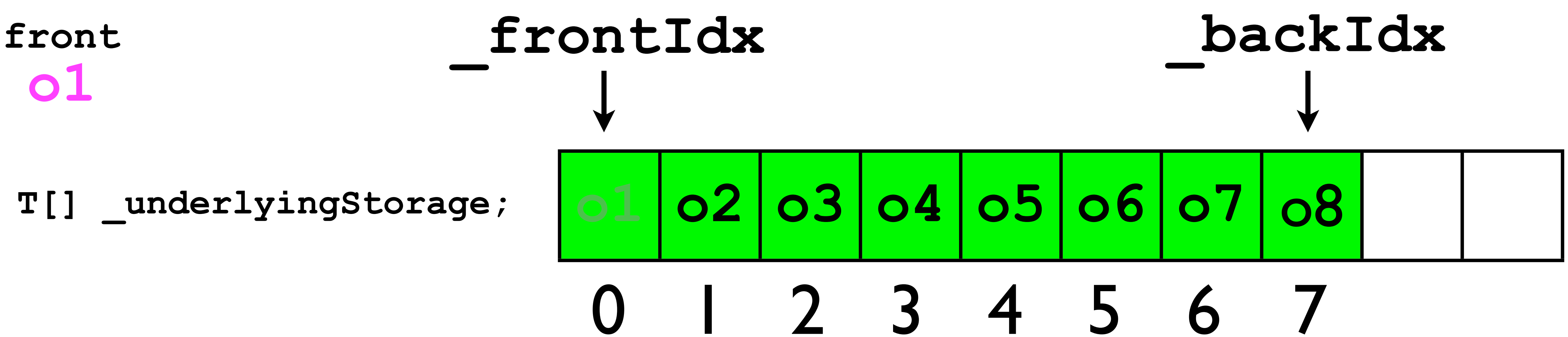
- Example: `_queue.dequeue();`



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  _underlyingStorage[i-1] = _underlyingStorage[i];
}
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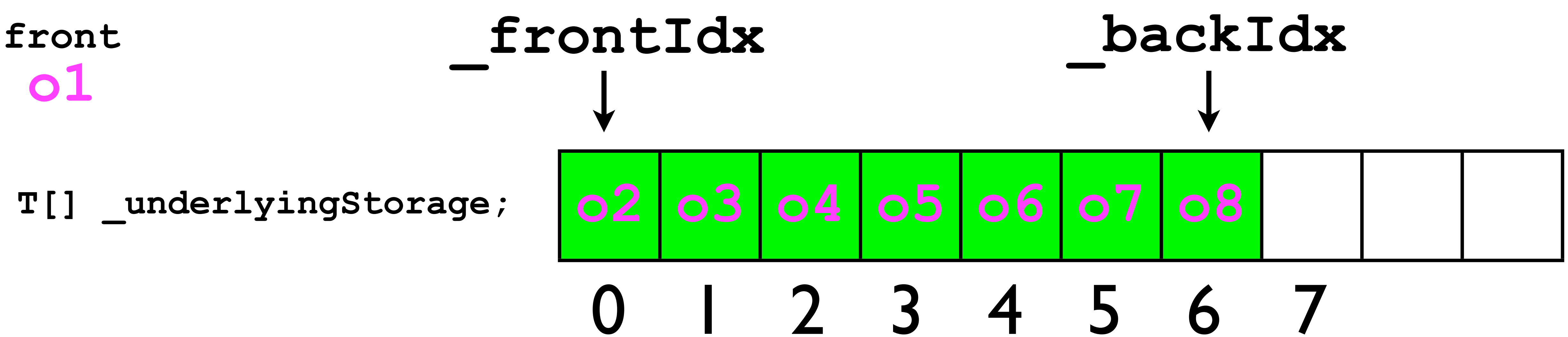
return front;
```

`_frontIdx` never changes -- always 1!

- Example: `_queue.dequeue();`



dequeue() -- Attempt #2

- Another possibility is to allocate a huge array for the **`_underlyingStorage`**, and then just keep advancing **`_frontIdx`** by 1 whenever **`dequeue()`** is called.

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final T front = _underlyingStorage[_frontIdx];
_frontIdx++;
return front;
```

