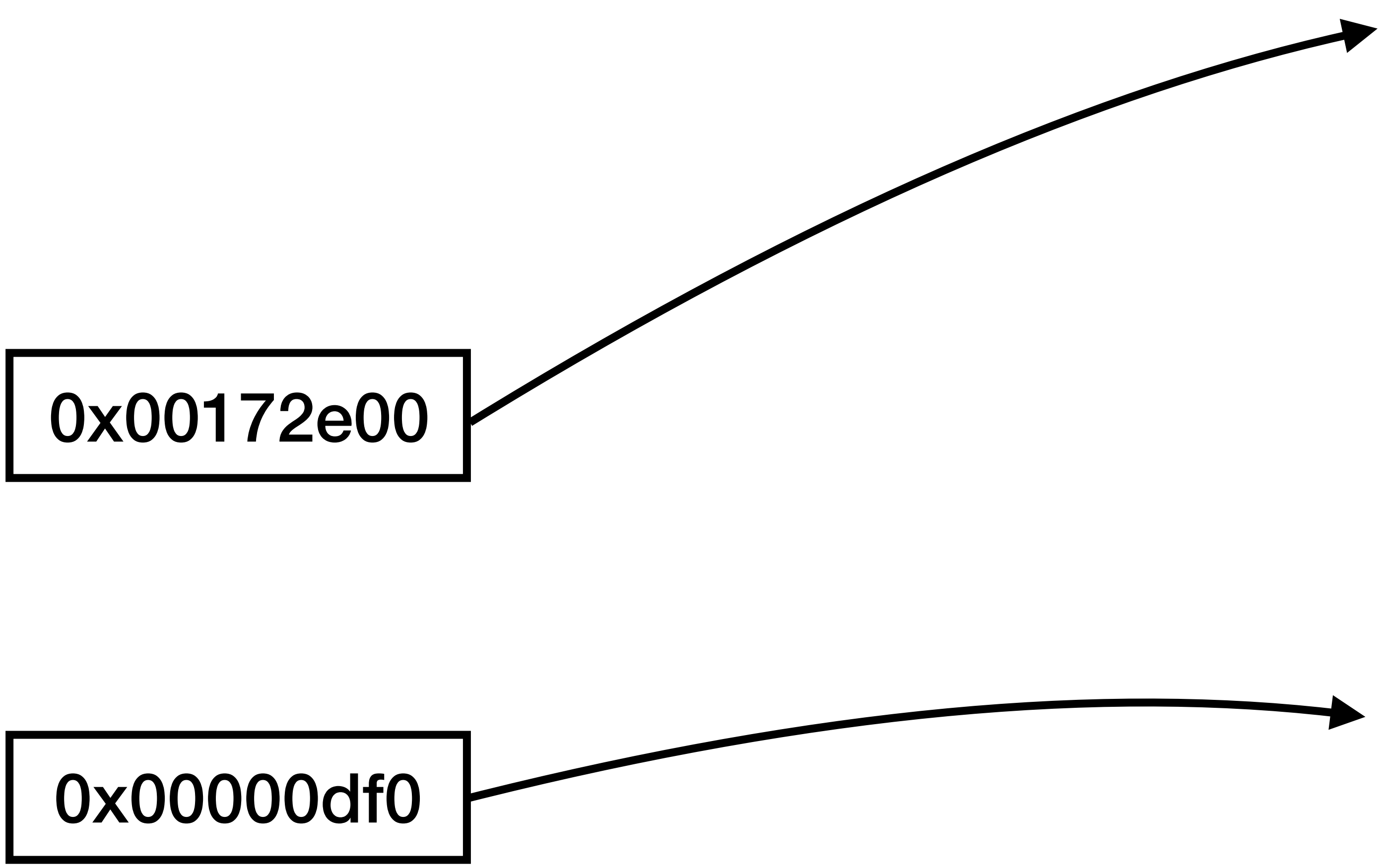
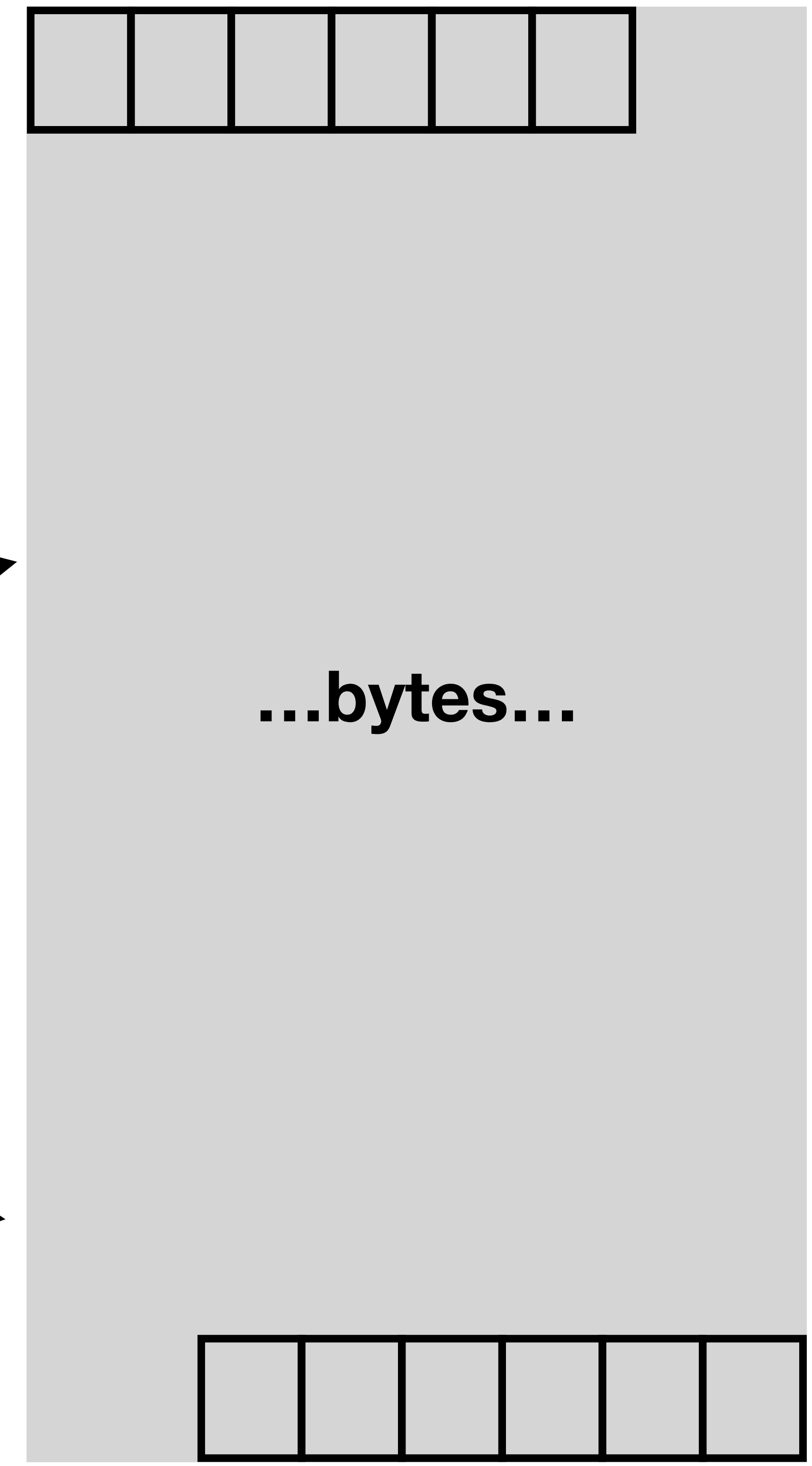
Memory Management

C++ semantics: memory model

Recall, in C++ all memory is viewed as a huge array of bytes. Available memory is requested from the operating system using a system-call (by a memory allocation library, e.g., malloc.c which is used by new/delete).





C++ semantics: memory model

Recall, in C++ all memory is viewed a a huge array of bytes. Available memory is requested from the operating system using a system-call (by a memory allocation library, e.g., malloc.c which is used by new/delete).

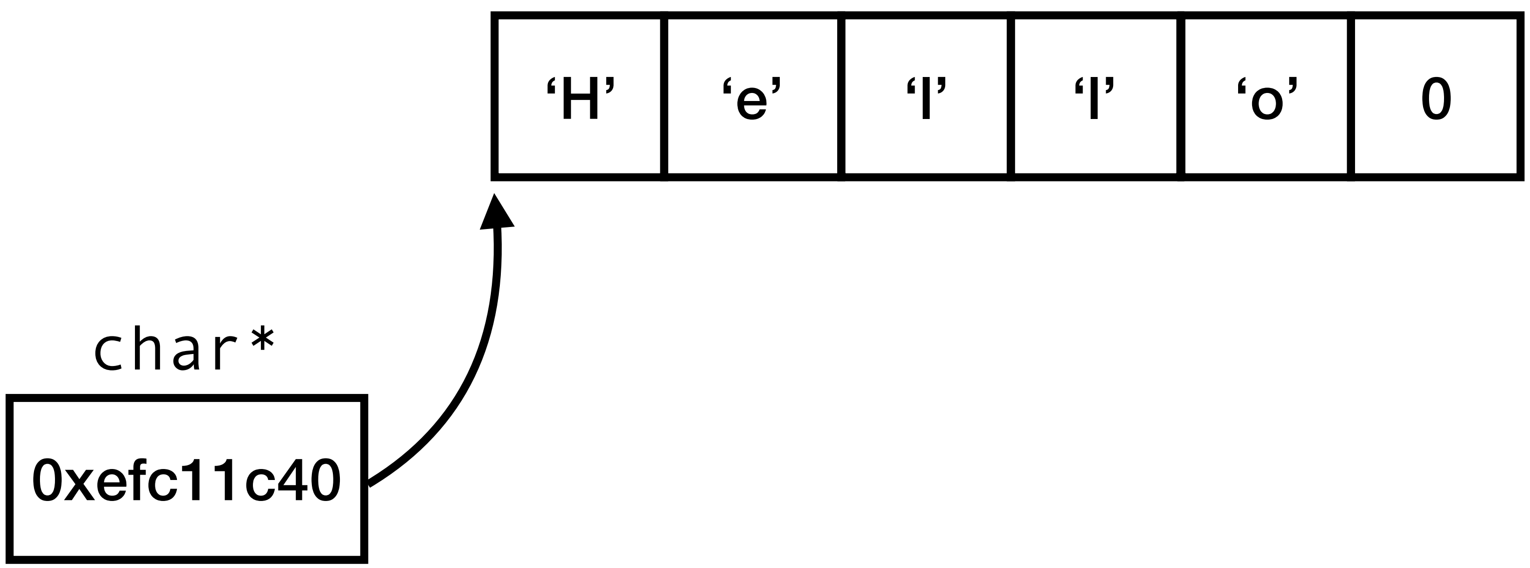
0x00172e00

0x00000df0

The stack starts growing down! The C++ runtime reserves a portion of memory (that is extended dynamically upon a page fault).

