How to Choose the Right Standard Library Container

And Why You Should Want Some More

CppCon 2019

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A Tale of Letters

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1980's

Minicomputer – 64 KB RAM

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1990's

Mac SE – 4 MB RAM

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2000's

32 bit PC – 4 GB RAM

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2010's

64 bit 8 core – 32 GB RAM

Program Runs Slow

- Simulation took 7.25 hours on my fast 2019 workstation
  - It was a lot slower on the customer's laptop

Container Variety

- Each container has different tradeoffs between speed and space and convenience
- There is a specific set of containers in the Standard Library which have withstood the test of time
  - Excepting perhaps vector<bool>
- New containers are regularly proposed which offer different speed/space/convenience tradeoffs

Container Choice

- **Vector:** contiguous, fast iteration, random access, growth invalidates everything, geometric growth behavior, reasonable overhead
- **Deque:** sort of contiguous, pretty fast iteration, random access, growth invalidates iterators only, chunk linear growth behavior, large overhead for small sizes
- **List:** noncontiguous, slow iteration, linear access, elements never move, fine linear growth, low overhead for large elements

Obvious Choice?

- **vector**
  - Has **push_back** and **pop_back** because they are (usually) *O*(1)
  - Doesn't have **push_front** and **pop_front** because they are *O*(n)
  - And **insert** is *O*(n)
  - Contiguous memory – fast iteration
- **deque**
  - Has **push_back** and **pop_back** because they are (usually) *O*(1)
  - Has **push_front** and **pop_front** because they are (usually) *O*(1)
  - But **insert** is *O*(n)
  - More or less contiguous memory – pretty fast iteration

Obvious Choice?

- **list**
  - Has **push_back** and **pop_back** because they are *O*(1)
  - Has **push_front** and **pop_front** because they are *O*(1)
  - And **insert** is *O*(1)
  - Noncontiguous memory – slow iteration

Obvious Choice?

- Need to insert and erase fast anywhere in a container?
  - **list** offers this ability
  - **vector** is faster if the container size is fairly small and it uses far less memory
- Need to store millions of records and access them fast?
  - **vector** offers this ability
  - **deque** is also fast to iterate and wastes far less memory if the container is large
  - **vector** can't be used at all if its size is a significant percentage of total memory
- Need to sort objects which can't be moved or copied?
  - **list** offers this ability
  - **list** is quite fast to iterate if elements are in cache

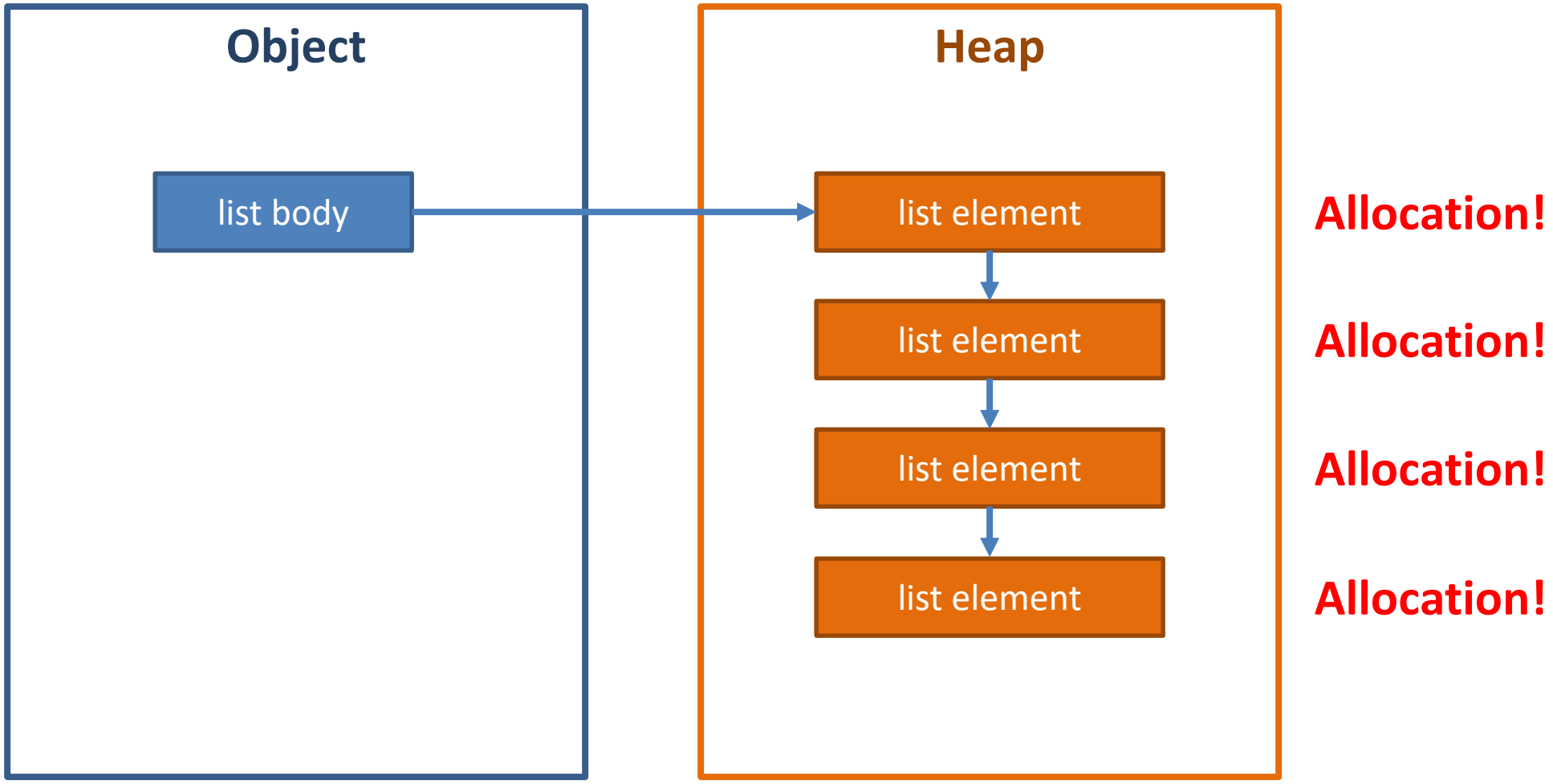
The Queue

- Suppose we want a number of objects, each with a small FIFO buffer
  - Assume that the buffer is typically small (around 10)
  - But it can't have a fixed max size because it can occasionally be much larger
  - What is the best way to implement this?
- The **queue** container adaptor is the Standard Library FIFO solution
  - Requires **push_back** and **pop_front**
  - So works (only) on **list** and **deque**

The Queue

```
vector<widget> widgets(count);
for (int i = 0; i < reps; ++i)
{
      for (auto& widget : widgets)
            for (int n = 0; n < adds; ++n) // 1 < adds < size
                  widget.push(n);
      for (auto& widget : widgets)
            for (int n = 0; n < subs; ++n) // 1 < subs < size
                  if (!widget.empty())
                        widget.pop();
}
```

The Queue – List



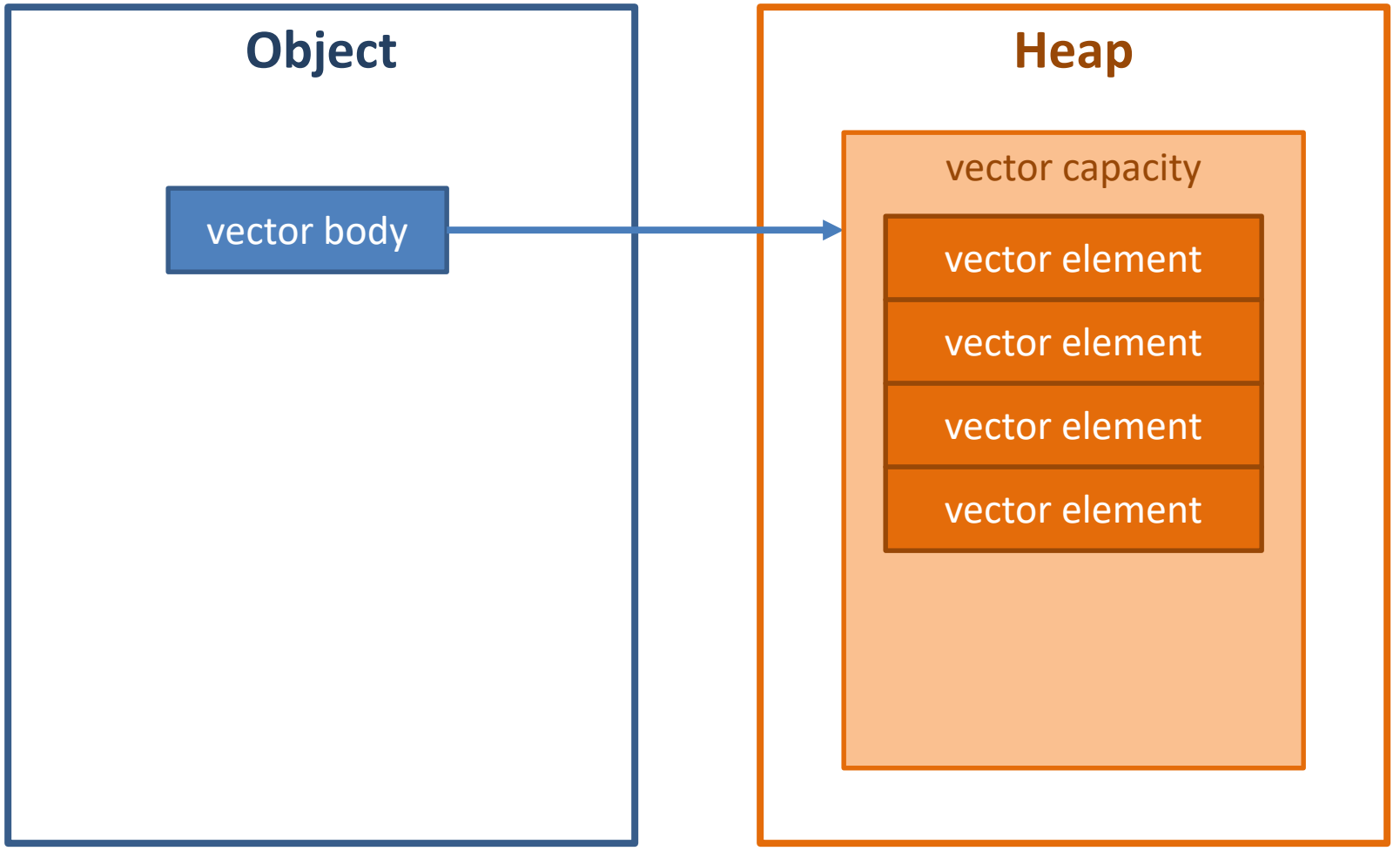
The Queue – List

```
struct widget {
    void push(int i) { fifo.push_back(i); }
    int pop() { int i = fifo.front(); fifo.pop_front(); return i; }
    bool empty() const { return fifo.empty(); }
    list<int> fifo;
};
```