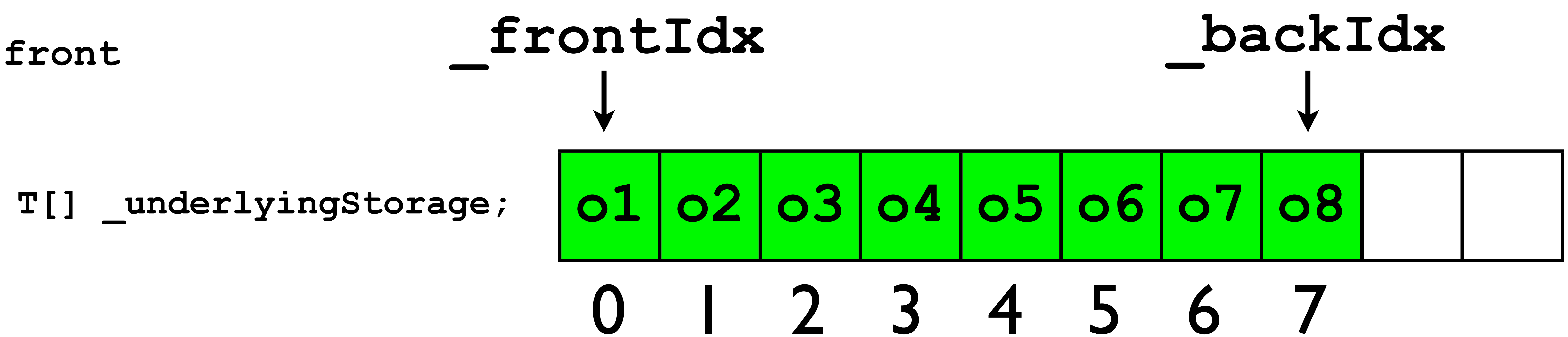

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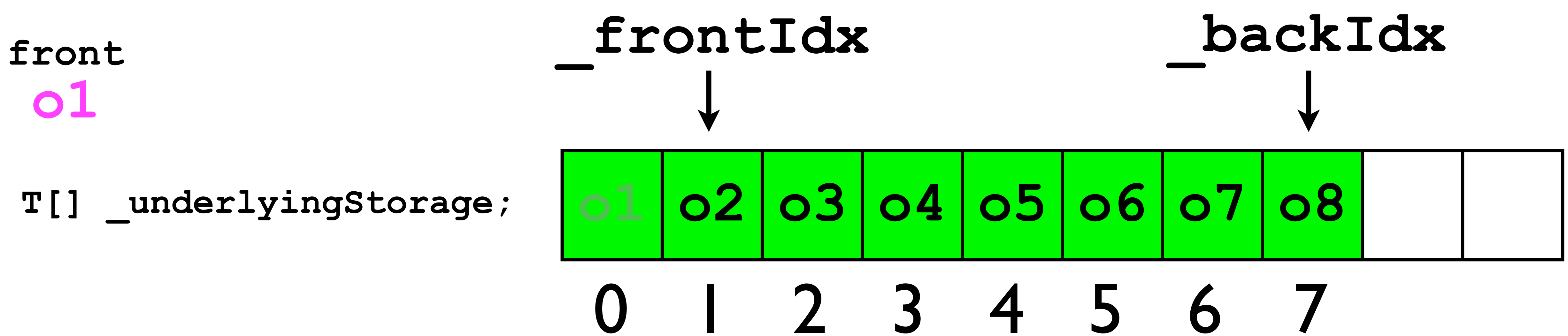

dequeue() -- Attempt #2

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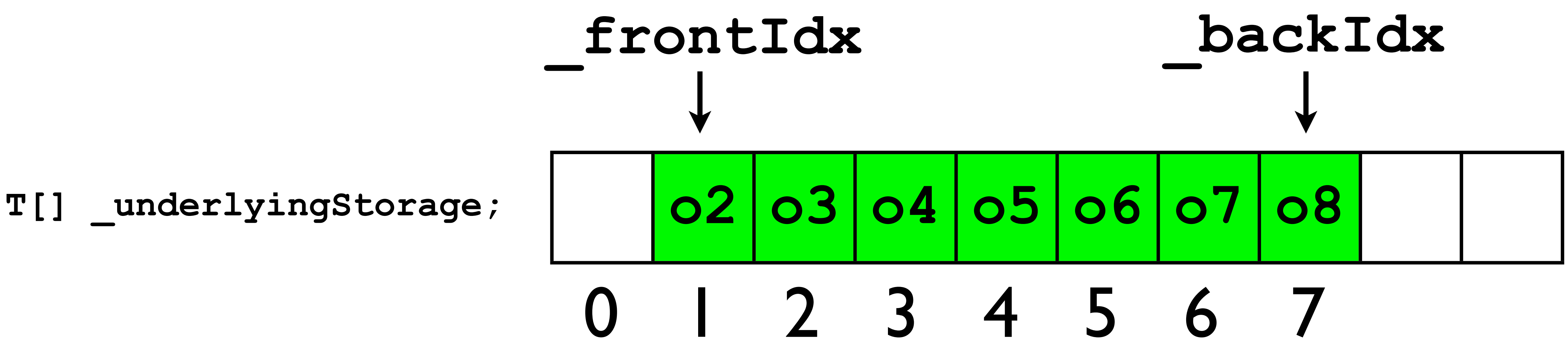
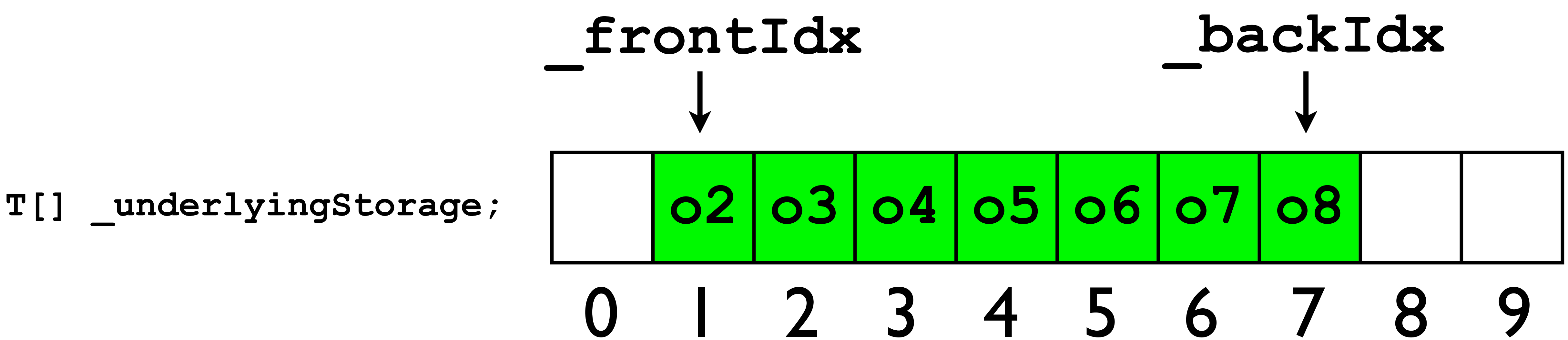


dequeue() -- Attempt #2

- Let's consider this implementation strategy when `enqueue(o)` and `dequeue()` are called many times...

```
_queue.enqueue(o9);
_queue.dequeue();
_queue.enqueue(o10);
_queue.dequeue();

...
```