The heap starts below the stack in memory and grows up, page by page.

C++ semantics: memory model



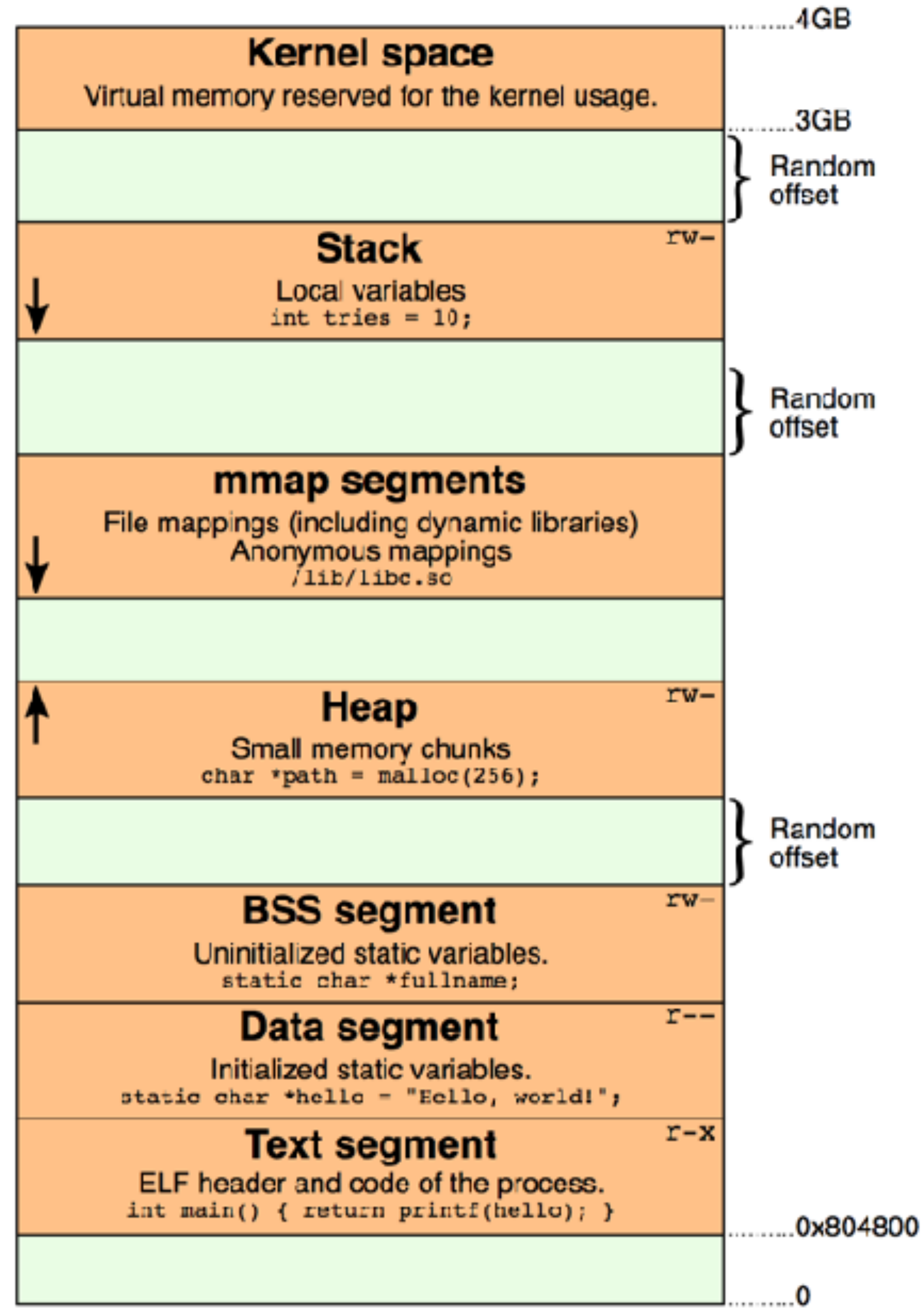
Recall, in C++ pointers are (virtual) memory addresses and refer to the <u>start</u> of a buffer. Exactly how many bytes are being used by this pointer, after that location, is determined by how the C++ program uses that pointer! **(E.g., C-strings are null-value terminated.)** This is not statically checked, leading to buffer overflow.

The stack starts growing down! The C++ runtime reserves a portion of memory (that is extended dynamically upon a page fault).

The heap starts below the stack in memory and grows up, page by page.

C++ semantics: memory model

The virtual memory for your C++ binary is organized like so:



Note: The stack grows down. The heap grows up (and is managed by a memory allocator such as malloc in libc).

C++ semantics: pointers and references

Prefix `*` operation turns a pointer into a reference! `*x` references the value at address `x`.

```
int* x = f(); // x is a pointer to an int
int y = *x;   // *x dereferences the ptr
```

```
int x = f(); // x is an int
int* y = &x; // &x takes address of x
```

Prefix `&` operation turns a reference into a pointer! `&x` is the address of the value referenced by `x`.

C++ semantics: field access, . and ->

```
A& a = f();    // a is a reference to an object
int y = a.y;  // a.y accesses field y of a
```

The . operation restricts a reference to a specific field; here, `a.y` turns a reference to a an object into a reference to its `y` field.

The -> operation dereferences a pointer and accesses a specific field all at once.

```
A* a = f();     // a is a pointer to an object
int y = a->y;  // a->y accesses field y off a
```

C++ semantics: indexing and dereference

Postfix [..] operation turns a pointer into a reference to the element specified as the index

```
int* x = f(); // x is a pointer to an int
int y = x[0]; // x[0] indexes the pointer
```

```
int* x = f(); // x is a pointer to an int
int y = *x;   // this is the same as x[0]
```

If the index is 0, then this is just the same as dereferencing the pointer!

C++ semantics: indexing and dereference

```
int* x = f();      // x is a pointer to an int
int y = *(x+3);    // this is the same as x[3]
```

If the index is non-0, then this is just the same as incrementing the pointer and then dereferencing

This is the same as incrementing the raw address by the appropriate number of bytes. The void* type gives access to the raw address.

```
int* x = f();
// x is a pointer to an int
int y = *(int*)((void*)x
                  + 3*sizeof(int));
// this is ALSO the same as x[3]
```

C++ semantics: Try an example!

```
int arr[8] = {0,5,1,2,3,4,5,9};
int*  x  = arr;          // Derive a ptr from arr
std::cout << arr[1] << std::endl;
// Which value is printed out?
```

C++ semantics: Try an example!

```
int arr[8] = {0,5,1,2,3,4,5,9};
int*  x  = arr;         // Derive a ptr from arr
std::cout << arr[1] << std::endl;
// Which value is printed out?
```

Answer: 5

C++ semantics: Try an example!

```
int arr[8] = {0,5,1,2,3,4,5,9};
int*  x  = arr;          // Derive a ptr from arr
std::cout << &arr << std::endl;
// Which value is printed out?
```

C++ semantics: Try an example!

```
int arr[8] = {0,5,1,2,3,4,5,9};
int*  x  = arr;          // Derive a ptr from arr
std::cout << &arr << std::endl;
// Which value is printed out?
```

Answer: 0xff443120 <— ptr to var `x`

in other words, `**(&arr) == 0`

C++ semantics: Try an example!

```
int arr[8] = {0,5,1,2,3,4,5,9};
int*  x  = arr;          // Derive a ptr from arr
std::cout << (&arr[3])+1 << std::endl;
// Which value is printed out?
```

C++ semantics: Try an example!

```
int arr[8] = {0,5,1,2,3,4,5,9};
int*  x  = arr;            // Derive a ptr from arr
std::cout << (&arr[3])+1 << std::endl;
// Which value is printed out?
```

Answer: 0xecff6604 <— ptr to elem 3

in other words, *((&arr[3])+1) == 3

C++ semantics: Try an example!

```
int arr[8] = {0,5,1,2,3,4,5,9};
int*  x  = arr;
int*  y  = x+3;
int   z  = *y;              // What is z?
int*  a  = &(y[z]);
void* b  = (void*)a + sizeof(int);
int   c  = *((int*)b - 2);  // What is c?
```

C++ semantics: Try an example!

```
int arr[8] = {0,5,1,2,3,4,5,9};
int*  x  = arr;
int*  y  = x+3;
int   z  = *y;              // What is z?
int*  a  = &(y[z]);
void* b  = (void*)a + sizeof(int);
int   c  = *((int*)b - 2);  // What is c?
```

Answer: z == 2 && c == 3

reverse.cpp solution

data layout in memory

value	next
int	linkedlist*

```
struct linkedlist
{
    int value;
    linkedlist* next;
};

int main()
{
    linkedlist* node = 0; //root
    int n;
    while (std::cin >> n)
    {
        linkedlist* next = node;
        node = new linkedlist();
        node->value = n;
        node->next = next;
    }//…
```

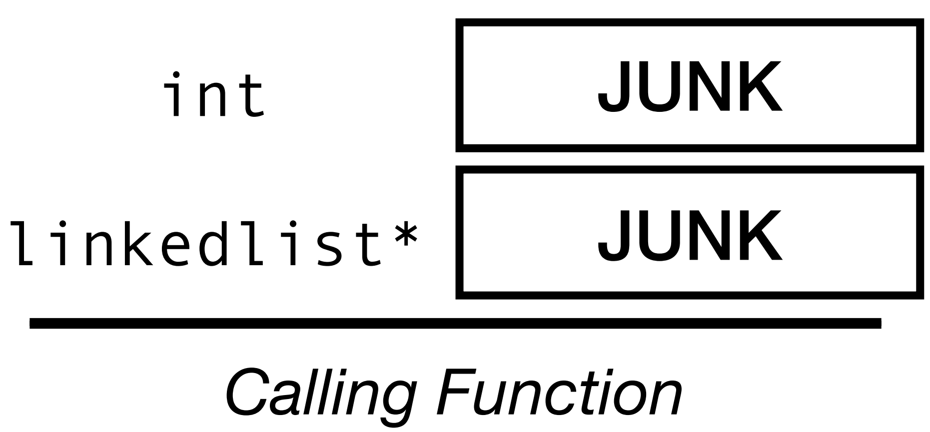
```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```

Calling Function

How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```



How C++ sees the **stack**

How C++ sees the **heap**