The Queue – List

Container	Count	Reps	Size	Time (s)	Memory (MB)
List	10000	10000	10	35.4	95.7

The Queue – Vector



1 Allocation

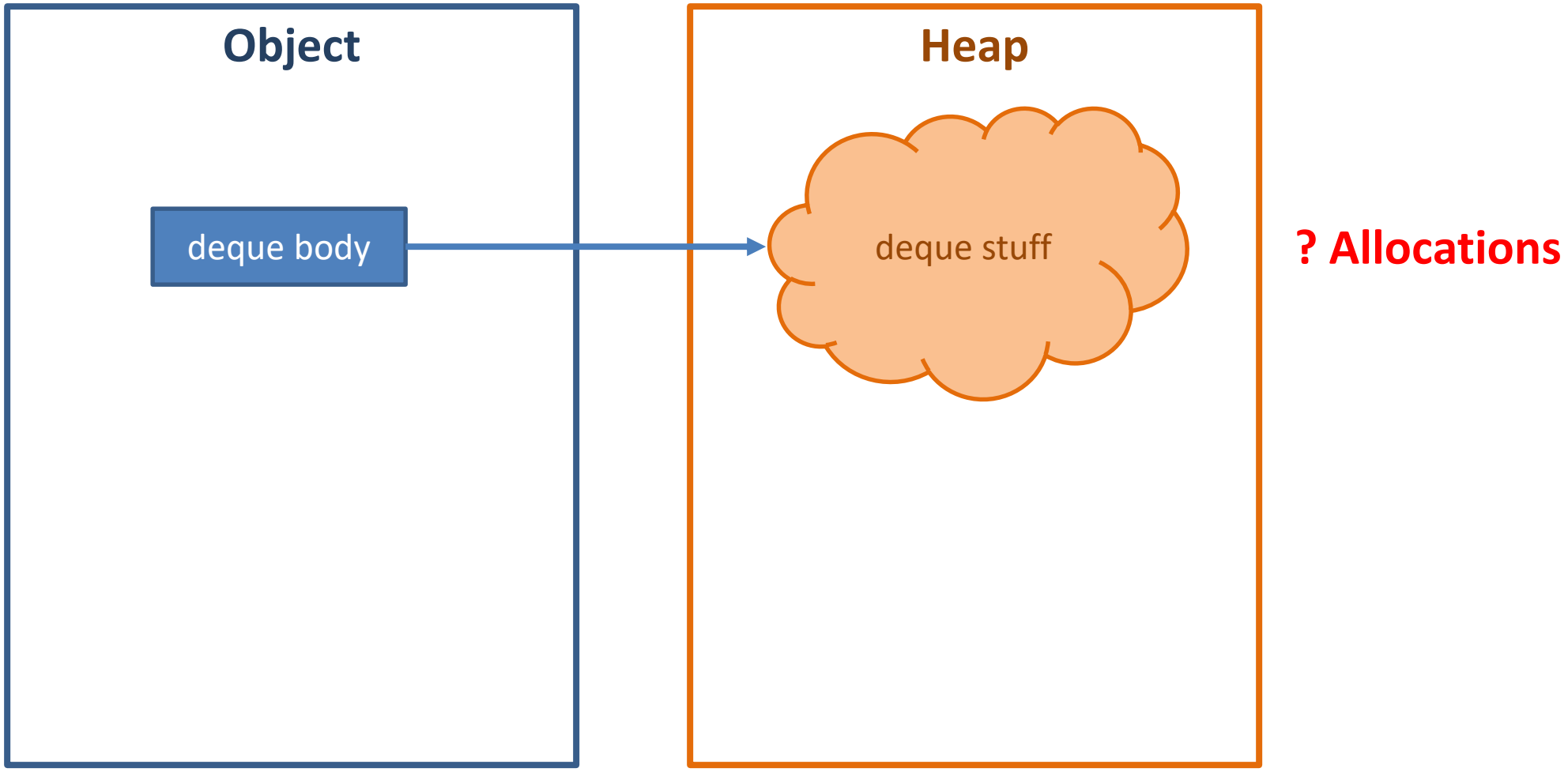
The Queue – Vector

```
struct widget {
    widget() { fifo.reserve(size); }
    void push(int i) { fifo.push_back(i); }
    int pop() {
        int i = fifo.front();
        fifo.erase(fifo.begin());
        return i;
    }
    bool empty() const { return fifo.empty(); }
    vector<int> fifo;
};
```

The Queue – Vector

Container	Count	Reps	Size	Time (s)	Memory (MB)
List	10000	10000	10	35.4	95.7
Vector	10000	10000	10	10.3	19.6

The Queue – Deque



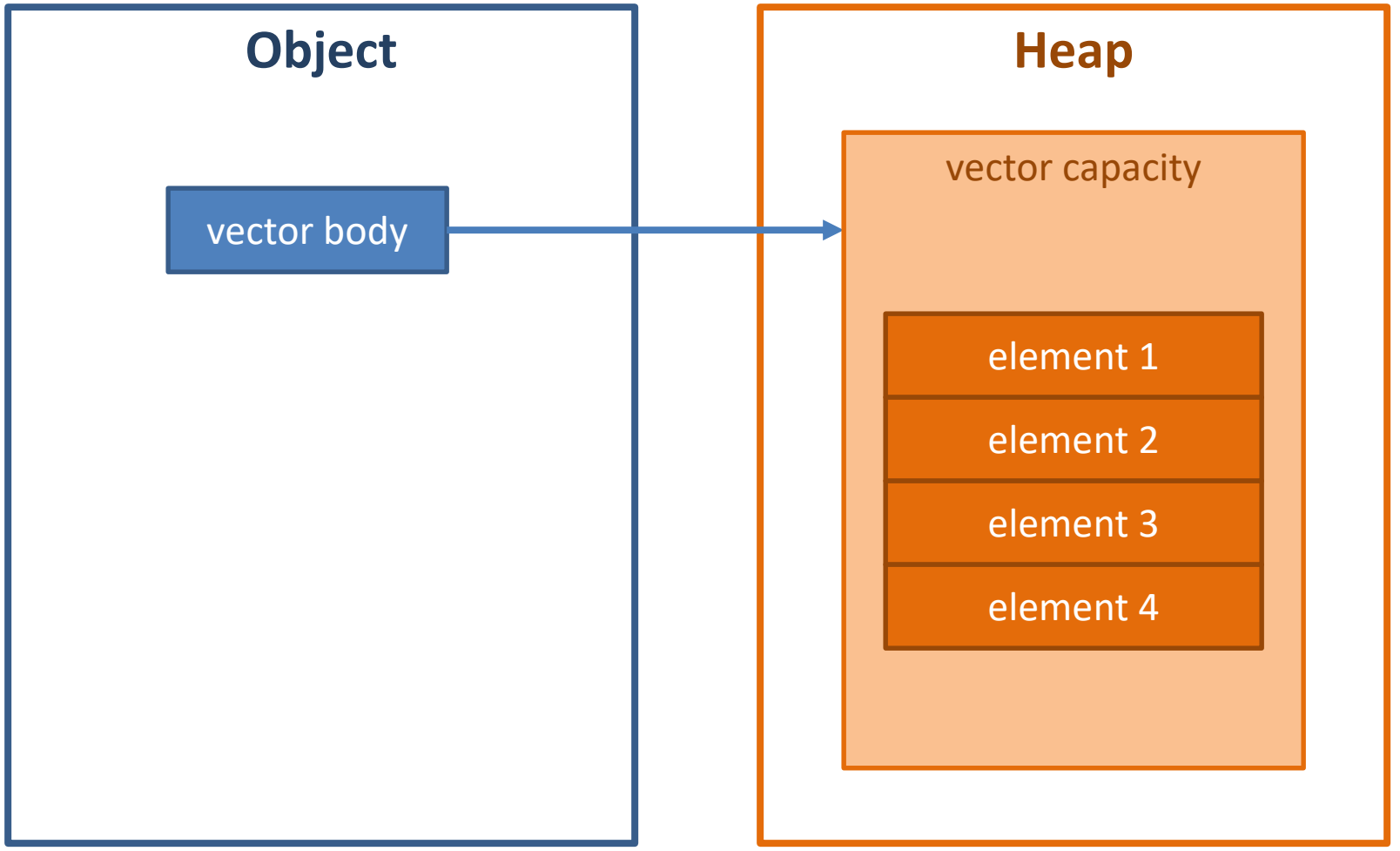
The Queue – Deque

```
struct widget {
    void push(int i) { fifo.push_back(i); }
    int pop() { int i = fifo.front(); fifo.pop_front(); return i; }
    bool empty() const { return fifo.empty(); }
    deque<int> fifo;
};
```

The Queue – Deque

Container	Count	Reps	Size	Time (s)	Memory (MB)
List	10000	10000	10	35.4	95.7
Vector	10000	10000	10	10.3	19.6
Deque	10000	10000	10	5.7	55.9

The Queue – Shifty Vector



1 Allocation

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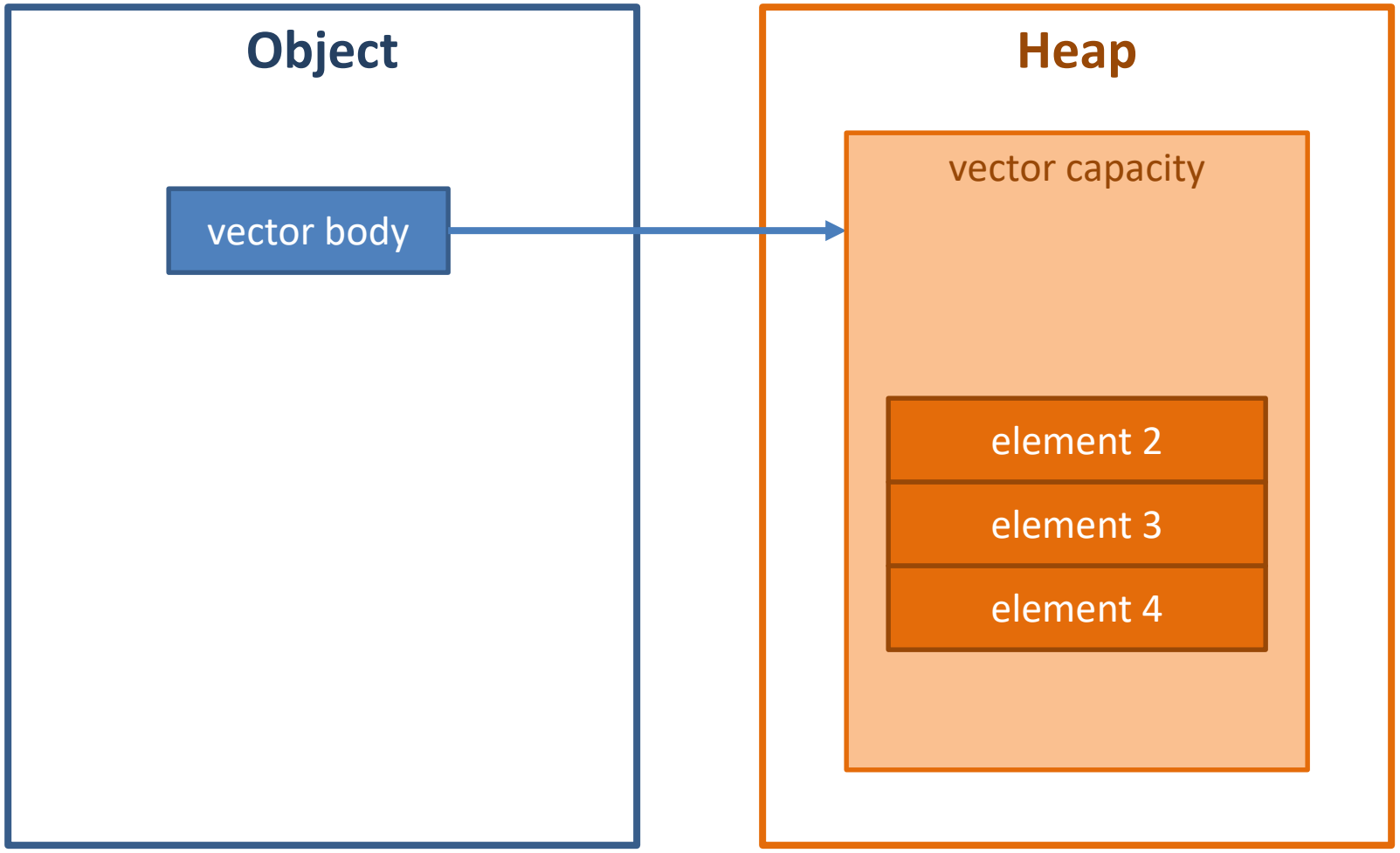