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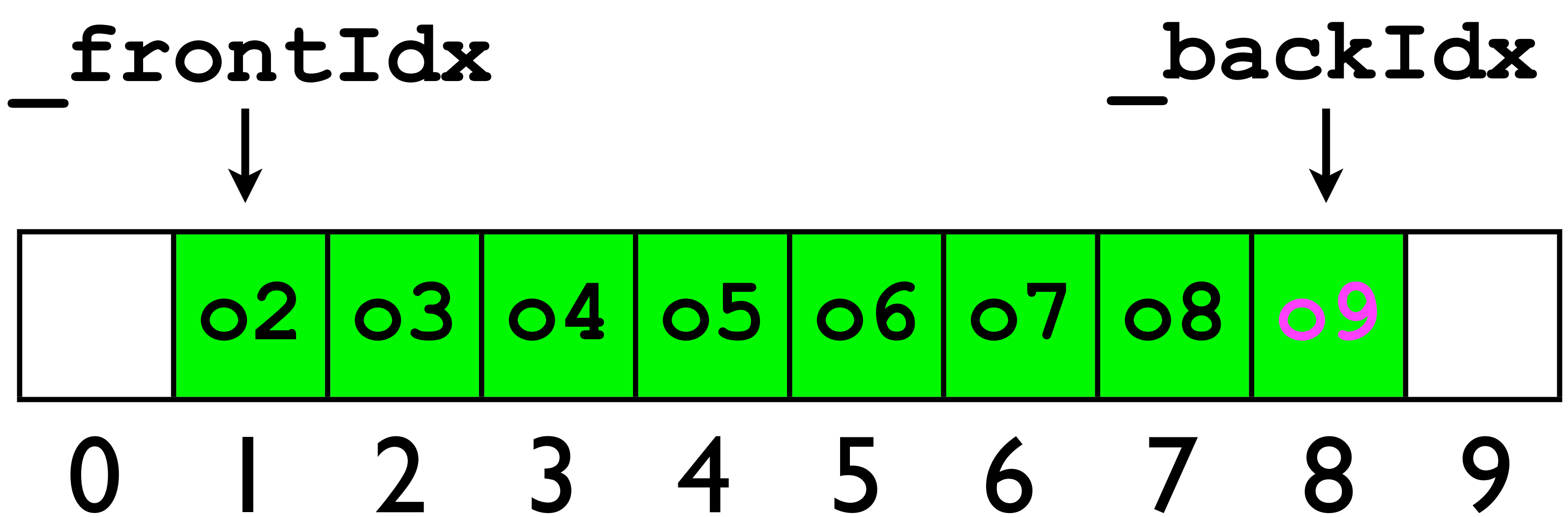

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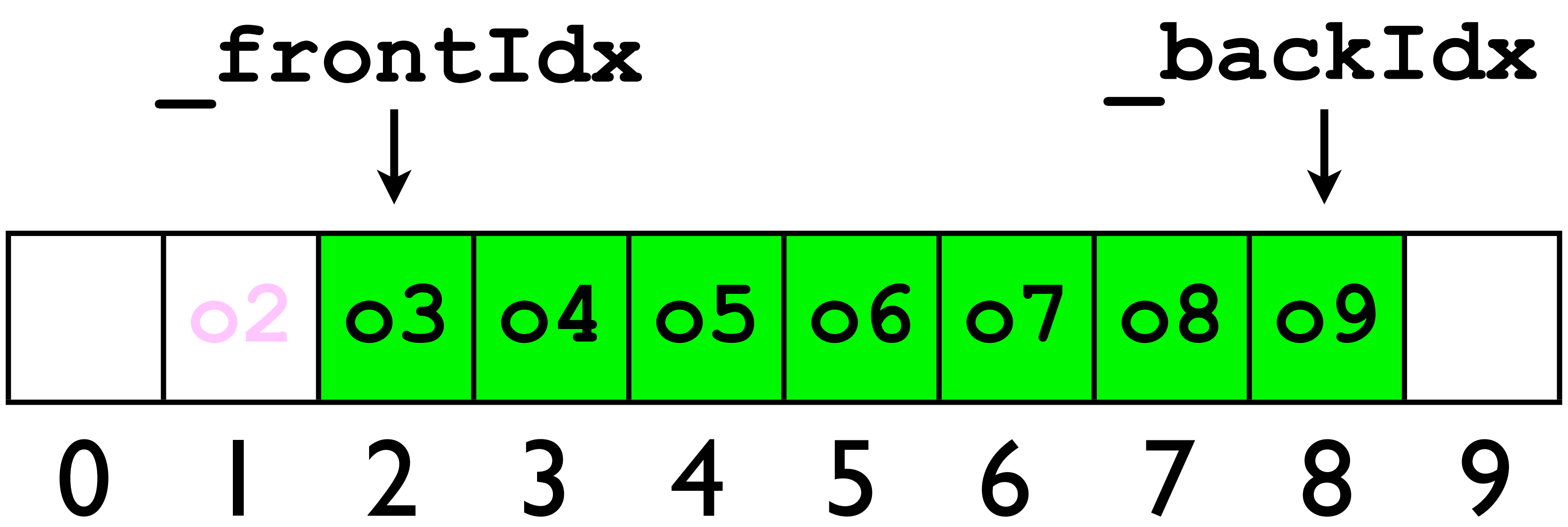

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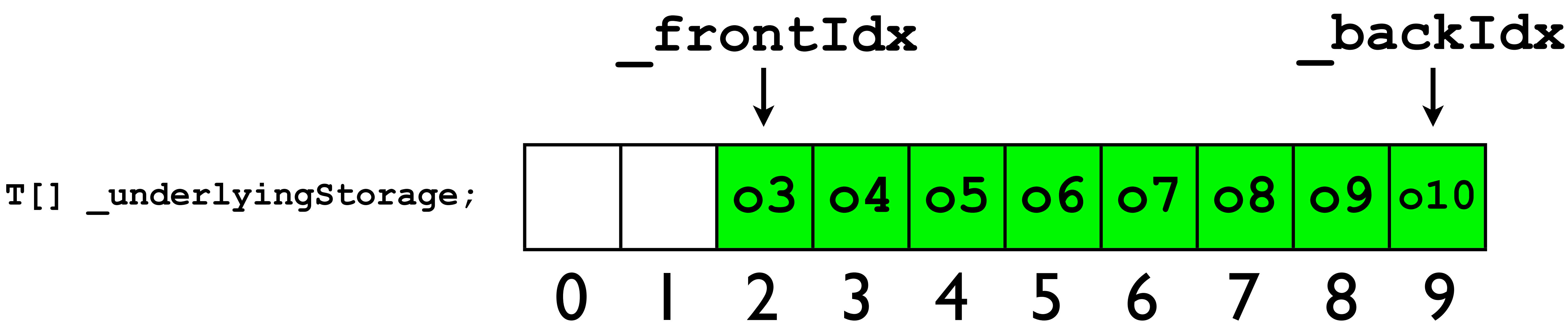