```cpp
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```

`int`	JUNK
`linkedlist*`	0x00000000

Calling Function

How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
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    node->value = n;
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}
```
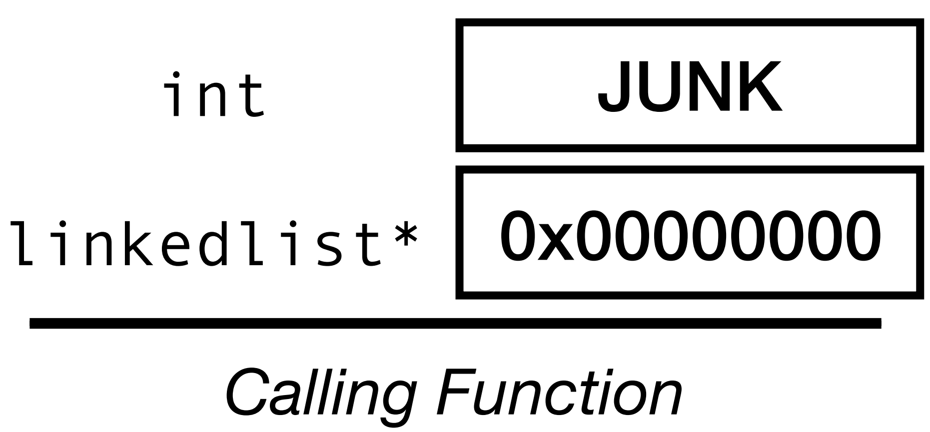
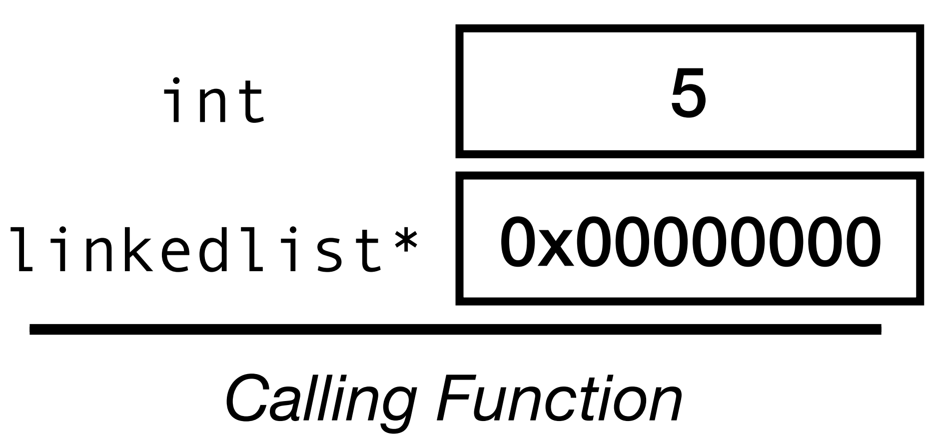



How C++ sees the **stack**

How C++ sees the **heap**

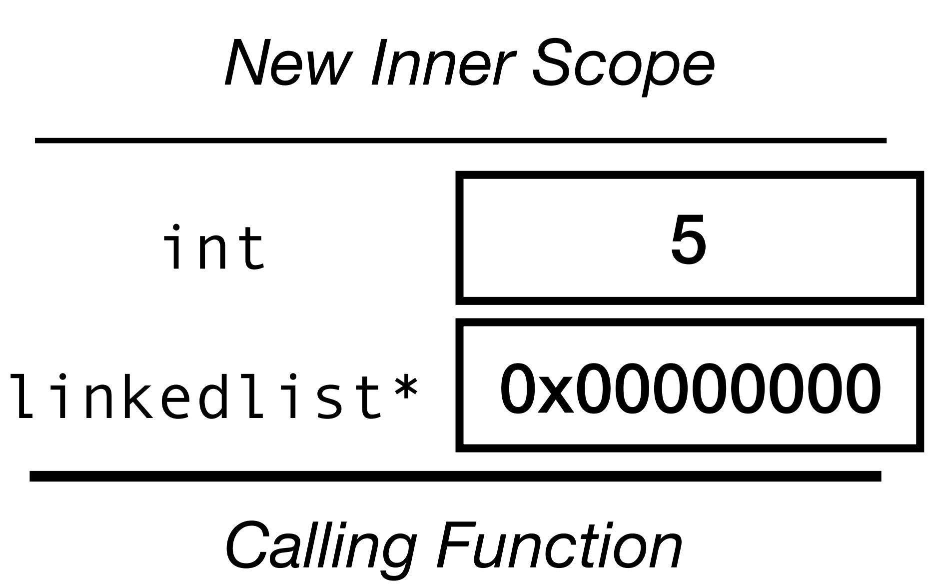
```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```



How C++ sees the **stack**

How C++ sees the **heap**

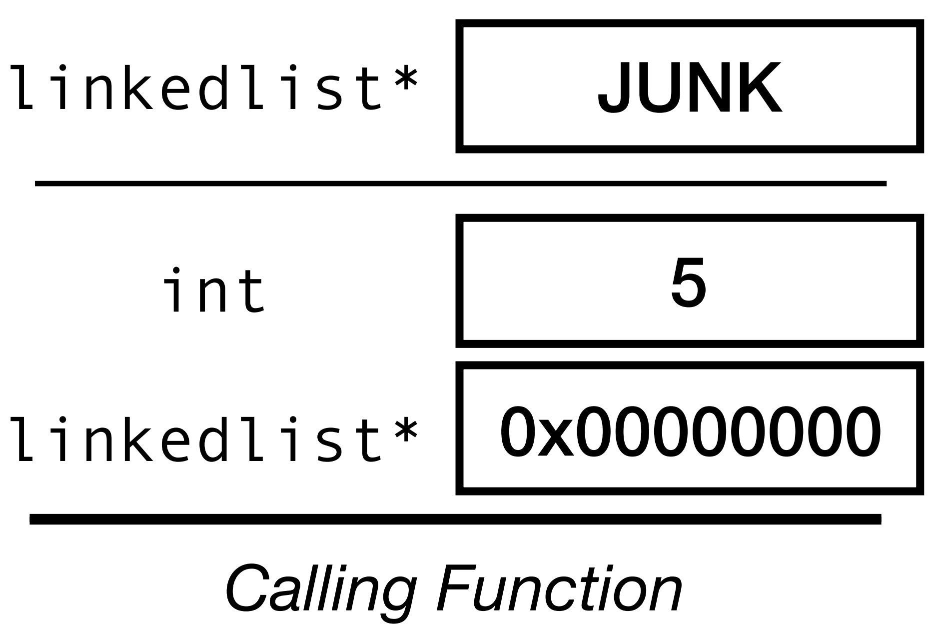
```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```



How C++ sees the **stack**

How C++ sees the **heap**

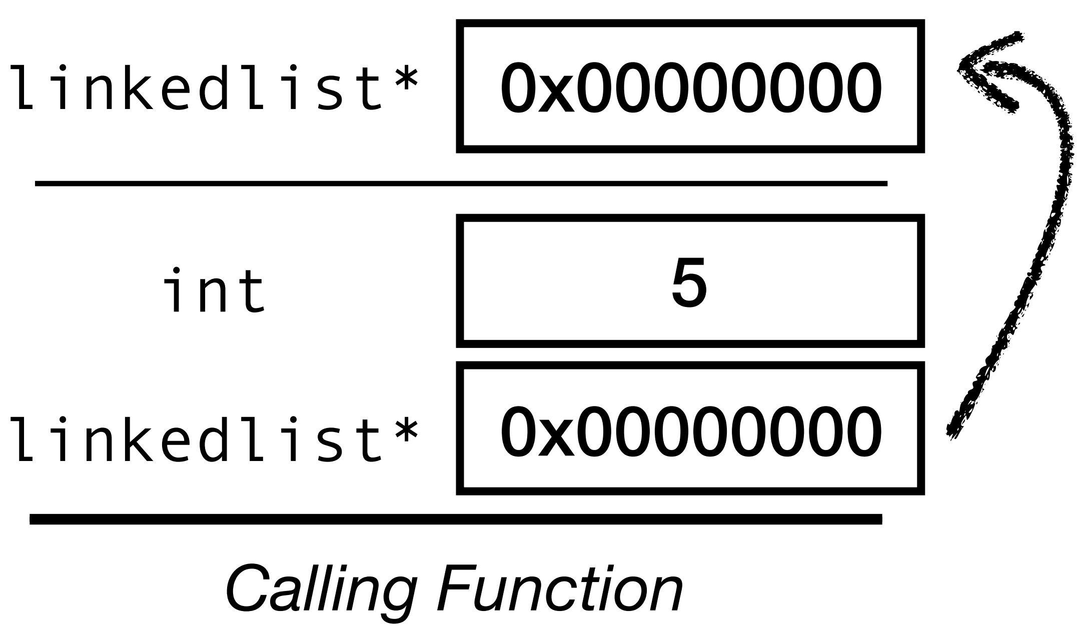
```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```