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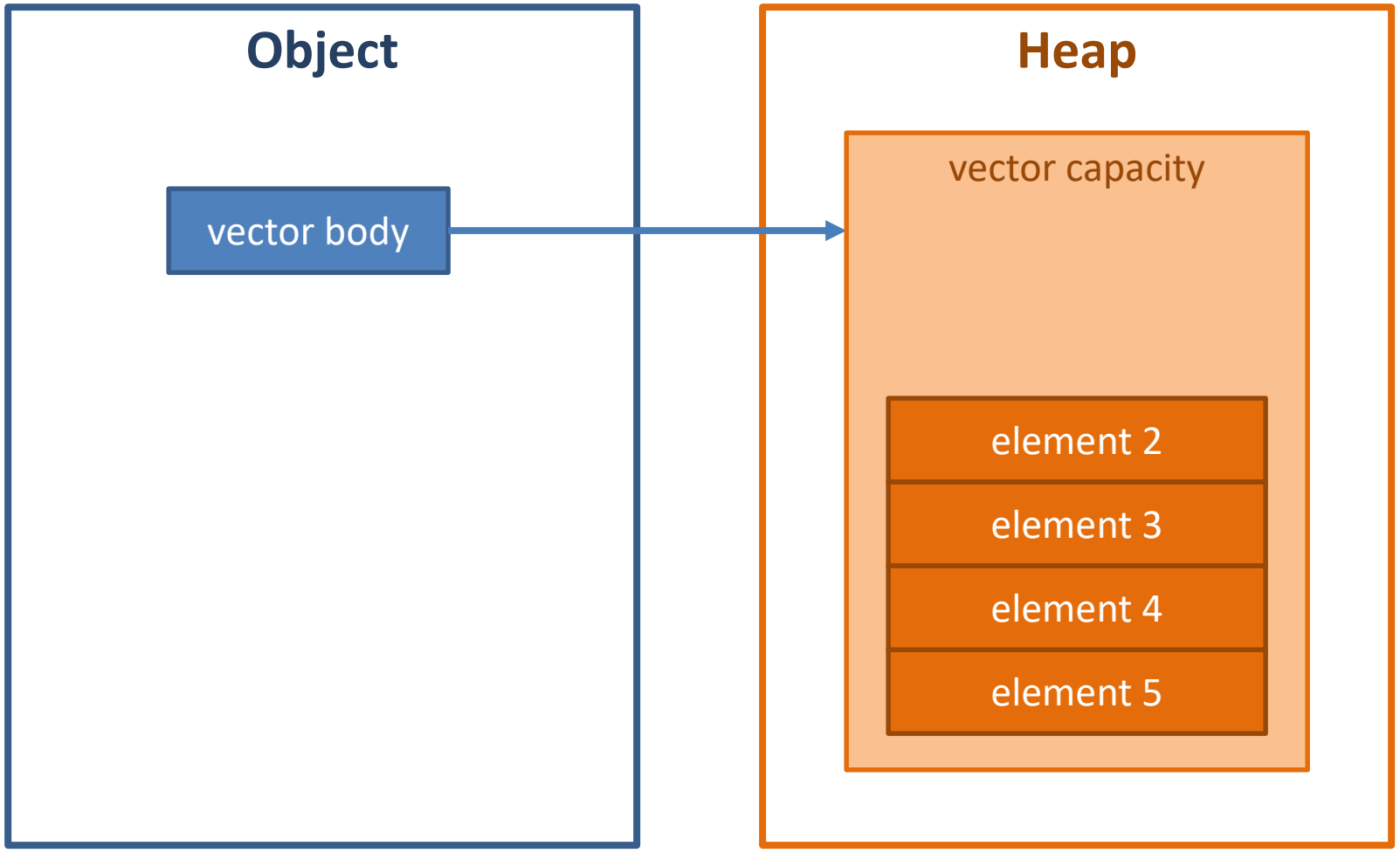

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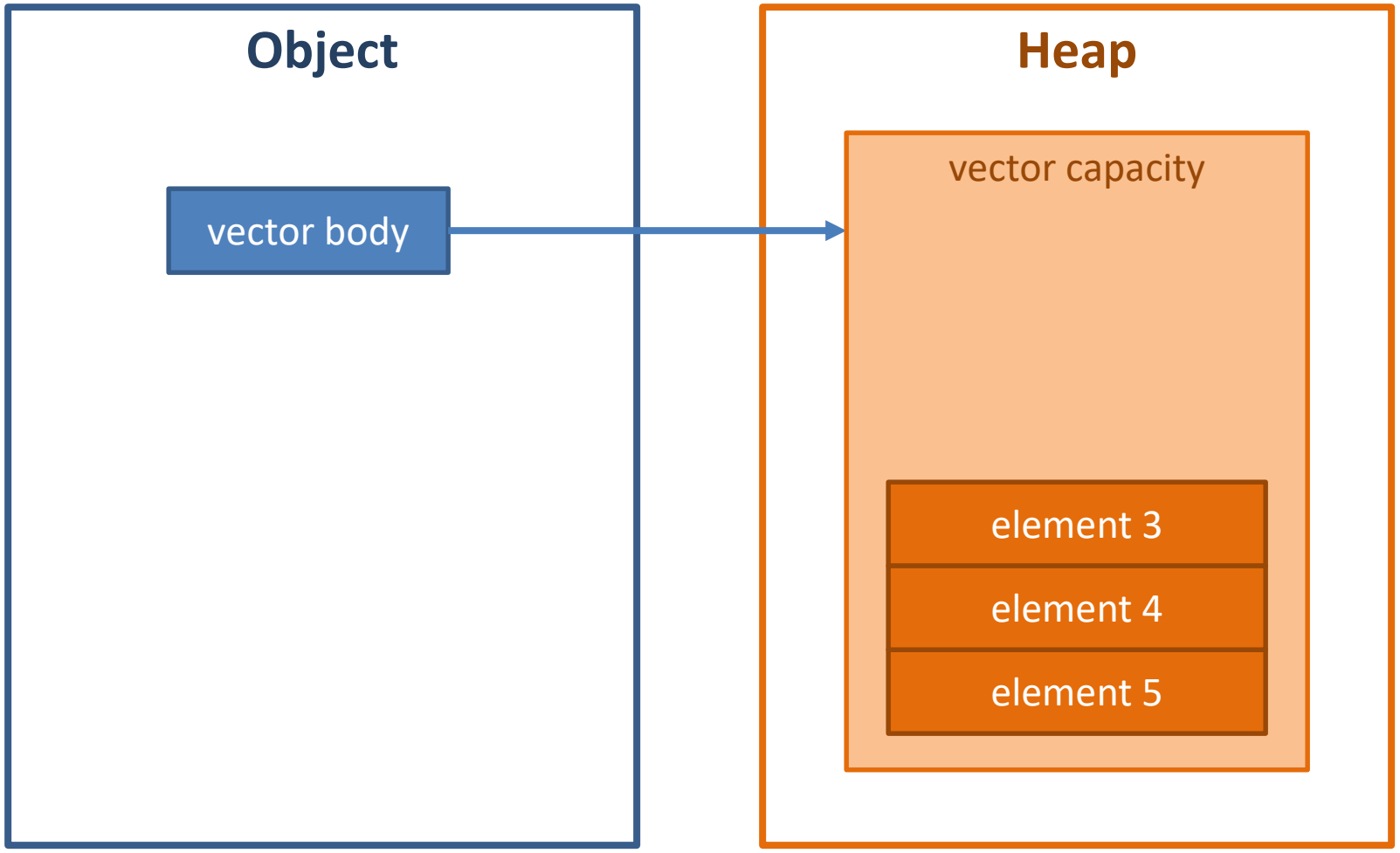