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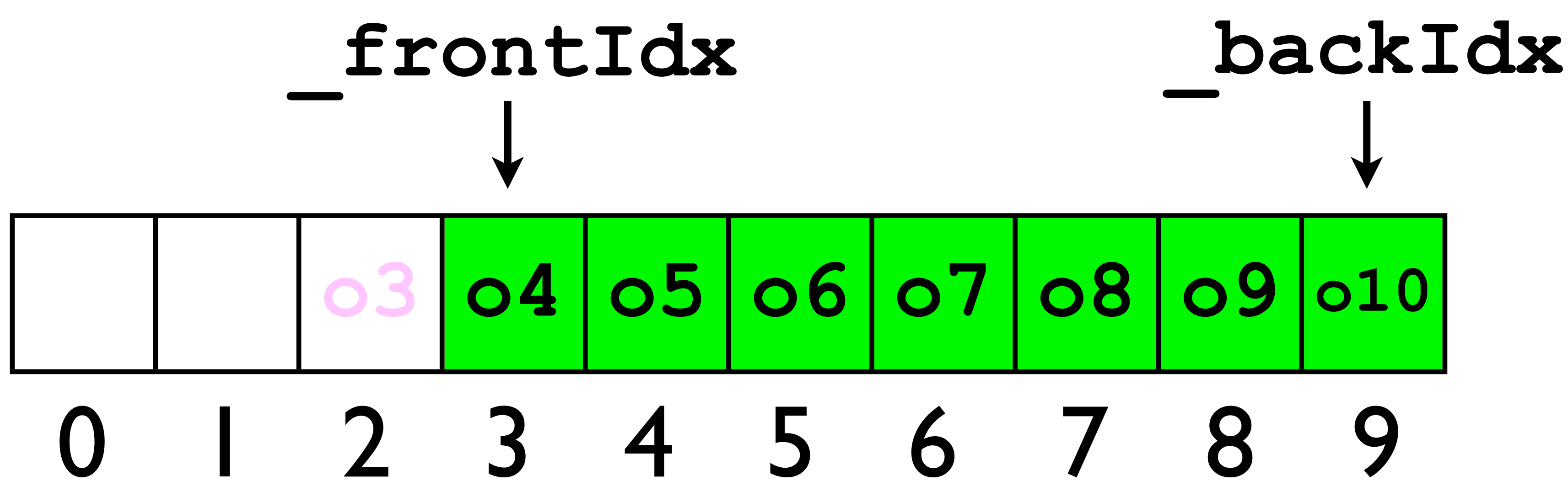

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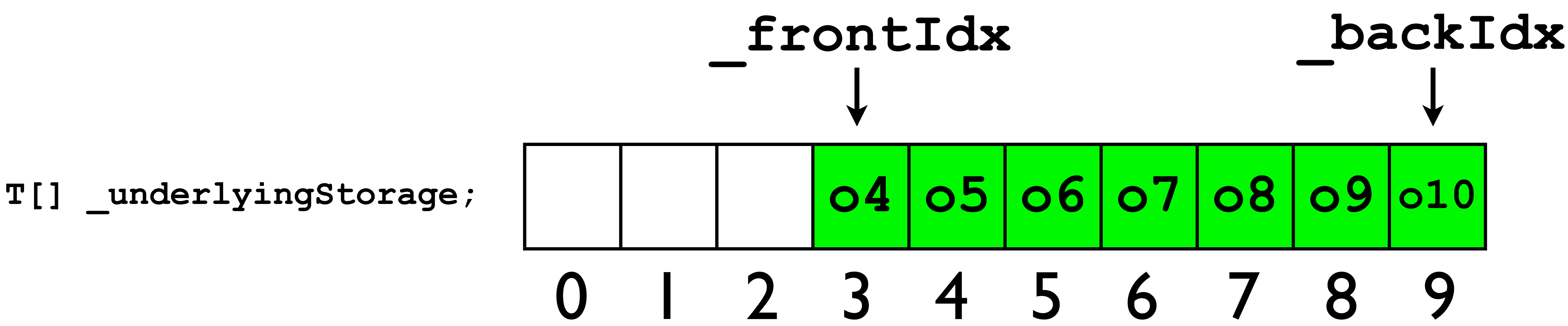
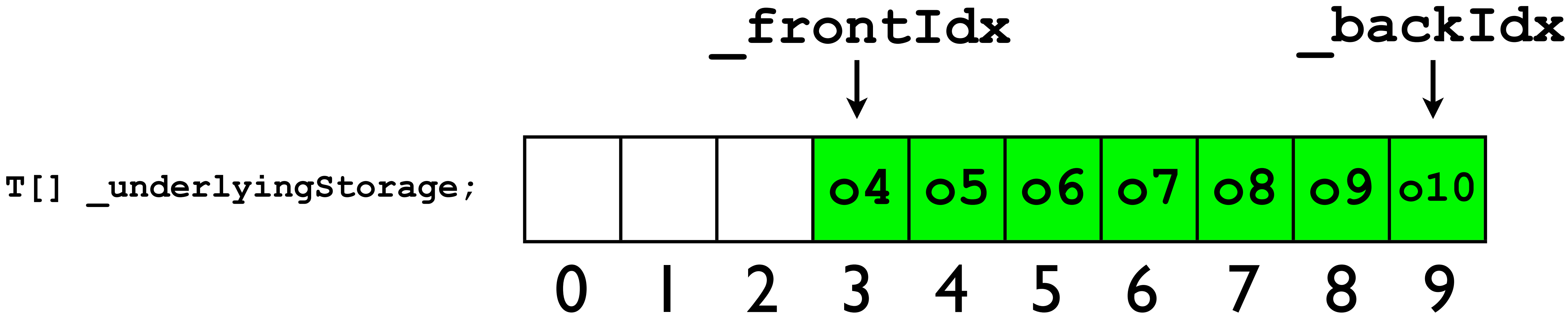


dequeue() -- Attempt #2

- This implementation of `dequeue()` is elegant and efficient.
  - The queue keeps “moving” to the right.
  - Even though the length of the queue may be small, the array would have to be of *infinite length* to accommodate the eternal “sliding down”.