How C++ sees the **stack**

How C++ sees the **heap**

```cpp
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```

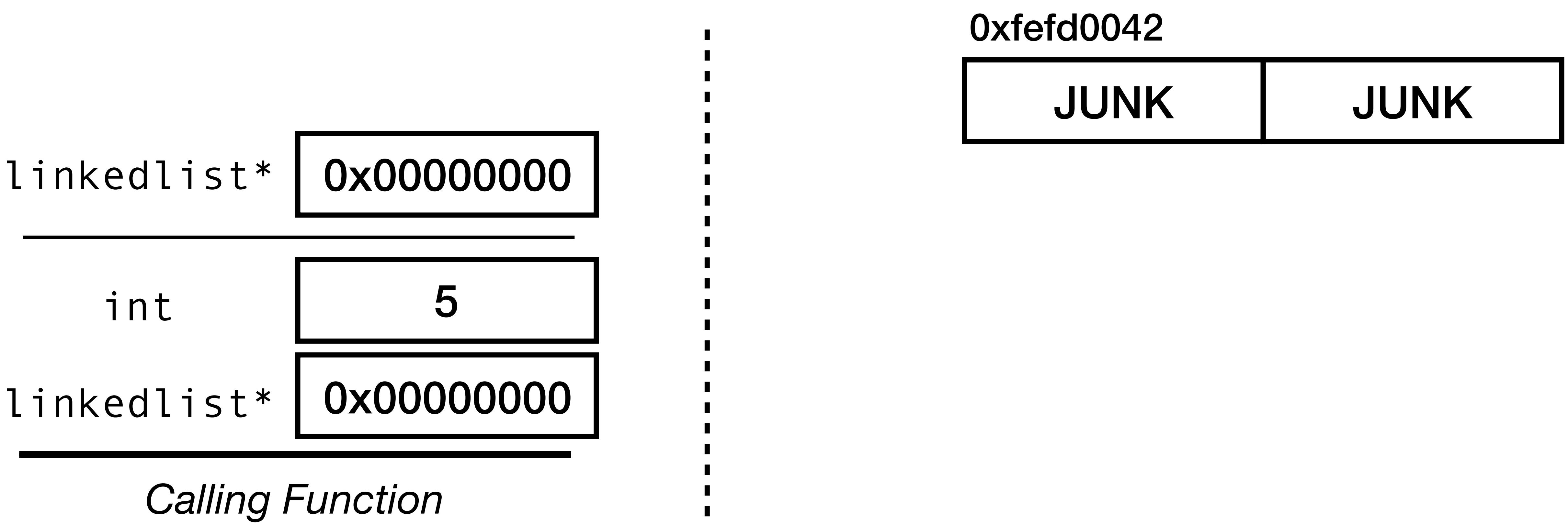


assignment
(copies null pointer value)

How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```



How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
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    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```

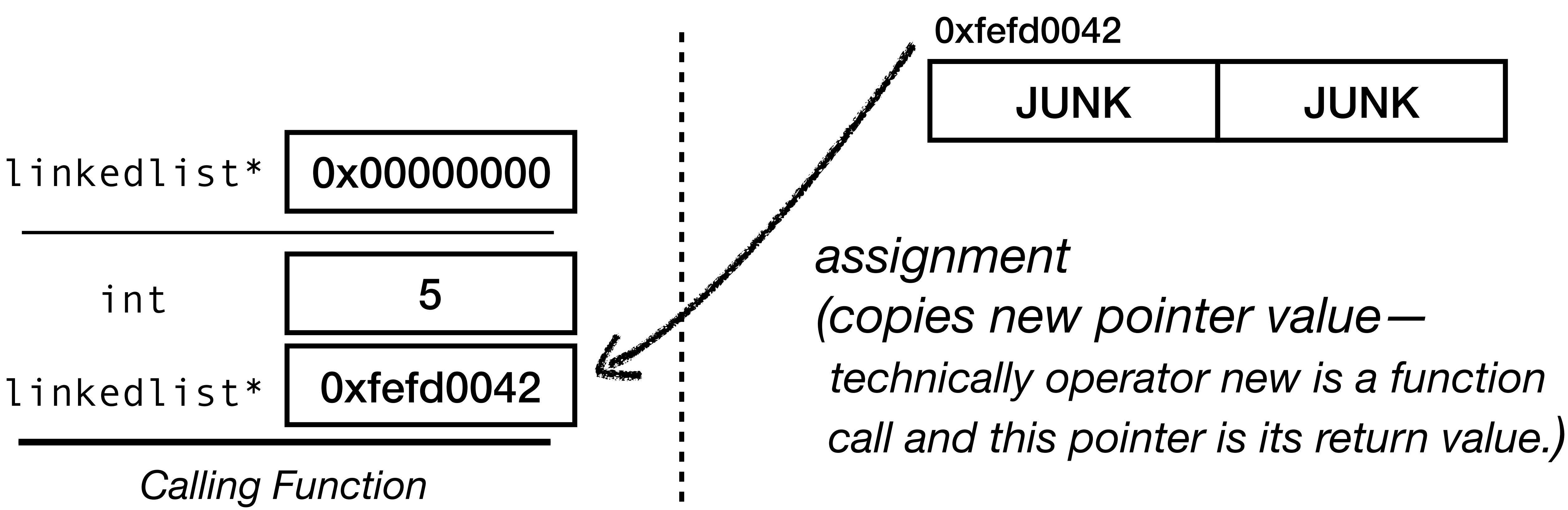

How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
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    node->next = next;
}
```

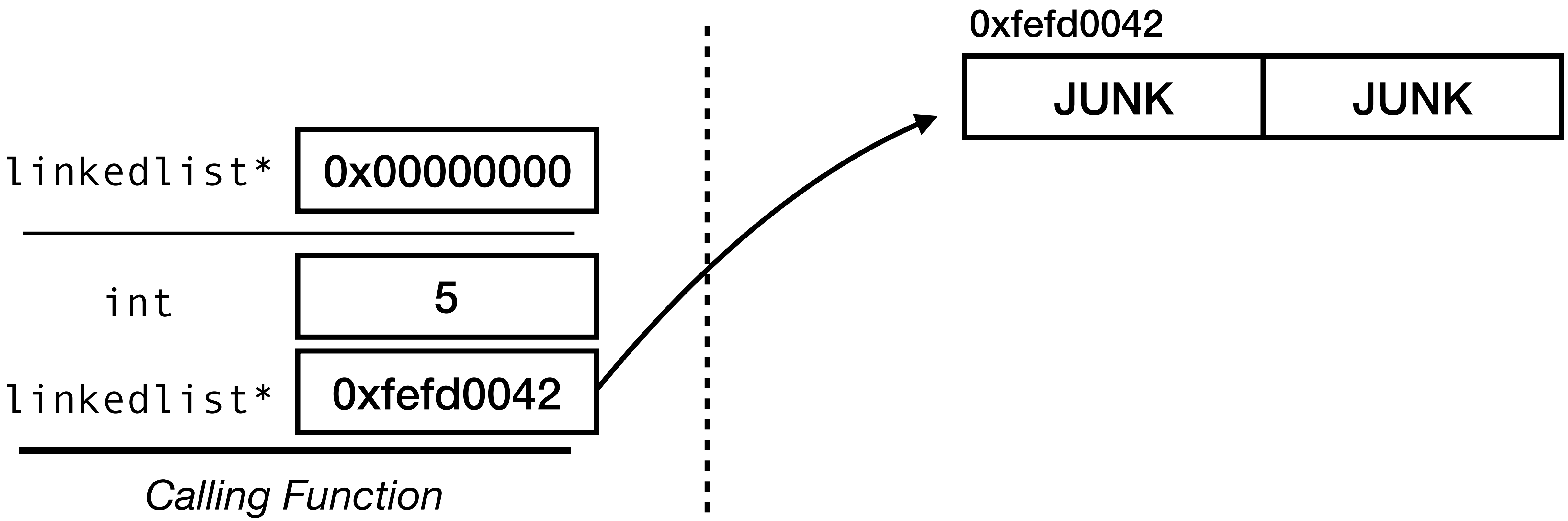

How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
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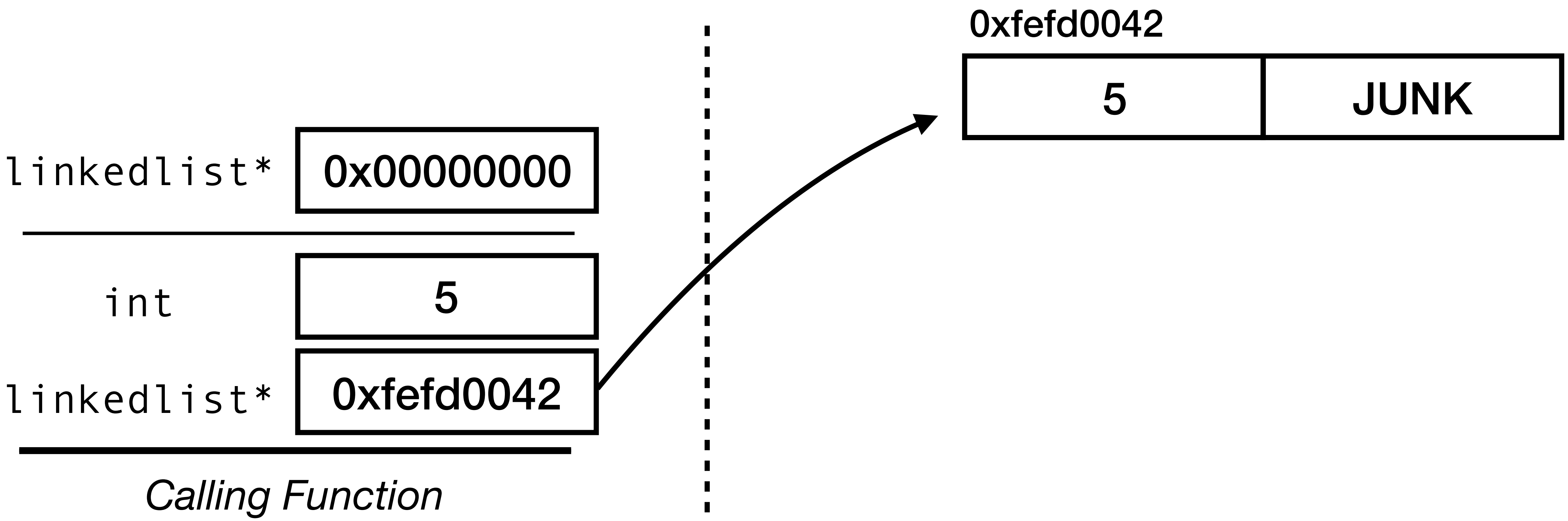
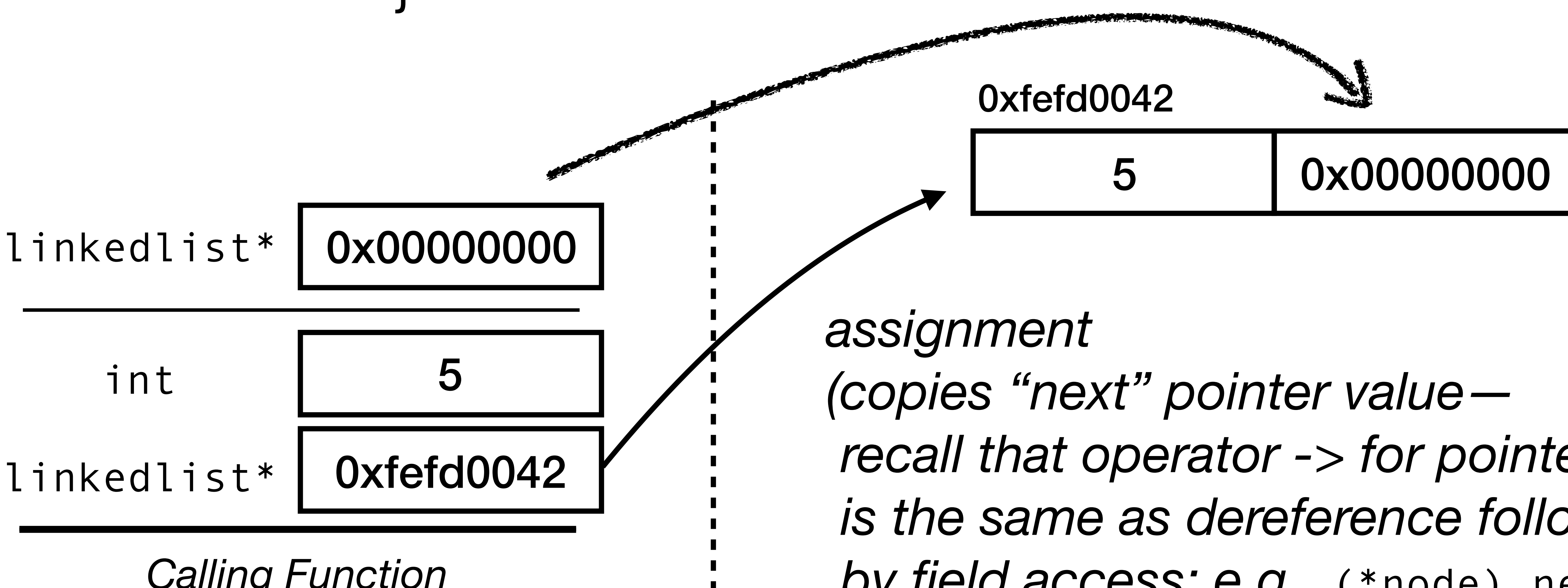