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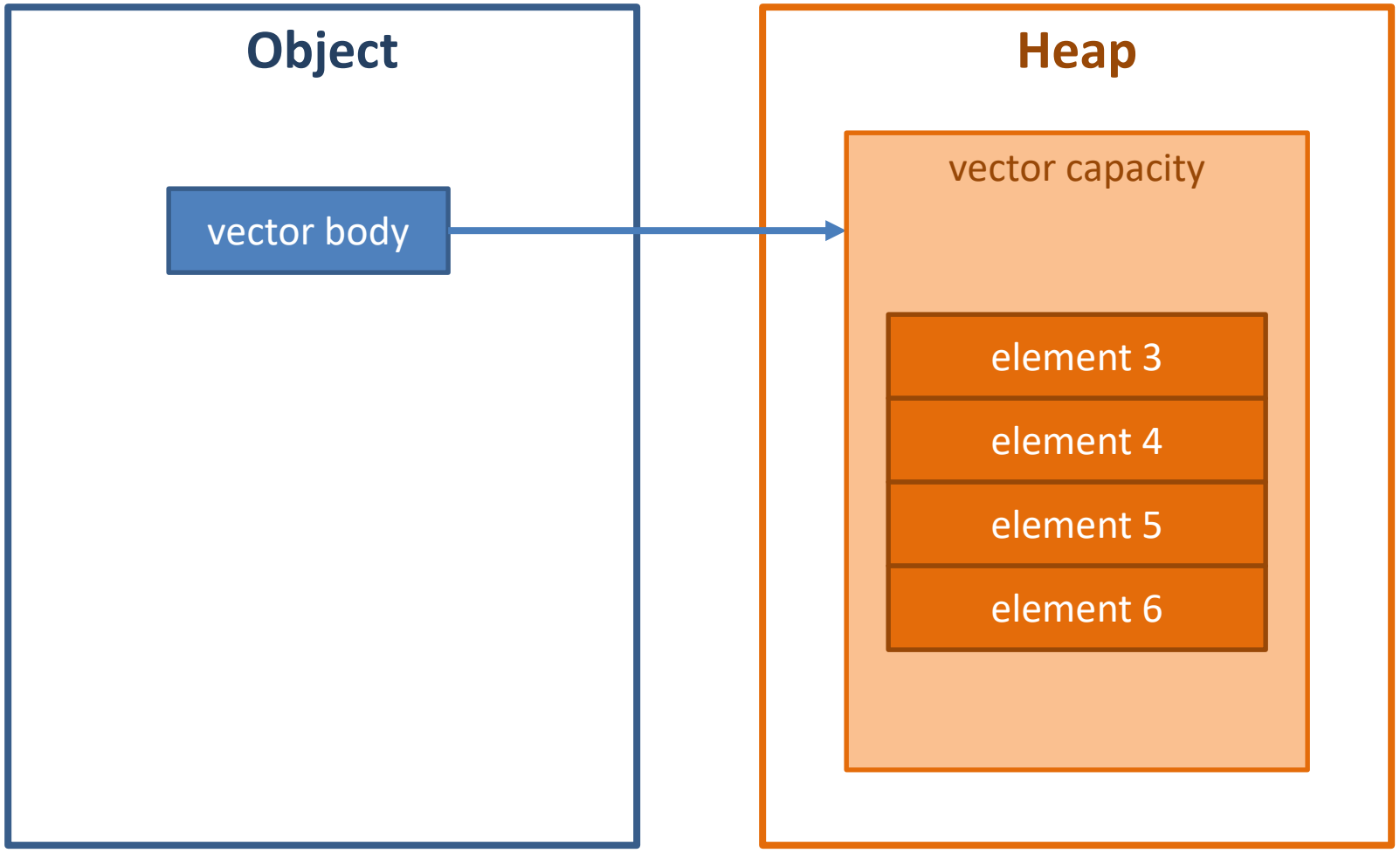

The Queue – Shifty Vector

```
struct widget {
    widget() {
        fifo.reserve(size);
        front = fifo.begin();
    }

    // More below ...

    vector<int> fifo;
    vector<int>::iterator front;
};
```

The Queue – Shifty Vector

```
int pop()
{
    return *front++;
}

bool empty() const
{
    return front == fifo.end();
}
```

The Queue – Shifty Vector

```
void push(int i) {
      vector<int>::difference_type x;
      if (fifo.size() == fifo.capacity()) {
            if (front != fifo.begin())
                  fifo.erase(fifo.begin(), front);
            x = 0;
      }
      else
            x = front - fifo.begin();
      fifo.push_back(i);
      front = fifo.begin() + x;
}
```

The Queue – Shifty Vector

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List	10000	10000	10	35.4	95.7
Vector	10000	10000	10	10.3	19.6
Deque	10000	10000	10	5.7	55.9
Shift Vector	10000	10000	10	2.2	19.5

Don't Assume – Measure

- You can't depend on rules of thumb
  - **set** can be a very slow way to maintain a sorted list
  - It might be faster to look something up linearly than with a binary search
- Or even STL design
  - Vector does not have **push_front** or **pop_front**
  - But vector might be faster in your situation
- You have to try different implementations
  - And measure performance
  - Your assumption, which may be correct most of the time, could be a HUGE pessimization for your particular case
  - Sometimes you have to think about it rather hard and be a bit clever

Other Vectors

- Fixed capacity
  - Stores all elements locally; never uses the heap
  - Useful if you have a variable (but limited) number of elements
  - This is quite a common case (e.g. up to 4 phone numbers in a personnel record)
  - **std::array** is a fixed *size* vector (like a C array), not the same thing
- Local cache ("short string optimization")
  - Stores up to a specified number of elements locally, then uses the heap
  - This avoids the heap for common cases at the expense of local size
  - **std::string** typically does this, but you can't choose the local size

The Game

- Suppose we want a data structure with the following traits:
  - A fairly large number of objects (1000's)
  - Frequent turnover (insert/erase)
  - Pointers and iterators must remain valid with turnover
  - Order is not important
  - Rapid and reliable iteration is essential
- **list** is the only Standard Library solution that comes close
  - But the limitations mentioned above all apply
  - Lack of locality of reference will cause iteration to be slow and to vary in performance, even during a single pass

The Game

- Create a container of **count** elements
  - Elements are roughly 100 bytes
- Do the following **reps** times
  - Do **reads** times
    - Access each of **count** elements in turn
  - Delete every **stride**-th element in the container
  - Insert **count** / **stride** new elements

The Game – List

Container	Count	Reps	Reads	Stride	Time (s)	Memory (MB)
List	10000	1000	100	5	14.5	8.4

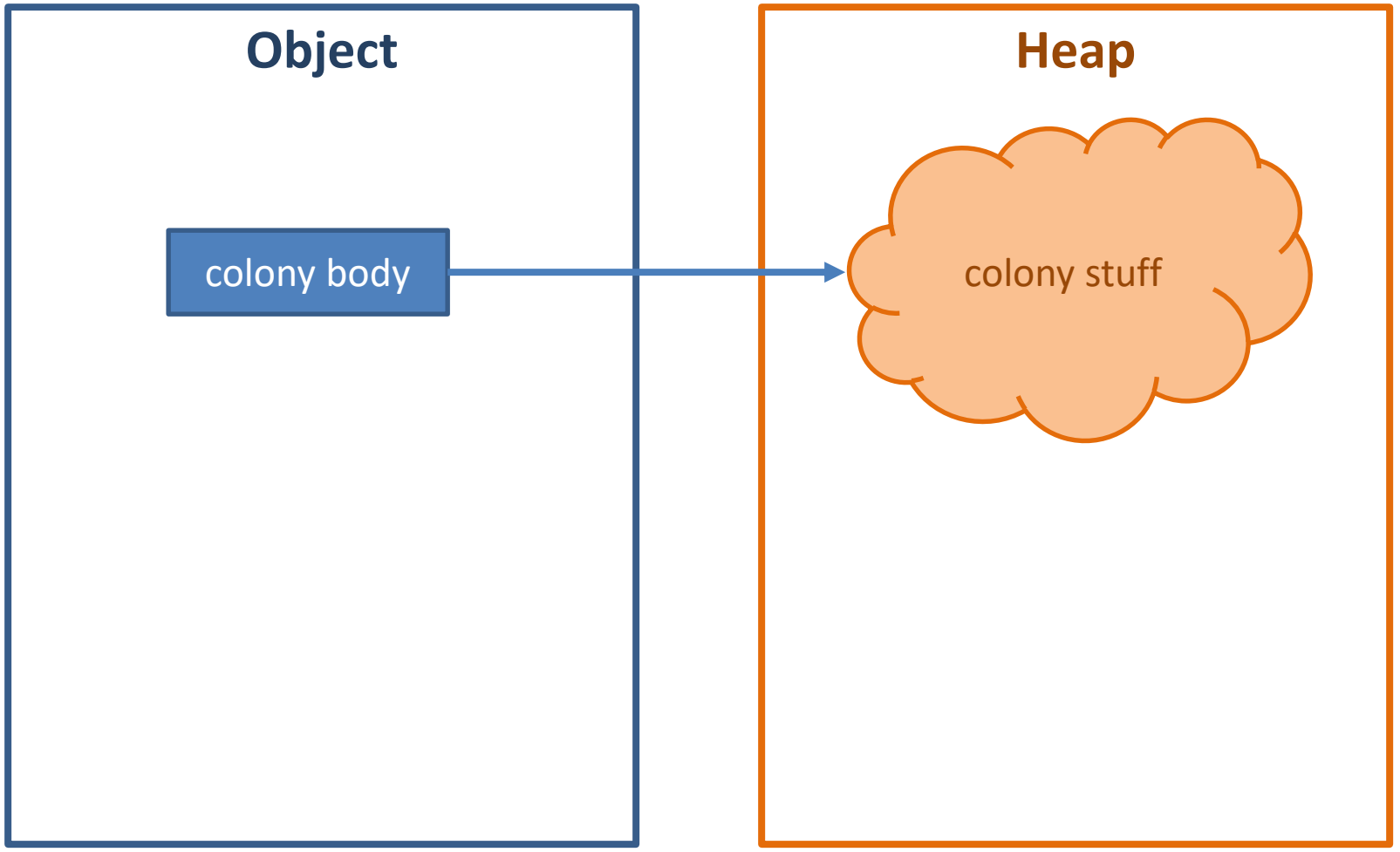
The Game – Colony

- **colony** container
  - An extension of the bucket array container design
  - Stores the elements in a series of blocks of increasing size
  - Pointers and iterators are not invalidated by **insert** or **erase**
  - Memory for deleted elements is reused by new elements or freed
  - A separate data structure called a skipfield marks deleted elements in a way which optimizes iteration
  - Other structures are maintained to identify deleted elements

https://www.youtube.com/watch?v=wBER1R8YyGY

https://plflib.org/colony.htm

The Game – Colony



? Allocations

The Game – Colony

Container	Count	Reps	Reads	Stride	Time (s)	Memory (MB)
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Colony	10000	1000	100	5	2.8	7.7