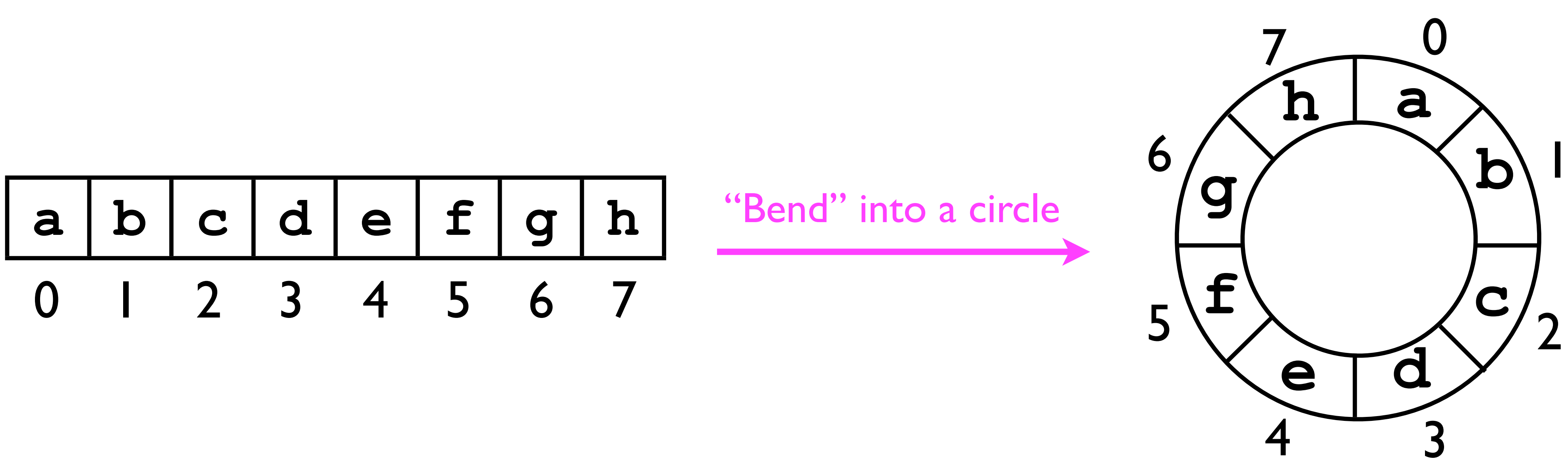


dequeue() -- Attempt #3

- Let's try one more time...
- Let's assume that the maximum length of the queue is *bounded*, i.e., it will never exceed some **`MAX_LENGTH`**.
  - Note -- in general, **`MAX_LENGTH`** and **`_underlyingStorage`** could be different.
- We can simulate an "infinite array" by implementing a *ring buffer*.
  - In a ring buffer, the back of the array is connected to the front of the array by "bending the array into a circle".

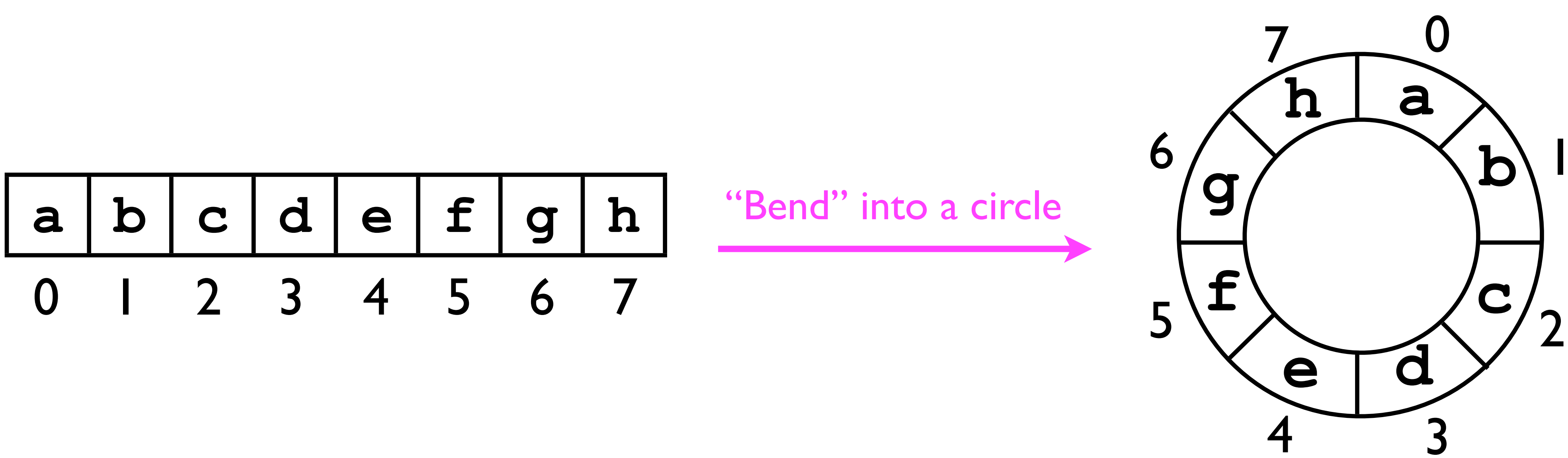
dequeue() -- Attempt #3

- Example: `T[] _ringBuffer = (T[]) new Object[8];`
- In a ring buffer, the array indices 7 and 0 are adjacent.
  - The index "before" 0 is 7.
  - The index "after" 7 is 0.