How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```

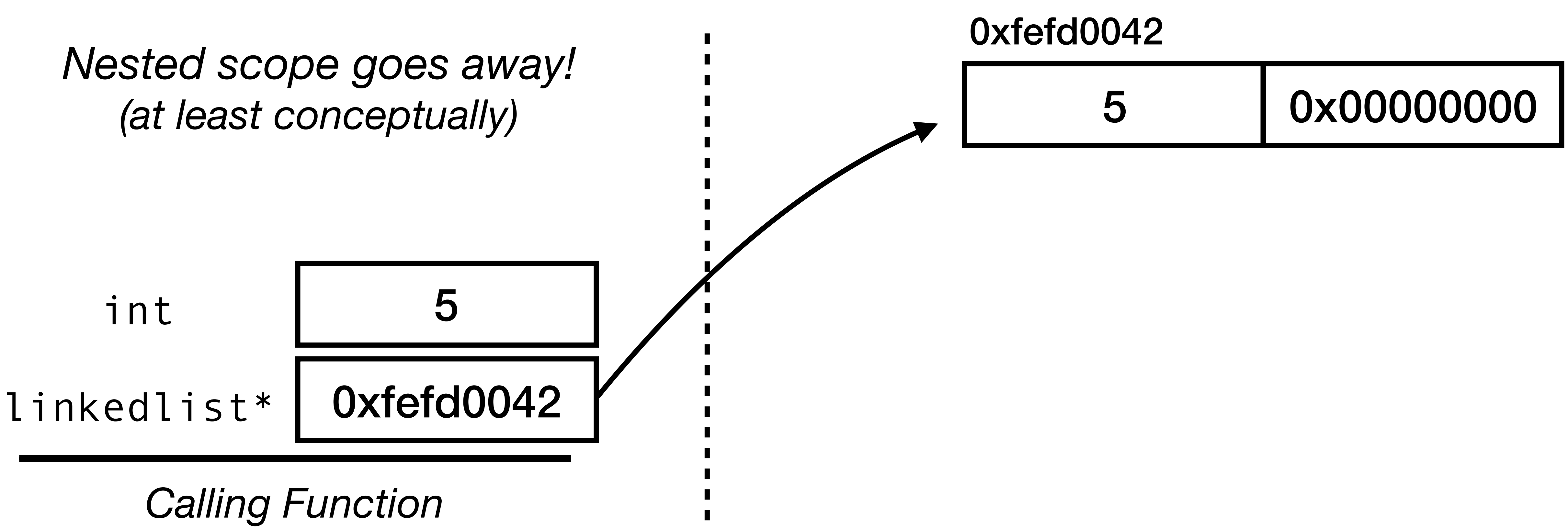


assignment
(copies "next" pointer value—
recall that operator -> for pointers
is the same as dereference followed
by field access; e.g., `(*node).next`*)*

How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```



How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
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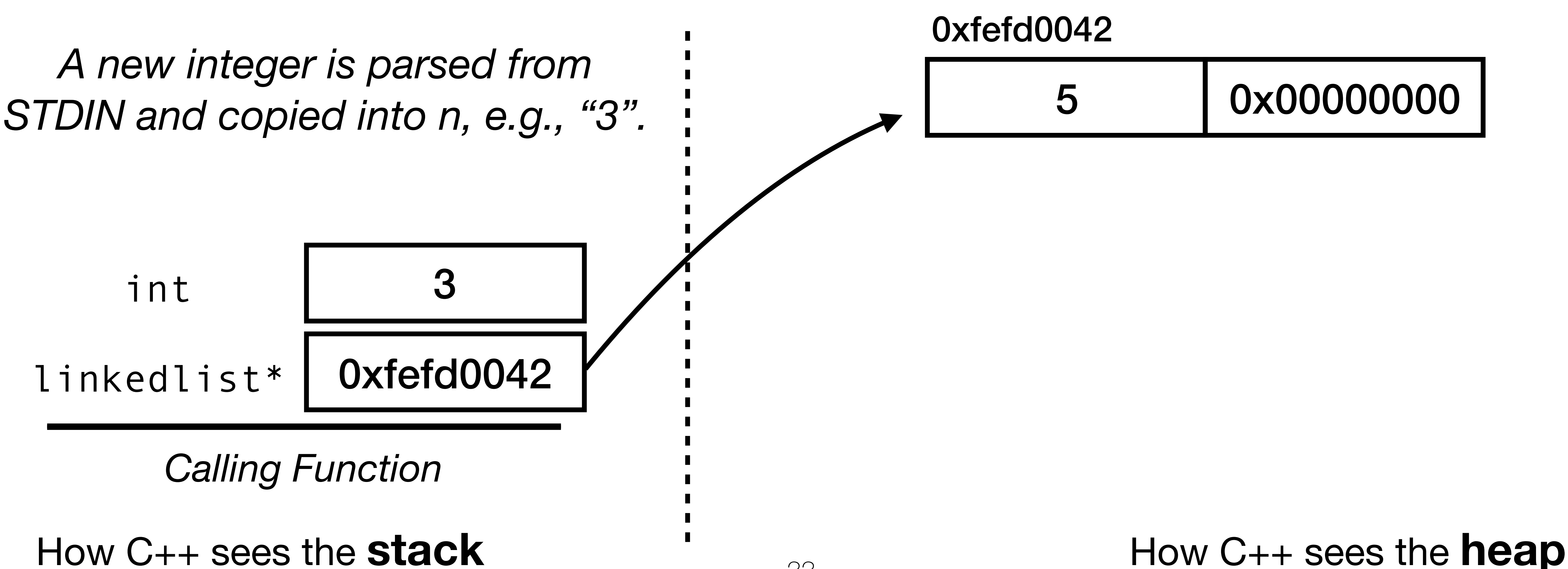
}
```



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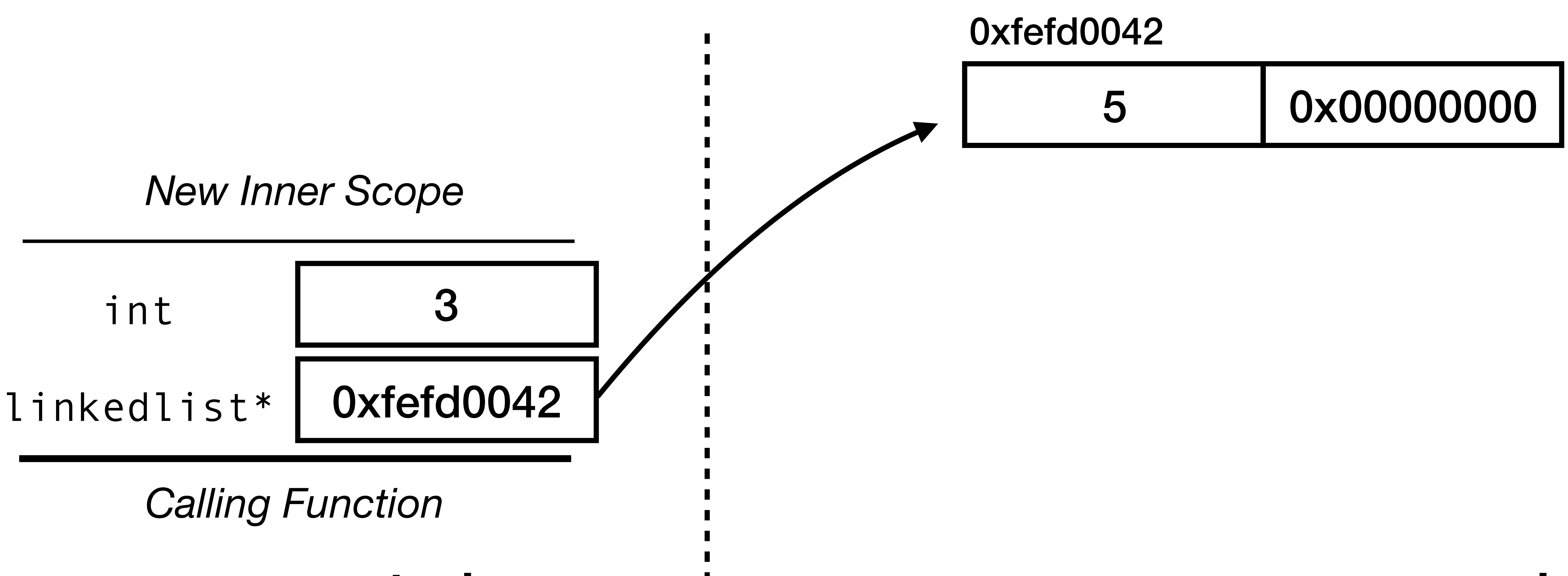

How C++ sees the **stack**

How C++ sees the **heap**

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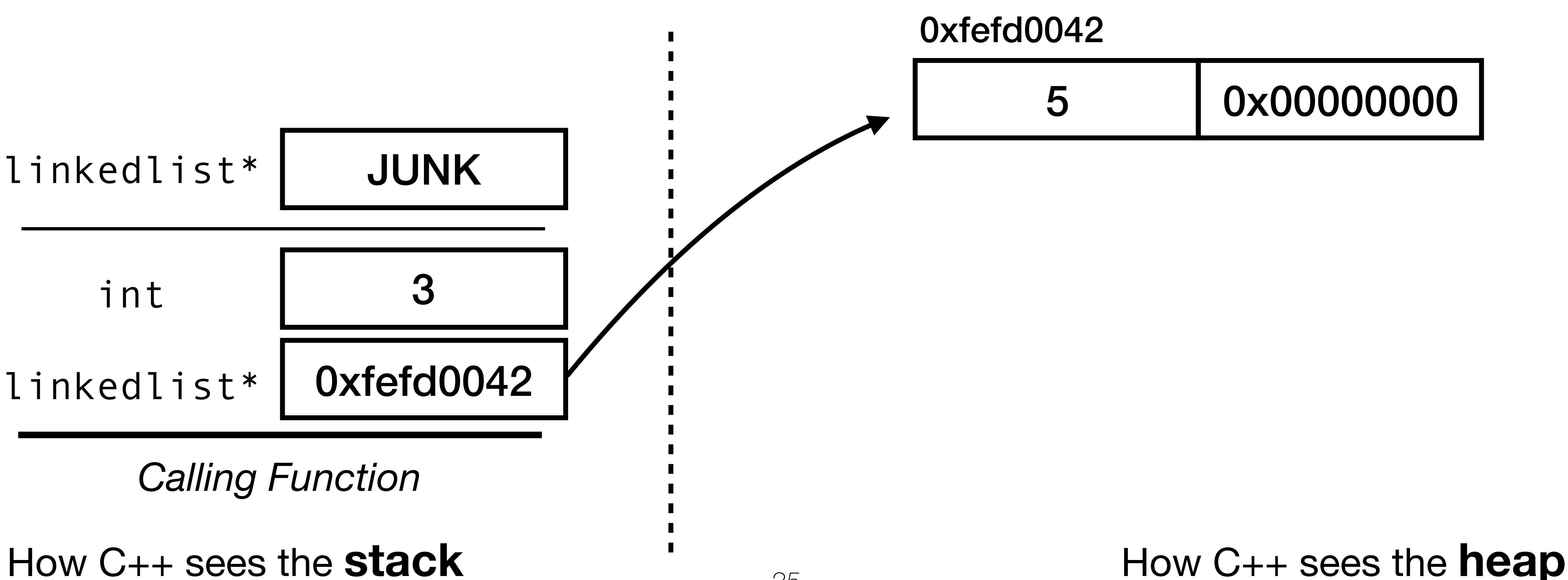

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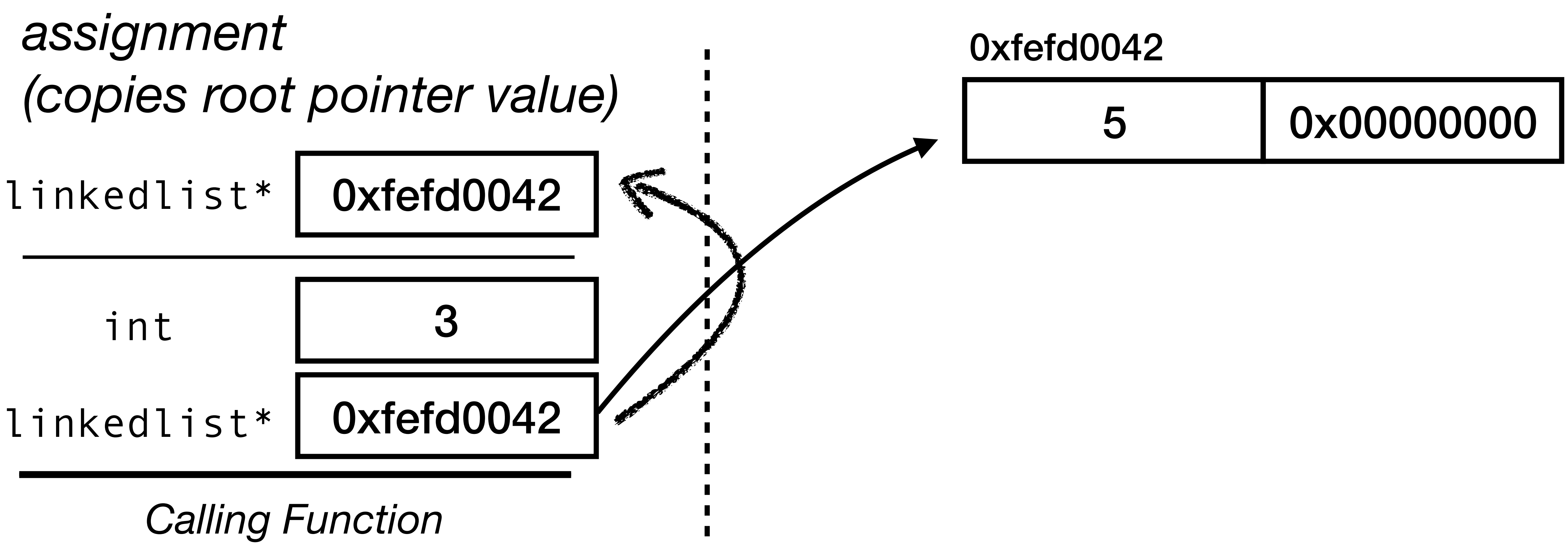

How C++ sees the **stack**

How C++ sees the **heap**