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  - But I was doing all the right things: reserving, using move semantics
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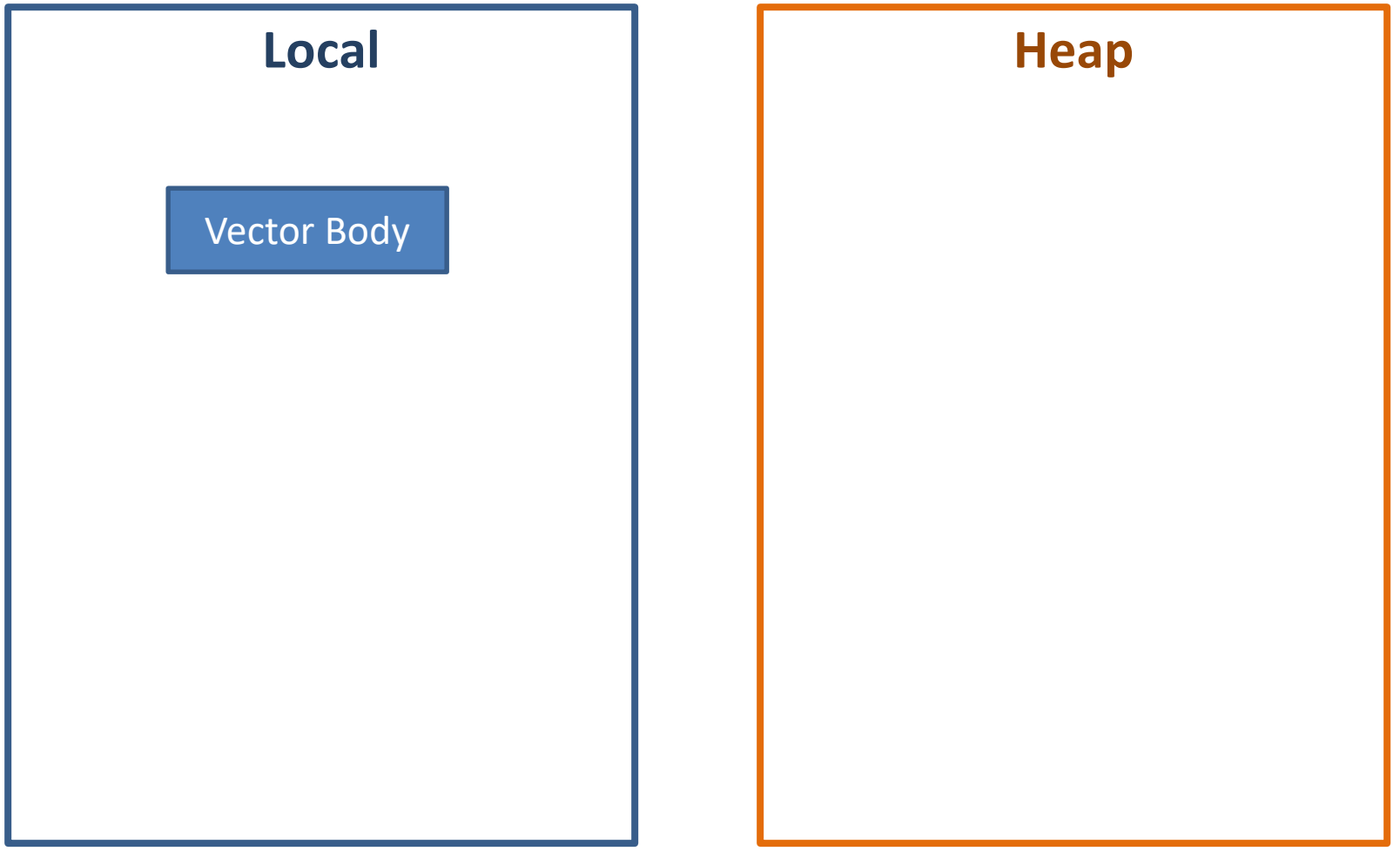
  - Electrical system generates lots more data per time step

Vector – Growth



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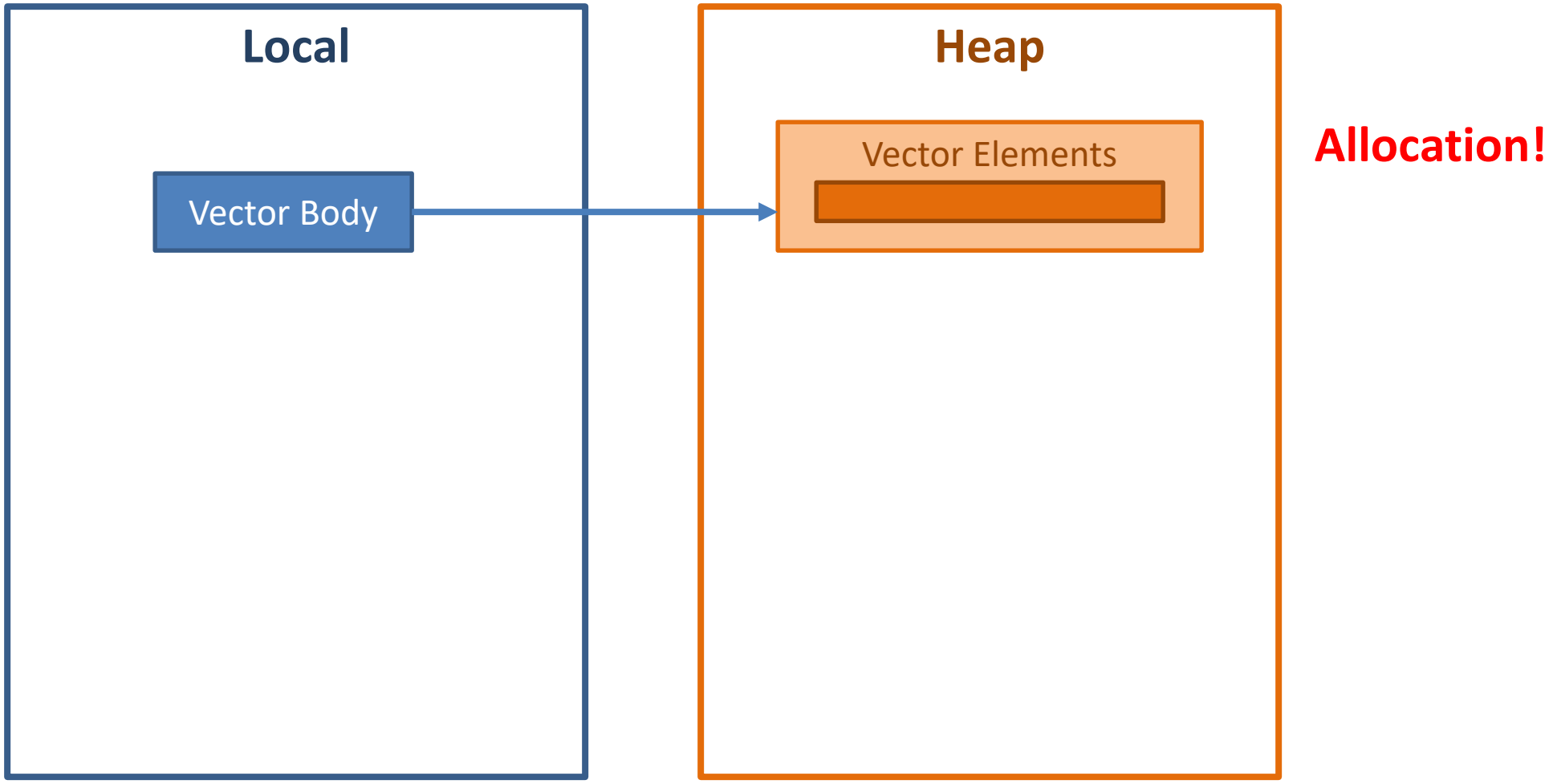

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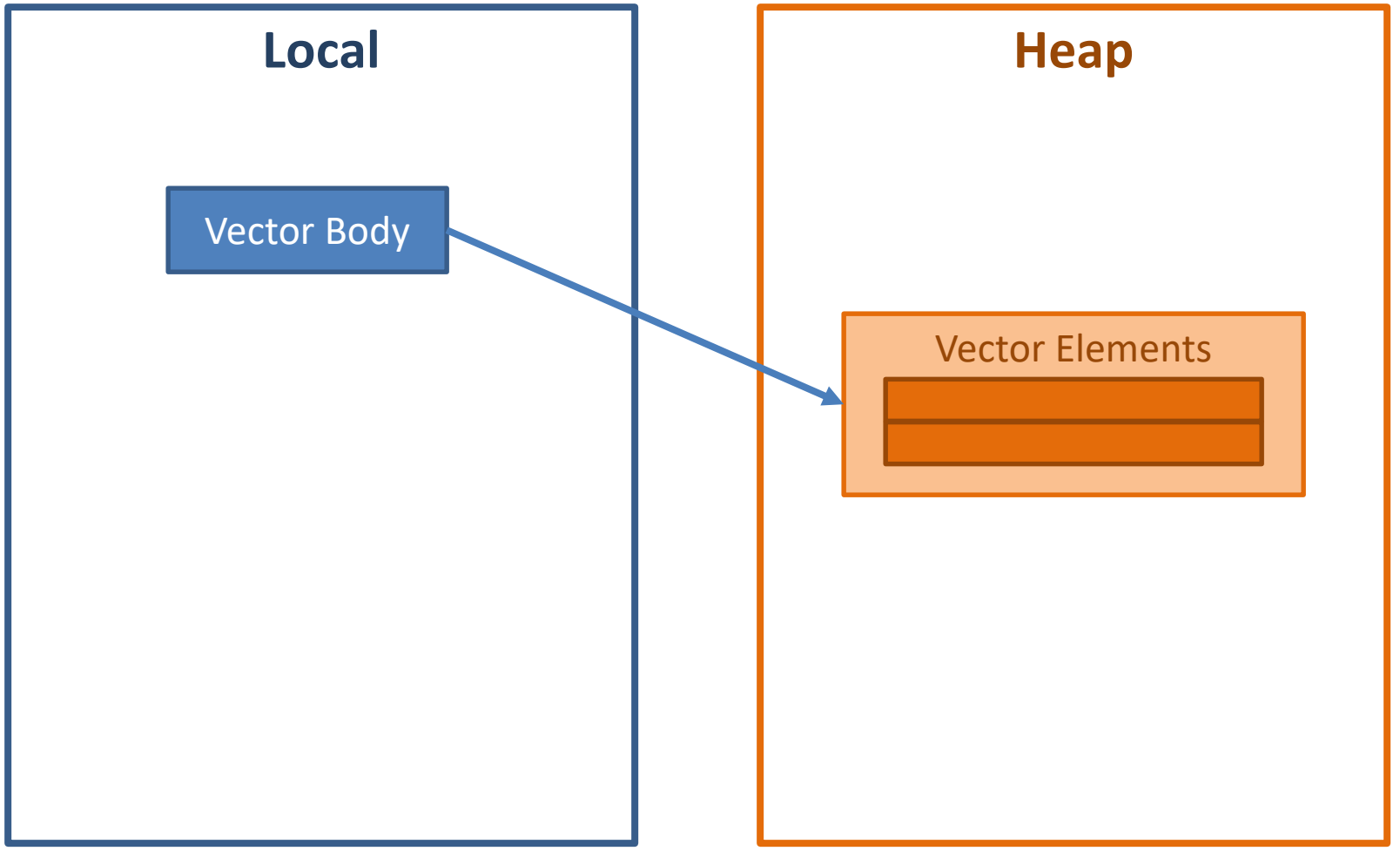
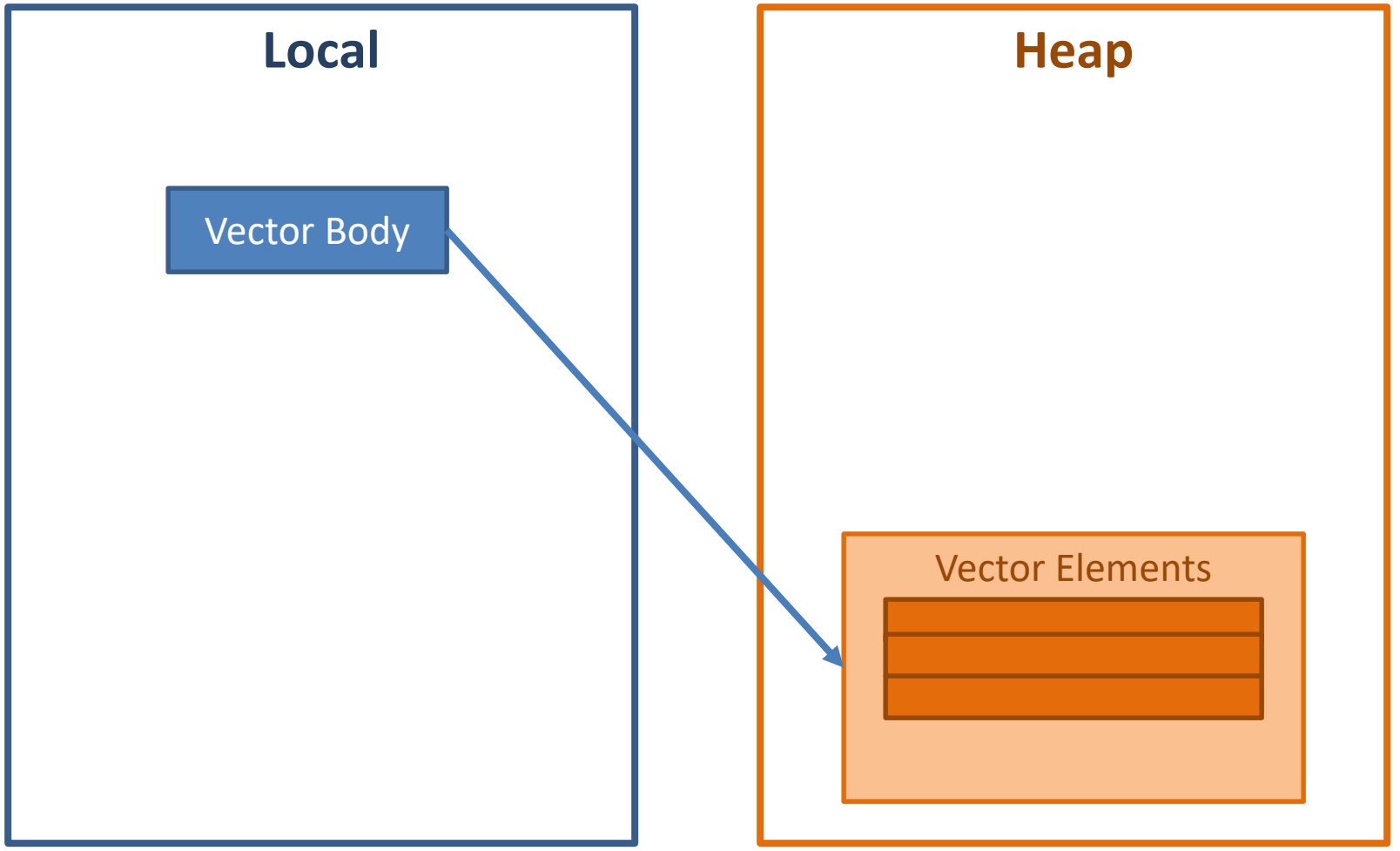