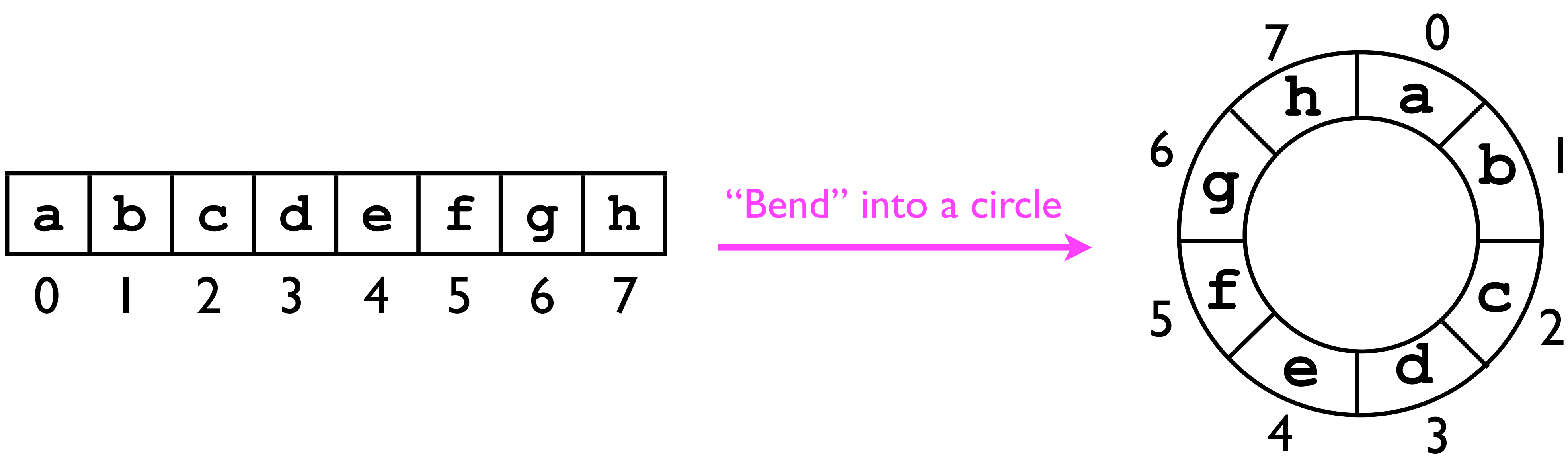
dequeue() -- Attempt #3

- A ring buffer is a convenient programming *abstraction*.
- With ring buffers, when we wish to "iterate around" the array, we can use an index variable **`currentIdx`**.
- Each time we wish to retrieve the "next" element, we return **`_ringBuffer[currentIdx];`**
- We then must "increment" **`currentIdx`**.
  - If **`currentIdx < 7`**, then: **`currentIdx++`**;
  - If **`currentIdx == 7`**, then: **`currentIdx = 0;`**



dequeue() -- Attempt #3

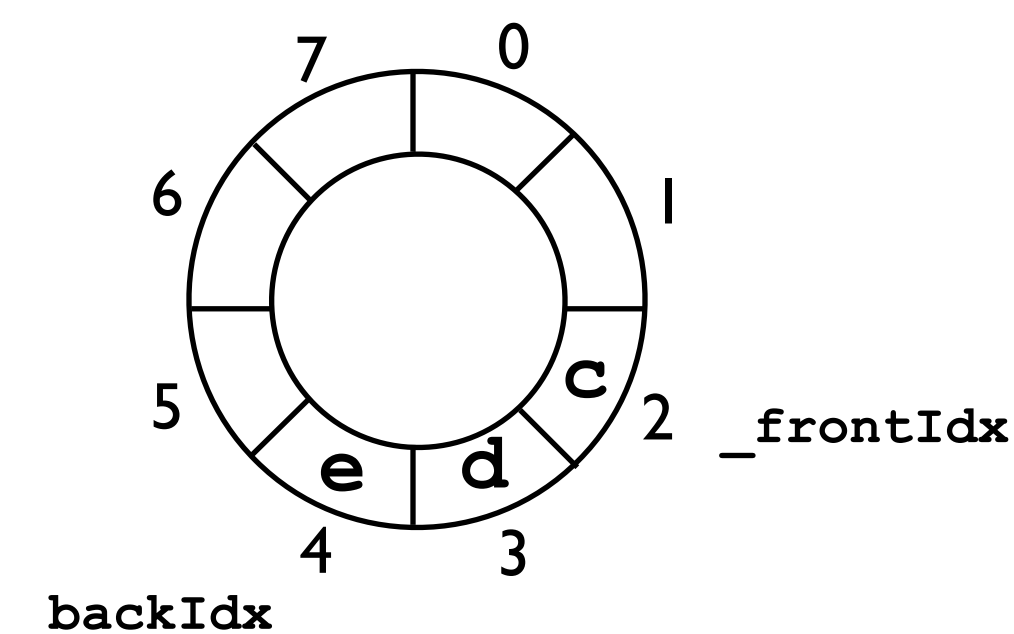
- Similar logic applies to iterating “backwards”:
- Each time we wish to retrieve the “previous” element, we return `_ringBuffer[currentIdx];`
- We then must “decrement” `currentIdx`.
  - If `currentIdx > 0`, then: `currentIdx--;`
  - If `currentIdx == 0`, then: `currentIdx = 7;`



dequeue() -- Attempt #3

- Ring buffers are useful when implementing queues because they allow us to keep "moving the queue to the right" *without actually requiring infinite storage*.
- Consider the queue below (initially `_frontIdx = 2` and `_backIdx = 4`).
- We can call enqueue and dequeue repeatedly -- the queue will appear to "slide around" the ring buffer.
- As long as `dequeue()` is called frequently enough (compared to `enqueue(o)`), the ring buffer will never get full.

```
enqueue(f);
enqueue(g);
dequeue();
enqueue(h);
enqueue(i);
dequeue();
```



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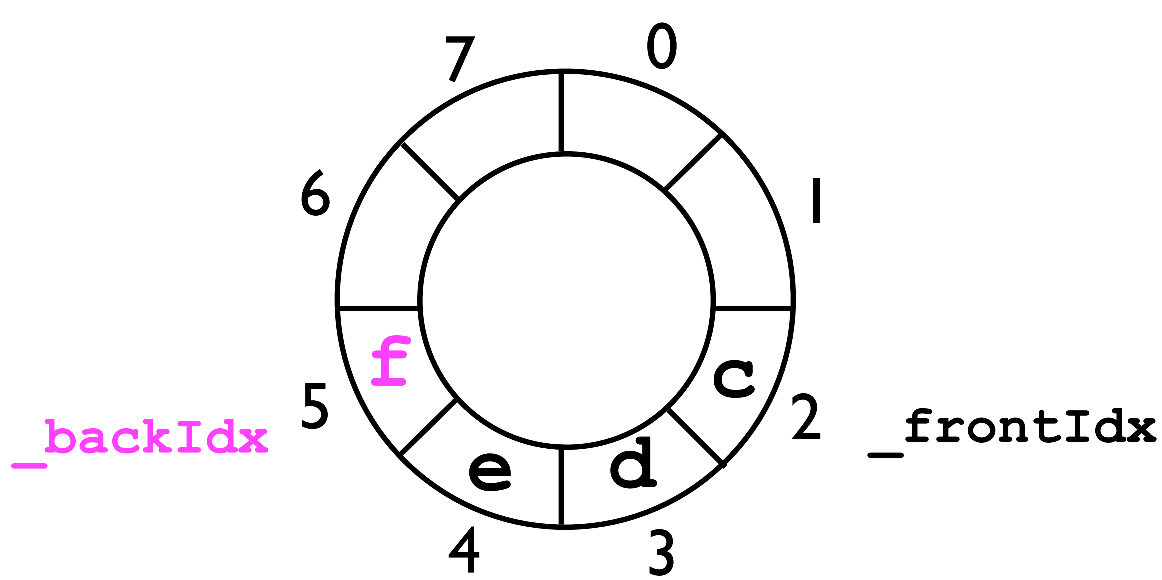