```
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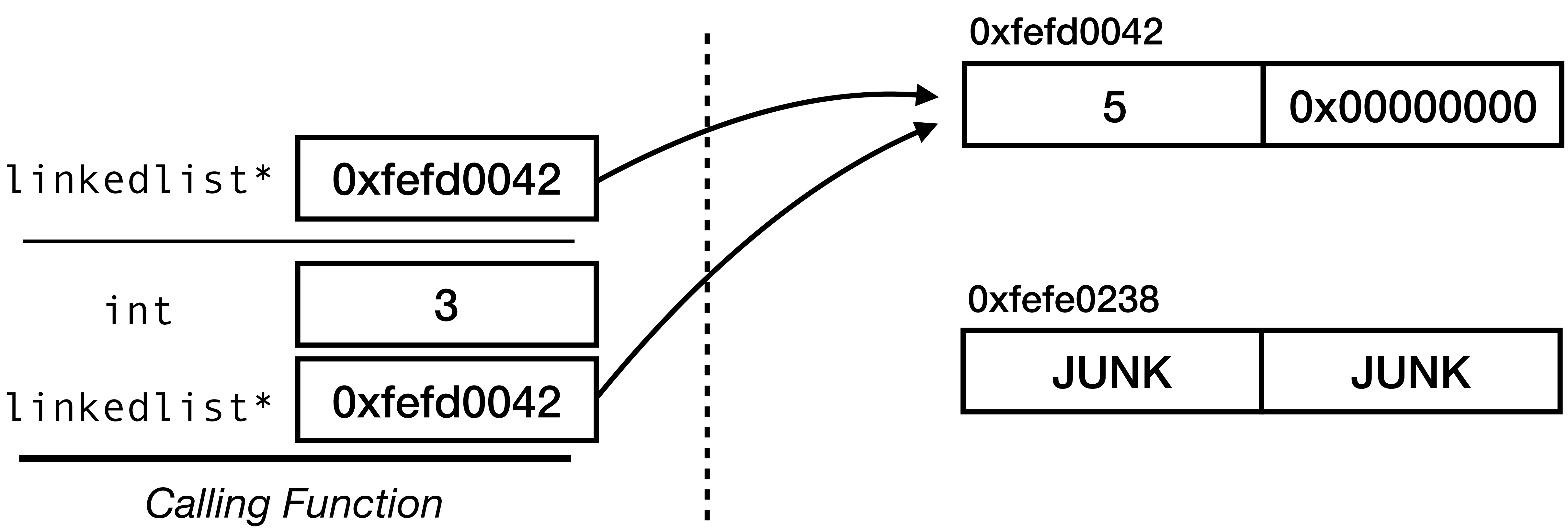

How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
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    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```

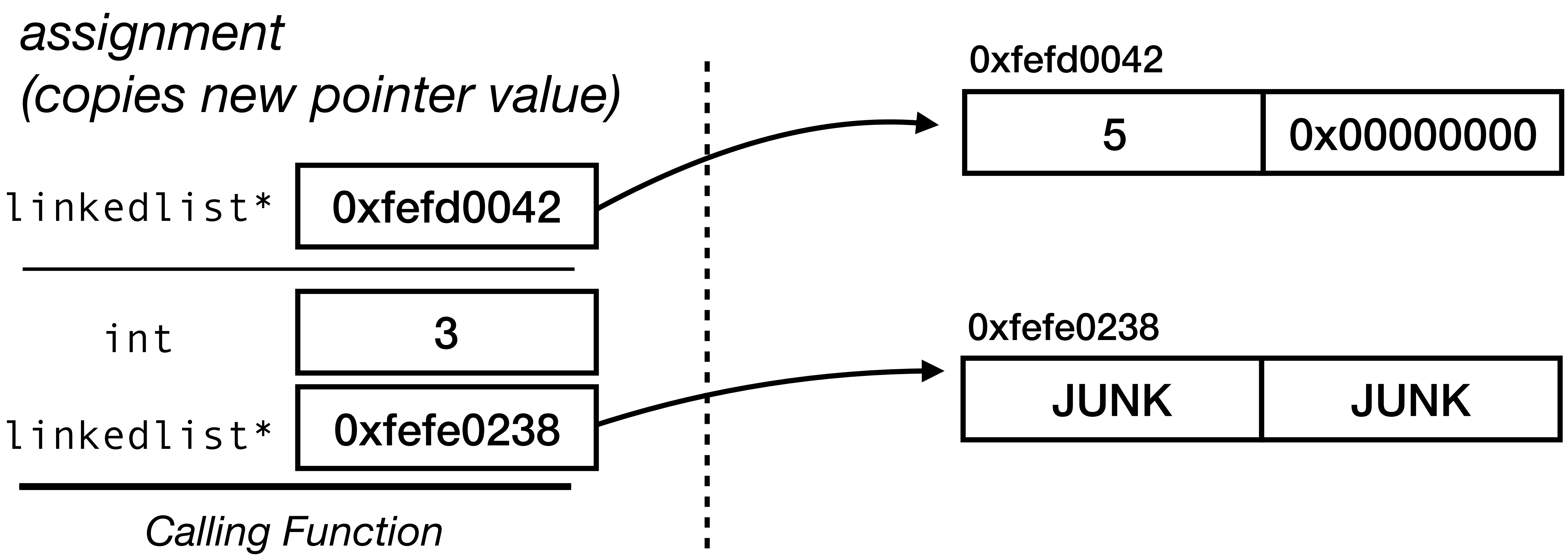

How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
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    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```