Allocation!

Vector – Growth



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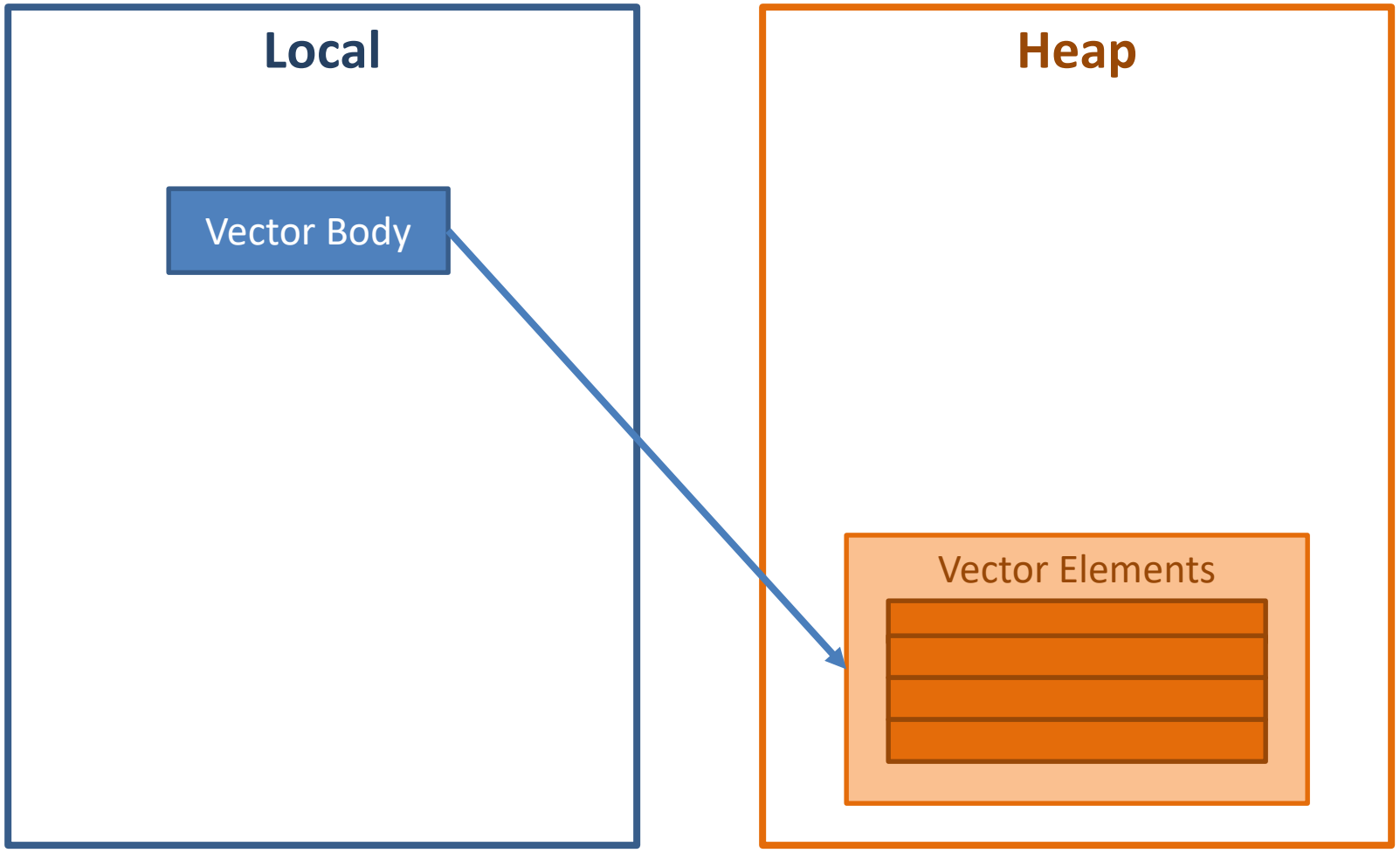
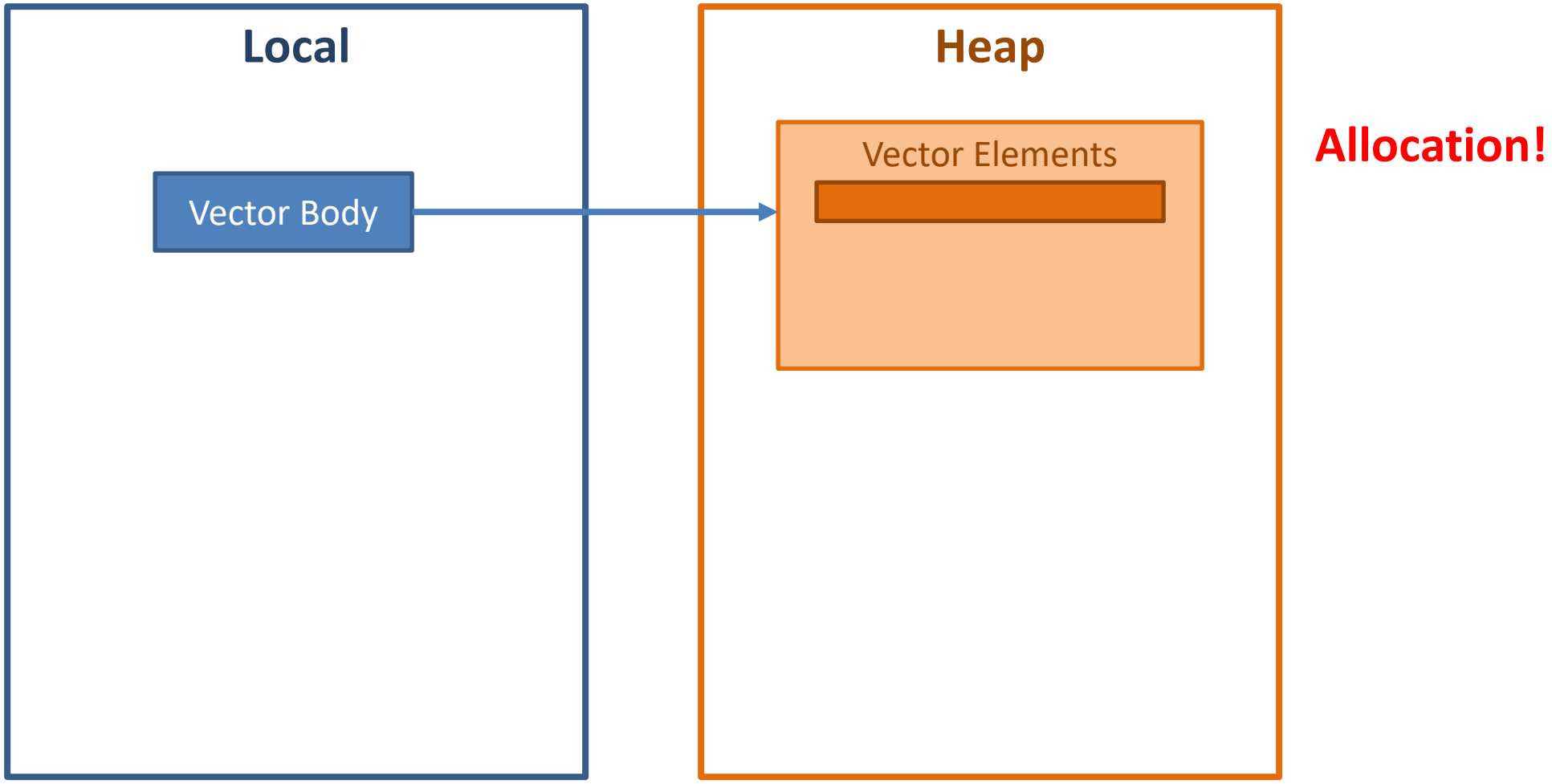