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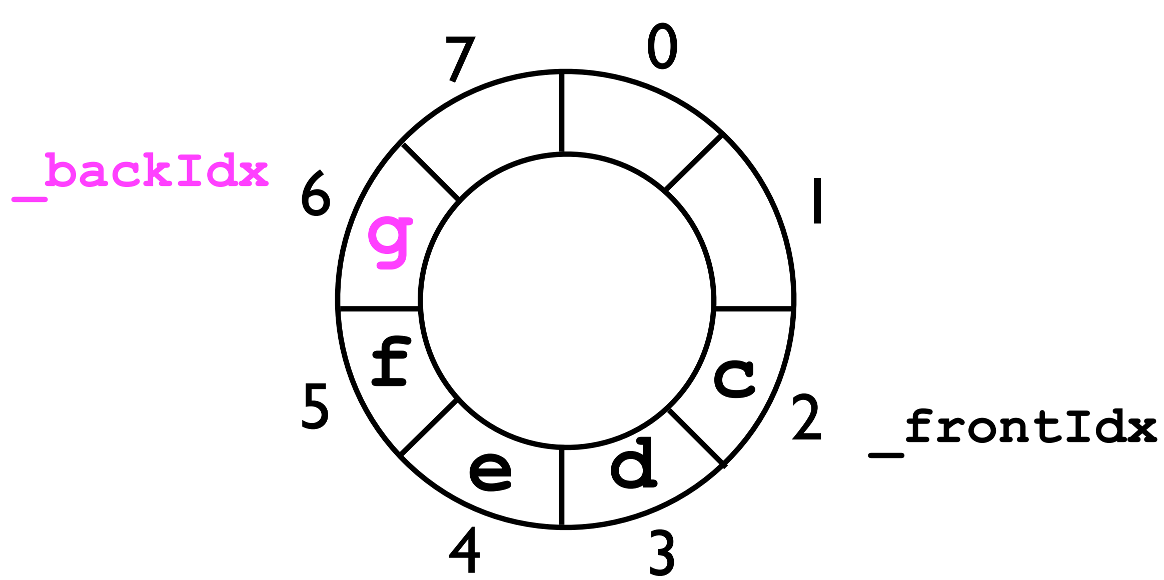

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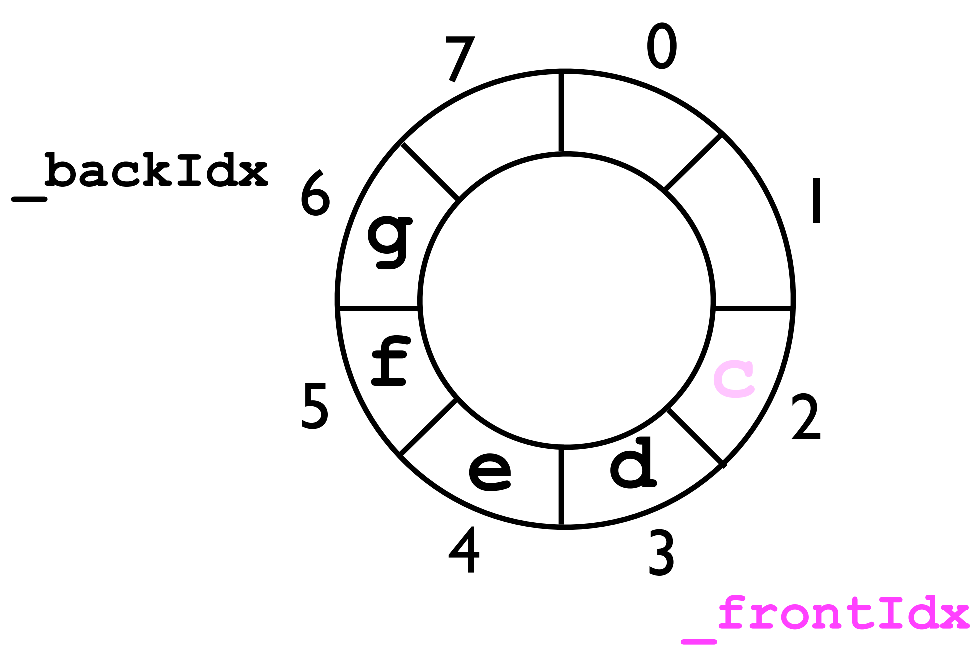