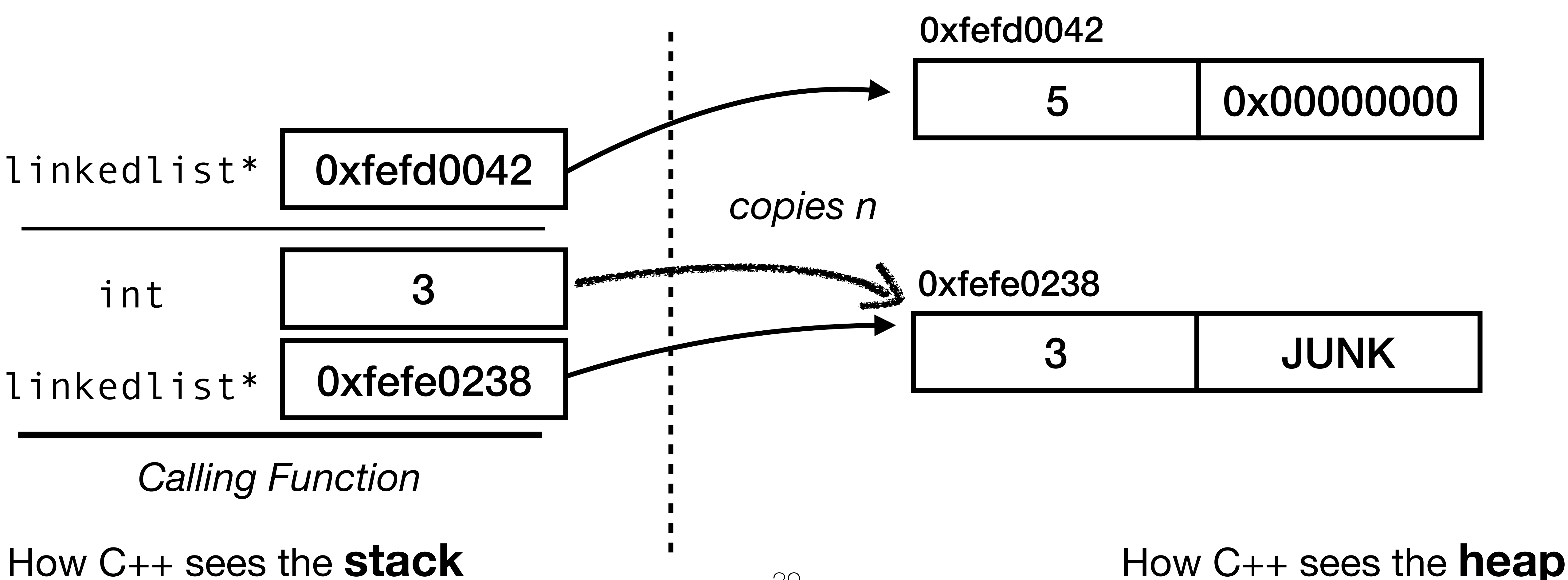

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
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    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```
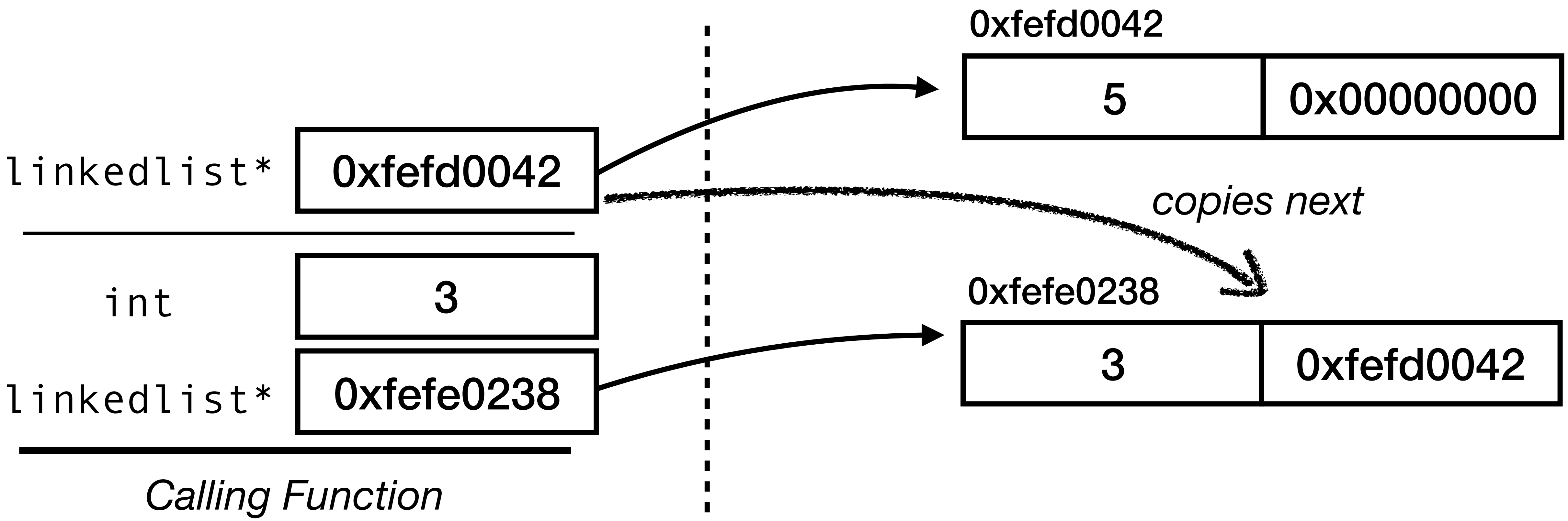
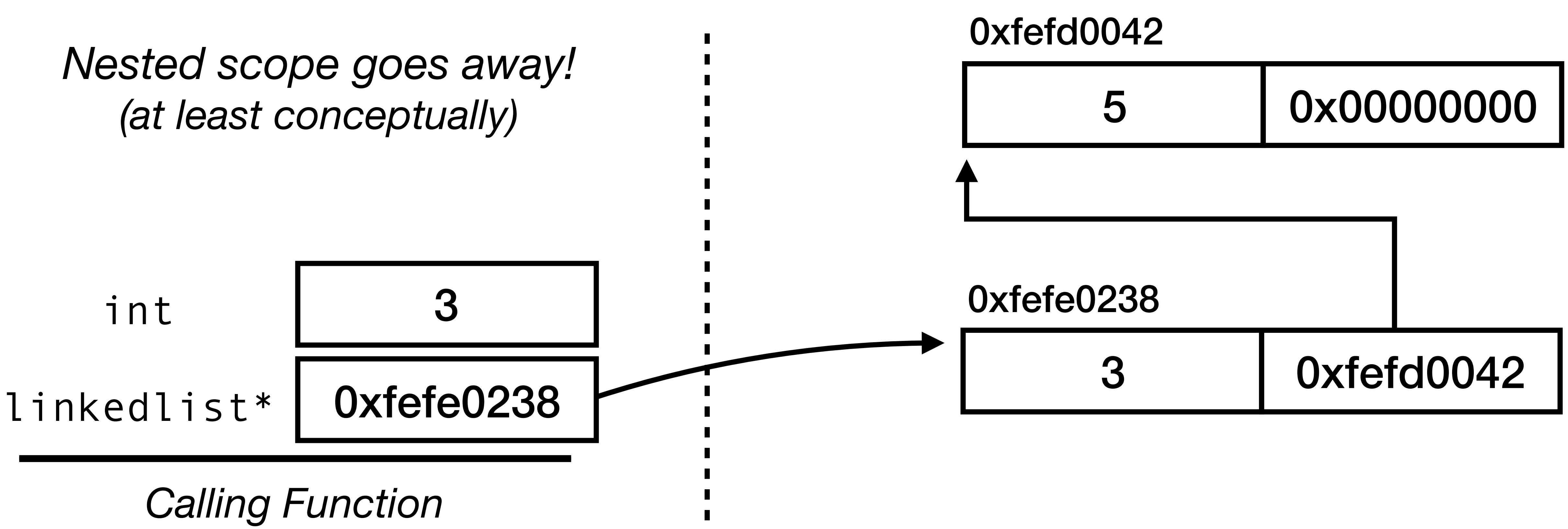



How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```

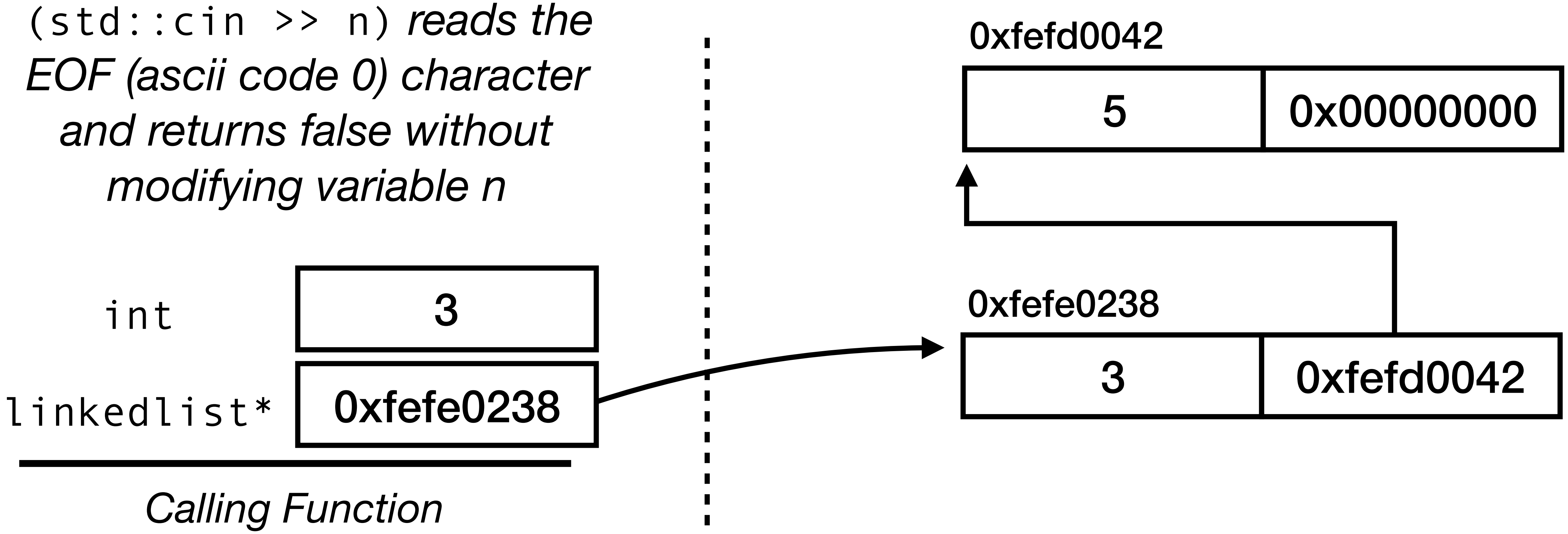


How C++ sees the **stack**

How C++ sees the **heap**

```
linkedlist* node = 0; //root
int n;
while (std::cin >> n)
{
    linkedlist* next = node;
    node = new linkedlist();
    node->value = n;
    node->next = next;
}
```

`(std::cin >> n)` *reads the EOF (ascii code 0) character and returns false without modifying variable n*



How C++ sees the **stack**

How C++ sees the **heap**

C++ semantics: taking pointers of stack values

```
char* badalloc()
{
    char bytes[4096] = {0};
    return &bytes[0];
}

int main()
{
    char* arr = badalloc();
    arr[0] = ‘h’;
    arr[1] = ‘i’;
    std::cout << arr << std::endl;
    return 0;
}
```

C++ semantics: Try an example

```
char* badalloc()
{
    char bytes[4096] = {0};
    return &bytes[0];
}

int main()
{
    char* arr = badalloc();
    arr[0] = ‘h’;
    arr[1] = ‘i’;
    std::cout << arr << std::endl;
    return 0;
}
```

What could go wrong when allocating memory this way?