Vector – Growth with Reserve



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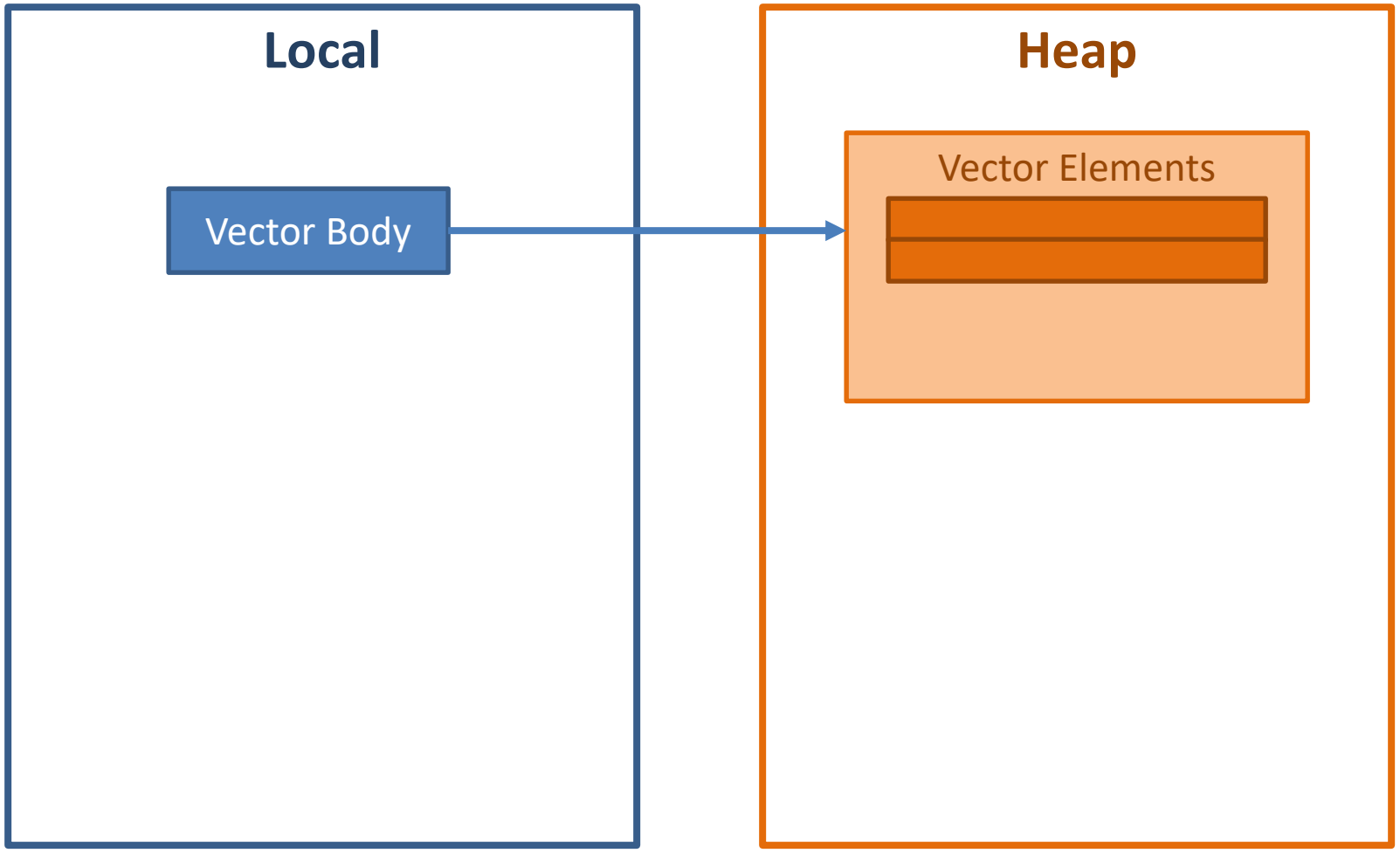

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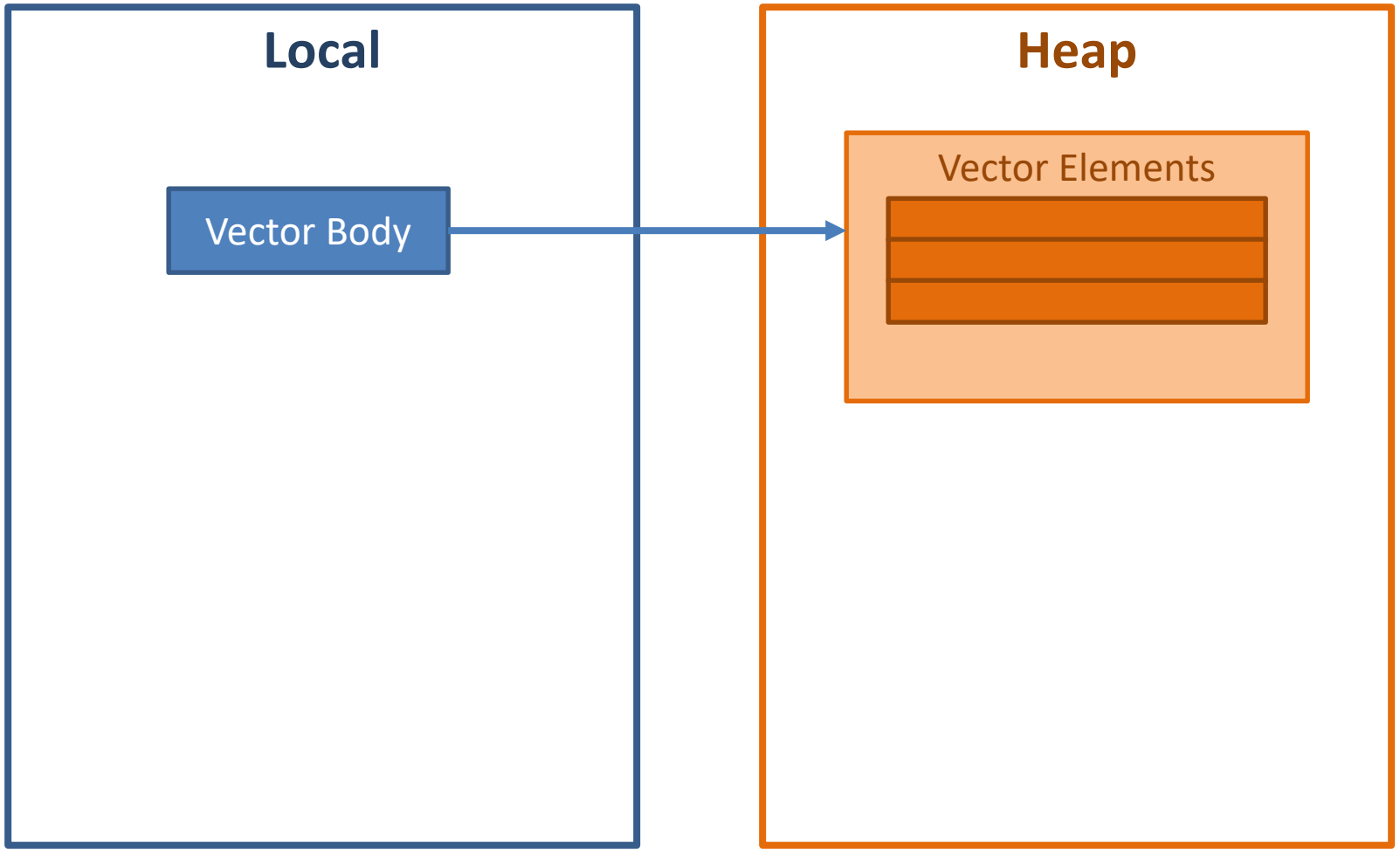

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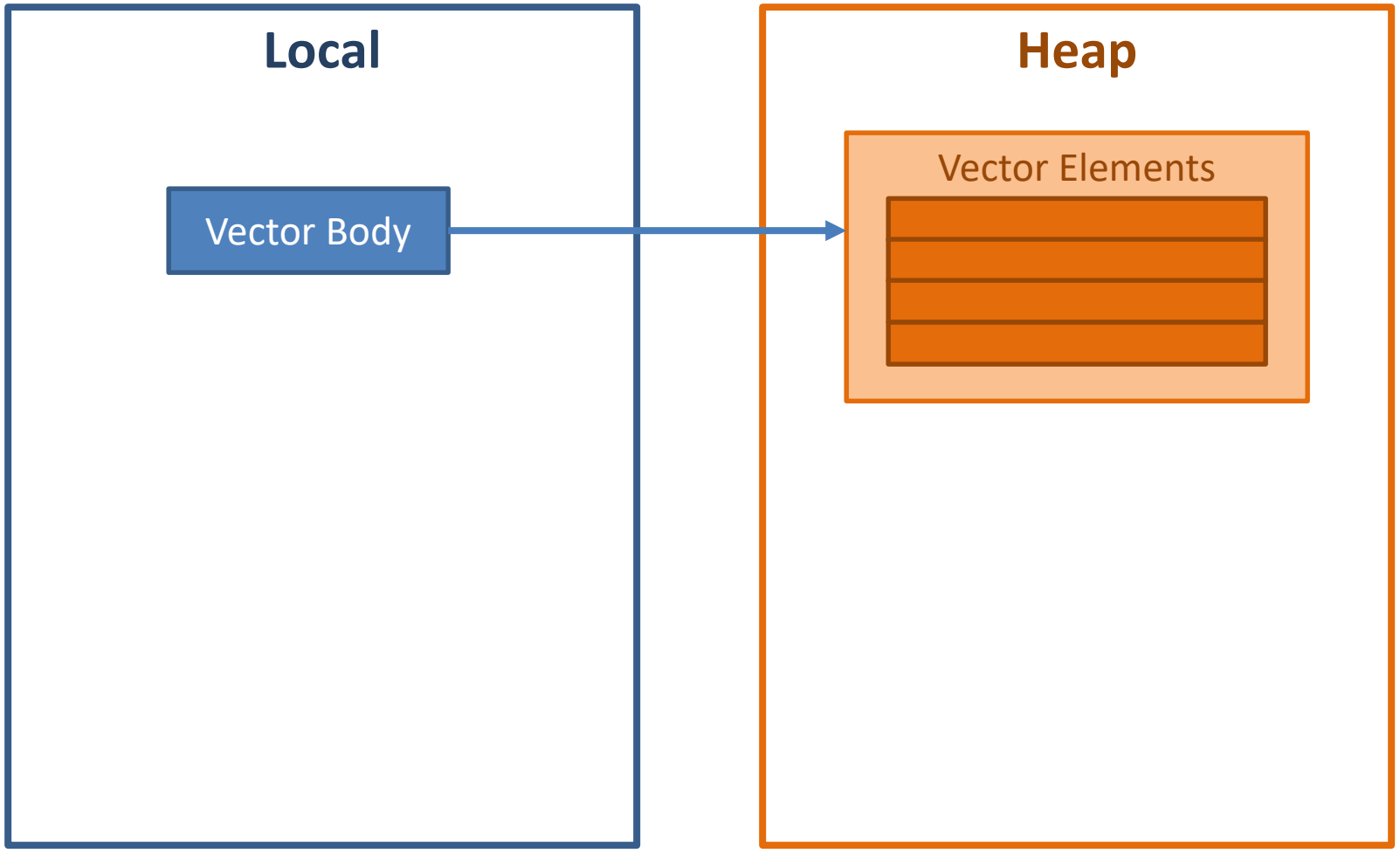