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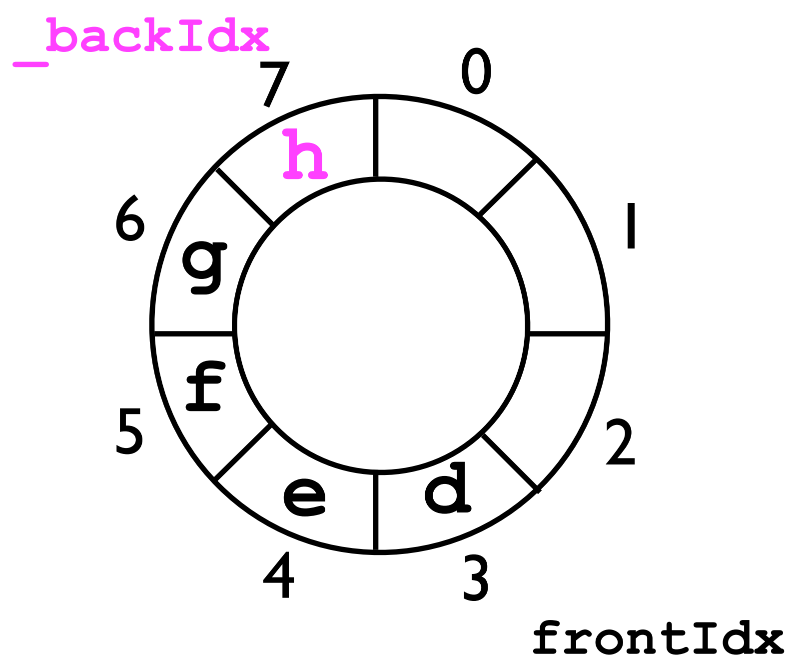

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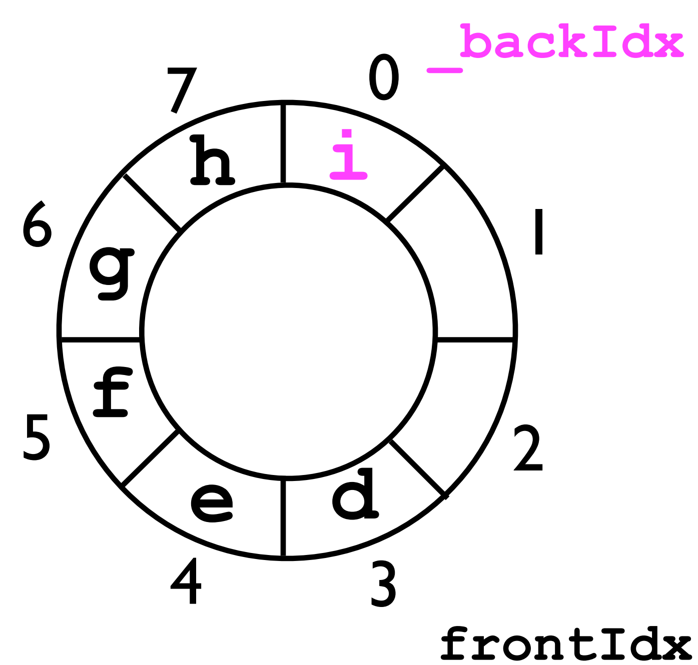

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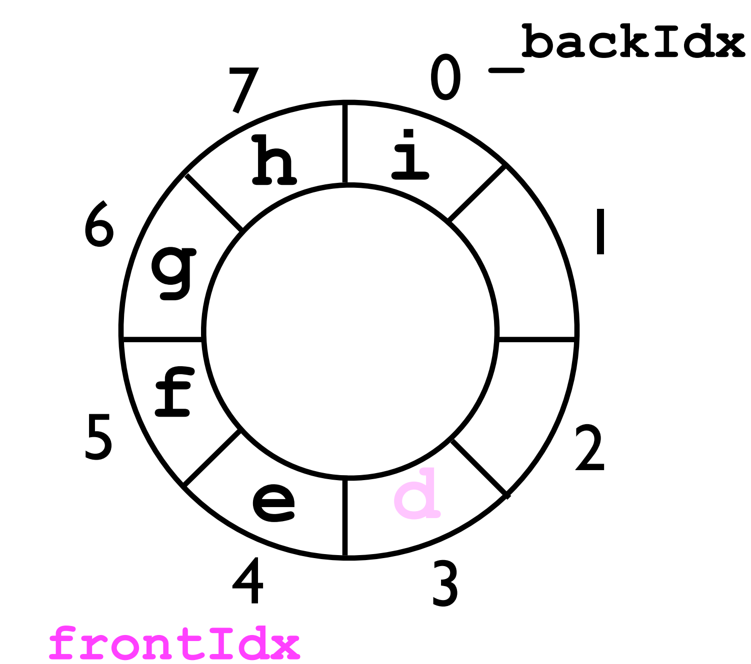

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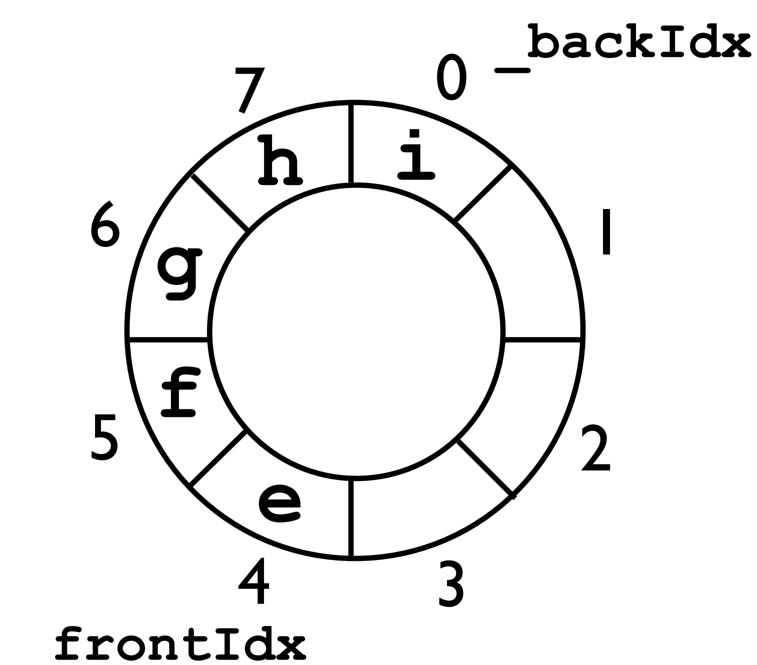

dequeue() -- Attempt #3

- Using a ring buffer as the underlying storage, a queue can be implemented so that both `enqueue(o)` and `dequeue()` operate efficiently.
- The disadvantage compared to a linked list-based implementation is that the maximum length of the queue must be known in advance.
  - When the queue is "full" and the user calls `enqueue(o)`, then either:
    - The queue will **block** -- hang until some other program/thread calls dequeue; or
    - Throw an exception.
  - With linked lists, the queue can grow arbitrarily long.