C++ semantics: taking pointers of stack values

```
$ clang++ -o bin badalloc.cpp
badalloc.cpp:8:13: warning: address
of stack memory associated with local
variable 'bytes' returned [-Wreturn-
stack-address]
    return &bytes[0];
            ^~~~~
1 warning generated.
$ ./bin
hi
$
```

C++ semantics: taking pointers of stack values

```
char* passthrough(char* ptr)
{
    return ptr;
}

char* badalloc()
{
    char bytes[4096] {0};
    return passthrough(&bytes[0]);
}

int main()
{
    …
```

C++ semantics: taking pointers of stack values

```
$ clang++ -o bin badalloc.cpp
$ ./bin
hi
$
```

The compiler wont always
catch this problem for us!

C++ semantics: taking pointers of stack values

Now we can try making the buffer small!

```
char* badalloc()
{
    char bytes[8] = {0};
    return passthrough(&bytes[0]);
}

int main()
{
    char* arr = badalloc();
    arr[0] = ‘h’;
    arr[1] = ‘i’;
    std::cout << arr << std::endl;
    return 0;
}
```

C++ semantics: taking pointers of stack values

```
$ clang++ -o bin badalloc.cpp
$ ./bin
\300I\211\350\376^?
$
```

Now the call to `std::cout` itself tramples on this stack space and overwrites these bytes with values that are, to us, junk!

How Objects Work

C++ dynamic dispatch: Try an example!

```
class B
{
    virtual int f() { return 1; }
};
class A : public B
{
    virtual int f() { return 2; }
};


B* a = new A(); // Get a pointer to an A obj
std::cout << a->f() << std::endl;
```

// Which value is printed out?

C++ dynamic dispatch: Try an example!

```
class B
{
    virtual int f() { return 1; }
};
class A : public B
{
    virtual int f() { return 2; }
};
```

```
B* a = new A(); // Get a pointer to an A obj
std::cout << a->f() << std::endl;
```

// Which value is printed out?   ANSWER: 2

Function pointers

```
int add1(int x) { return x+1; }
```

In stored-program machines, all code sits somewhere in memory.

In C/C++, you can obtain pointers to functions at run-time, and invoke them! The pointer for `add1` can be obtained with:

```
&add1
```

```
int add1(int x) { return x+1; }

int main()
{
    int (*f)(int) = &add1;

    // …

    int four = (*f)(3);
}
```

A function pointer, `cmp`,
passed to `sort` as an argument.

```
int sort(int* x, int len, bool (*cmp)(int,int))
{
    // …

        // …
            if ((*cmp)(*x,*y))
            {
                swap(*x,*y);

                // …
            }

    // …
}
```

The function pointer, `cmp`,
dereferenced and invoked.

```
{
    // …

    sort(buff, length, &lessthan);

    // …
}
```

A pointer to function `lessthan` **is passed into** `sort`**.**

C++: Try an example!

Talk to your neighbors. Can you think of another way to parameterize a `sort` method over the comparison predicate to be used?

A function pointer, `cmp`**, type** `int x int -> bool`**,**
is a template parameter to `sort`**.**

```
template <bool (*cmp)(int,int)>
int sort(int* x, int len)
{
        // …
            if ((*cmp)(*x,*y))
            {
                swap(*x,*y);
                // …
```

Templated function `sort` **is invoked with a template parameter like so:** `sort<…>(…)`

```
int main()
{
    // …
    sort<&lessthan>(buff, length);
```

C++ dynamic dispatch: class polymorphism

```
class Cmp
{
    virtual bool cmp(int x, int y) = 0;
};
class LessThan : public Cmp
{
    virtual bool cmp(int x, int y)
    { return x < y; }
};
class GreaterThan : public Cmp
{
    virtual bool cmp(int x, int y)
    { return x > y; }
};
```

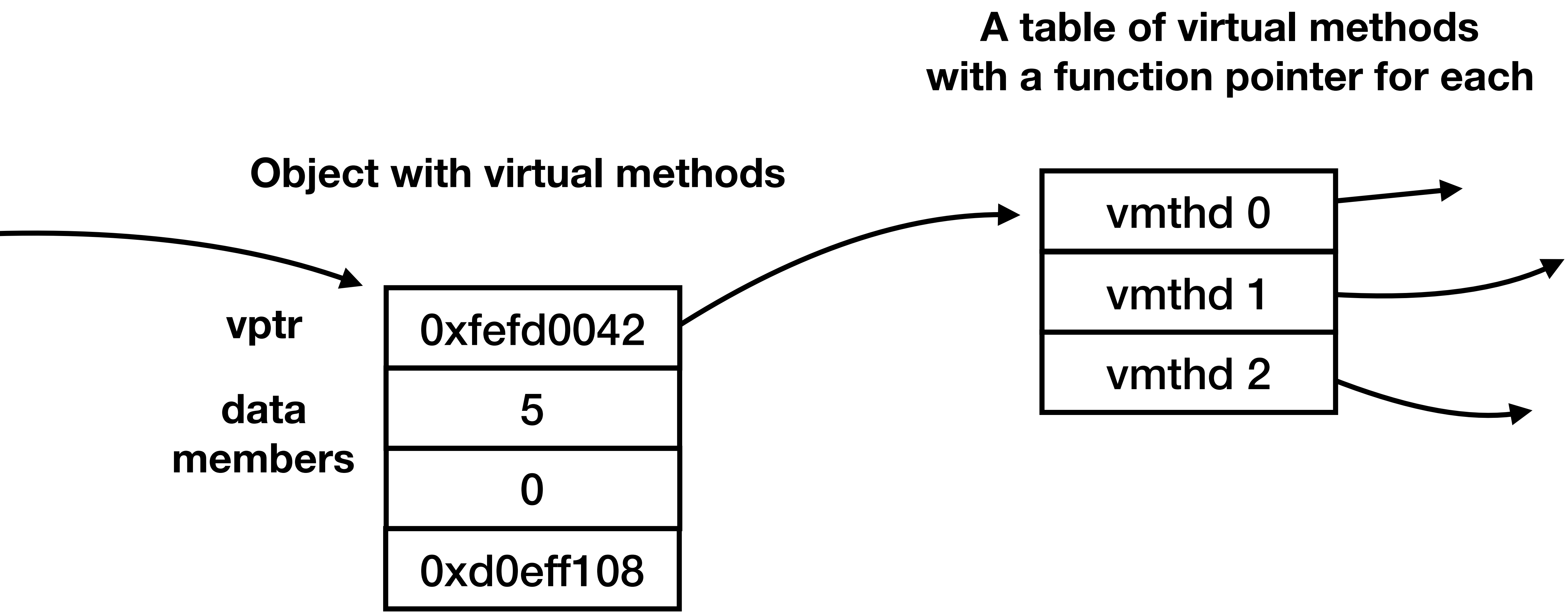
An instance of type `Cmp`, `cmp`, has overloaded method `cmp`.

```
int sort(int* x, int len, const Cmp& cmp)
{
        // …
            if (cmp->cmp(*x,*y))
            {
                swap(*x,*y);
                // …


int main()
{
    // …
    LessThan lessthan;
    sort(buff, length, lessthan);
```

Pass in object `lessthan` by reference to polymorphic type Cmp supporting the Cmp::cmp(int, int) member.

Virtual Tables (vtables)

Virtual Tables (vtables)



```
class Animal
{
    virtual const char* name() = 0;
    virtual int weight() const = 0;
    virtual void eat(Animal* prey)
    {
        if (this->weight()
                < 2 * prey->weight())
            return;
        delete prey;
        std::cout << prey->name()
                  << “ was eaten!\n”;
    }
};
```

```
class Mouse : public Animal
{
    int grams;

    Mouse(int grams)
        : grams(grams) {}

    virtual const char* name()
    {
        return “Mouse”;
    }

    virtual int weight() const
    {
        return this->grams;
    }
};
```

```
class Cat : public Animal
{
    Cat() {}

    virtual const char* name()
    {
        return “Cat”;
    }

    virtual int weight() const
    {
        return 4260;
    }
};
```

```
class Giraffe : public Animal
{
    virtual const char* name()
    {
        return “Giraffe”;
    }
    virtual int weight() const
    {
        return 1570000;
    }
    virtual void eat(Animal* prey)
    {
        std::cout << this->name()
                  << “ wont eat that.\n”;
    }
};
```

```
// vtable struct for Animal subclasses
struct AnimalVTable
{
    const char* (*name)(void*);
    int (*weight)(const void*);
    void (*eat)(void*,void*);

    AnimalVTable(const char* (*name)(void*),
                 int (*weight)(const void*),
                 void (*eat)(void*,void*))
      : name(name), weight(weight), eat(eat)
    {}
};

// Allocate a vtable for each concrete Animal
AnimalVTable mouse_vtable(&nameMouse,
                          &weightMouse,
                          &eatAnimal);
```

```
// Class Mouse compiled to a struct
struct Mouse
{
   AnimalVTable* vptr;
   int grams;
};


// An allocator/constructor for Mouse
Mouse* newMouse(int grams)
{
    Mouse* m = (Mouse*)malloc(sizeof(Mouse));
    m->vptr = &mouse_vtable;
    m->grams = grams;
    return m;
}
```

```
// A name method for Mouse instances
const char* nameMouse(void* _ths)
{
    return “Mouse”;
}


// A weight method for Mouse instances
int weightMouse(const void* _ths)
{
    const Mouse* ths = (const Mouse*)_ths;
    return ths->grams;
}
```

```
// Looks up the vtable for an object
VTable* vtable(void* obj)
{
    return (VTable*)((void**) obj)[0];
}




{
    // To call a member function f:
    // e.g., obj->f(arg0, arg1, …);

    vtable(obj)->f(obj, arg0, arg1, …);
}
```

```
// Looks up the vtable for an Animal object
AnimalVTable* vtable(void* obj)
{
    return (AnimalVTable*)((void**) obj)[0];
}

// A default eat method for Animals
void eatAnimal(void* ths, void* prey)
{
    if (vtable(ths)->weight(ths)
            < 2 * vtable(prey)->weight(prey))
        return;
    delete prey; // vtable(prey)->~Animal…
    std::cout << vtable(prey)->name(prey)
              << “ was eaten!\n”;
}
```

Try an example:

How do you define the constructor for Giraffe?

```
// Class Giraffe compiled to a struct
struct Giraffe
{
   AnimalVTable* vptr;
   // No data members
};

AnimalVTable giraffe_vtable(&nameGiraffe,
                            &weightGiraffe,
                            &eatGiraffe);

// An allocator/constructor for Giraffe
Giraffe* newGiraffe()
{
    Giraffe* g = new Giraffe();
    g->vptr = giraffe_vtable;
    return g;
}
```

Try an example:

How do you define the virtual member functions for Giraffe?

```
const char* nameGiraffe(void* _ths)
{
    return “Giraffe”;
}

int weightGiraffe(const void* _ths)
{
    return 1570000;
}

void eatGiraffe(void* _ths)
{
    Giraffe* ths = (Giraffe*)_ths;
    std::cout << vtable(ths)->name(ths)
              << “ wont eat that.\n”;
}
```