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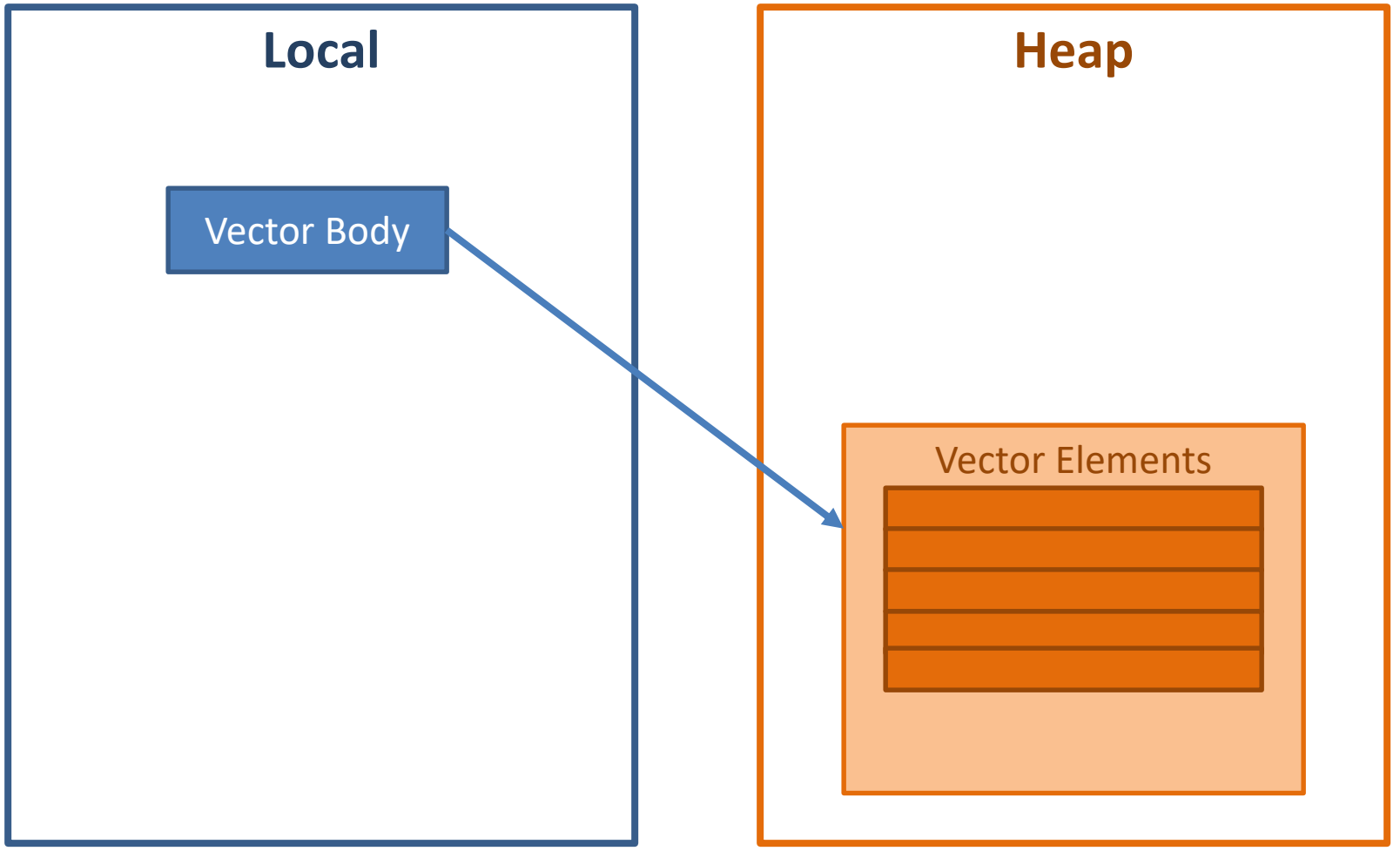
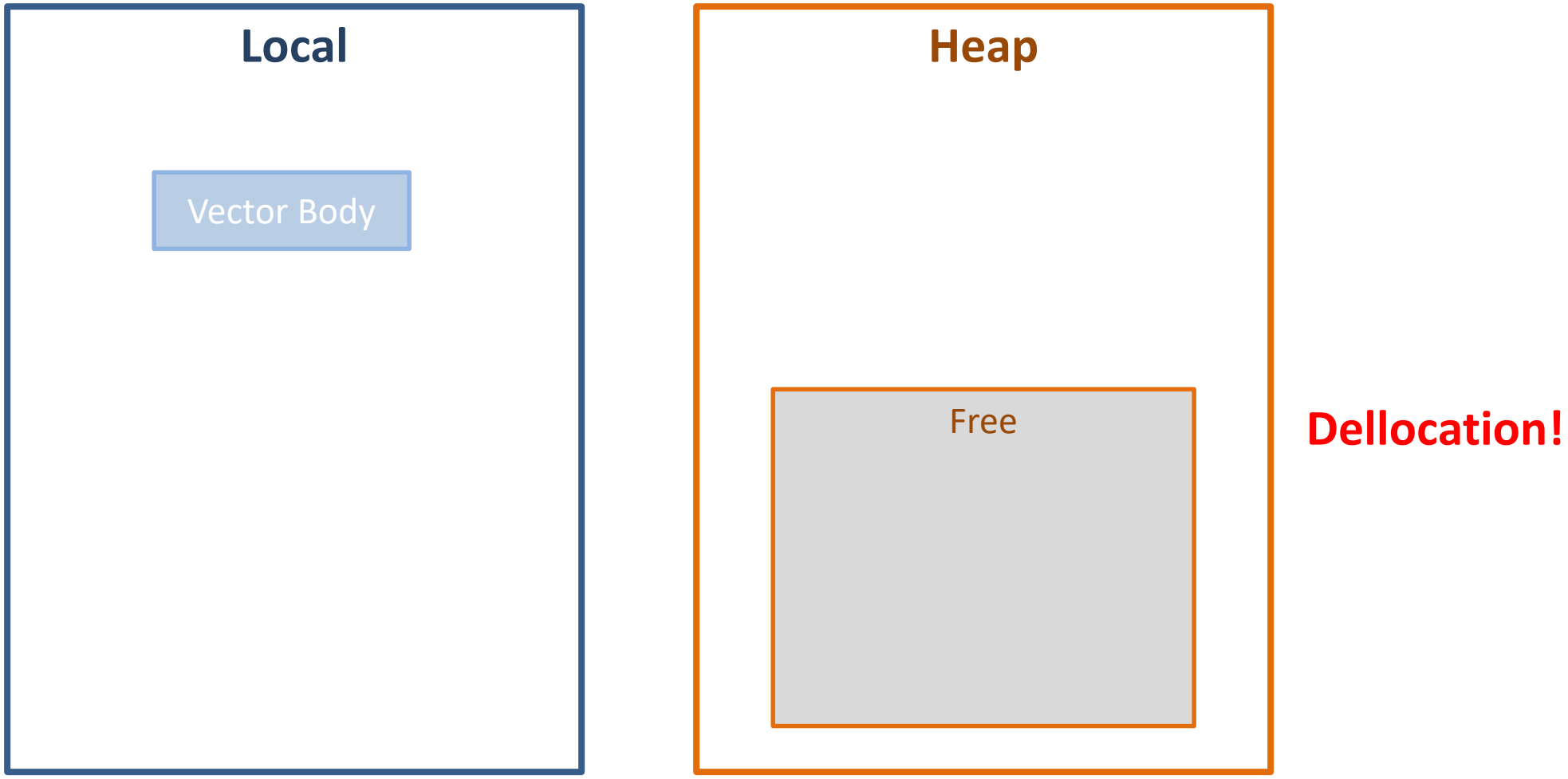


Allocation!

Vector – Creating Another



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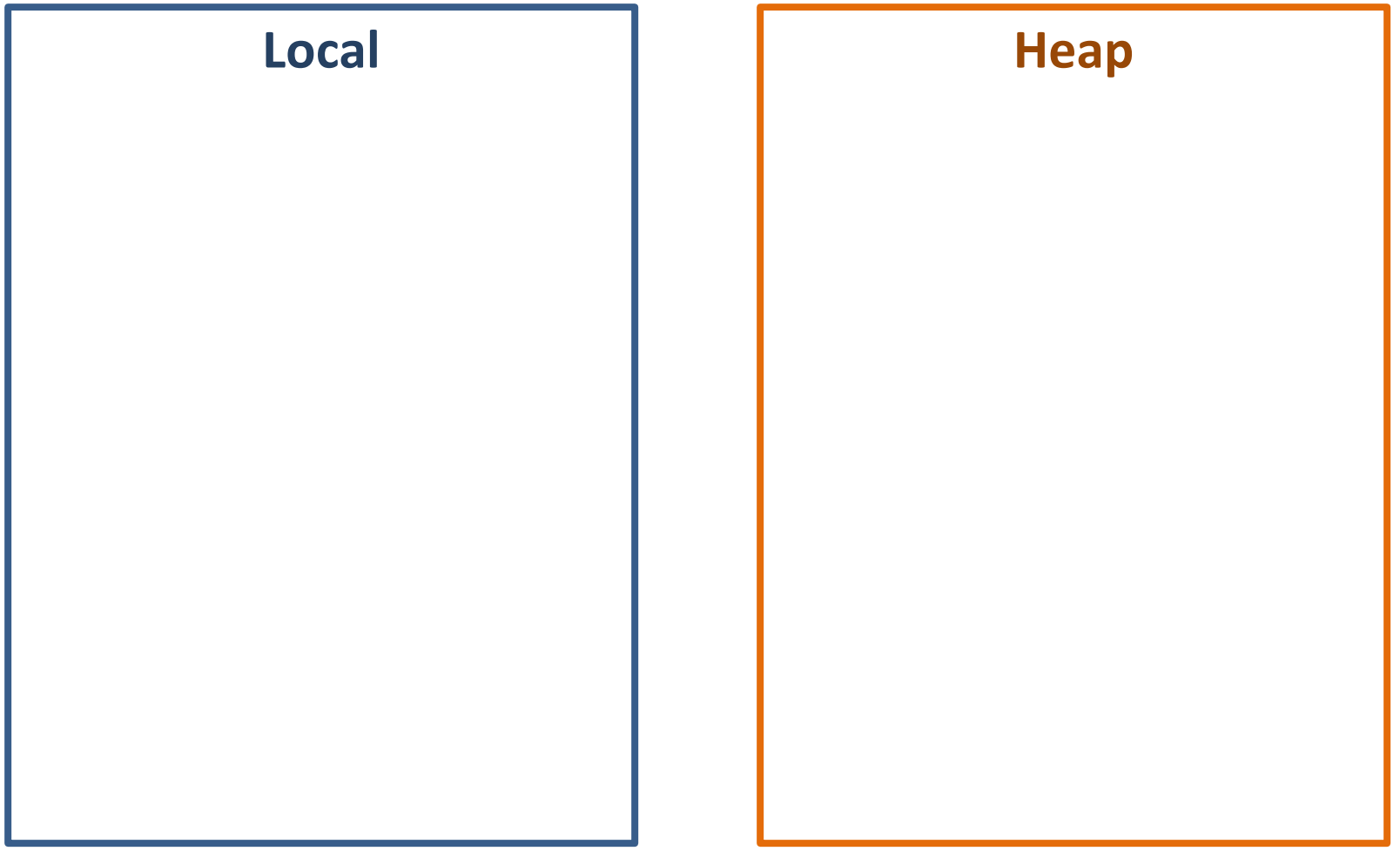
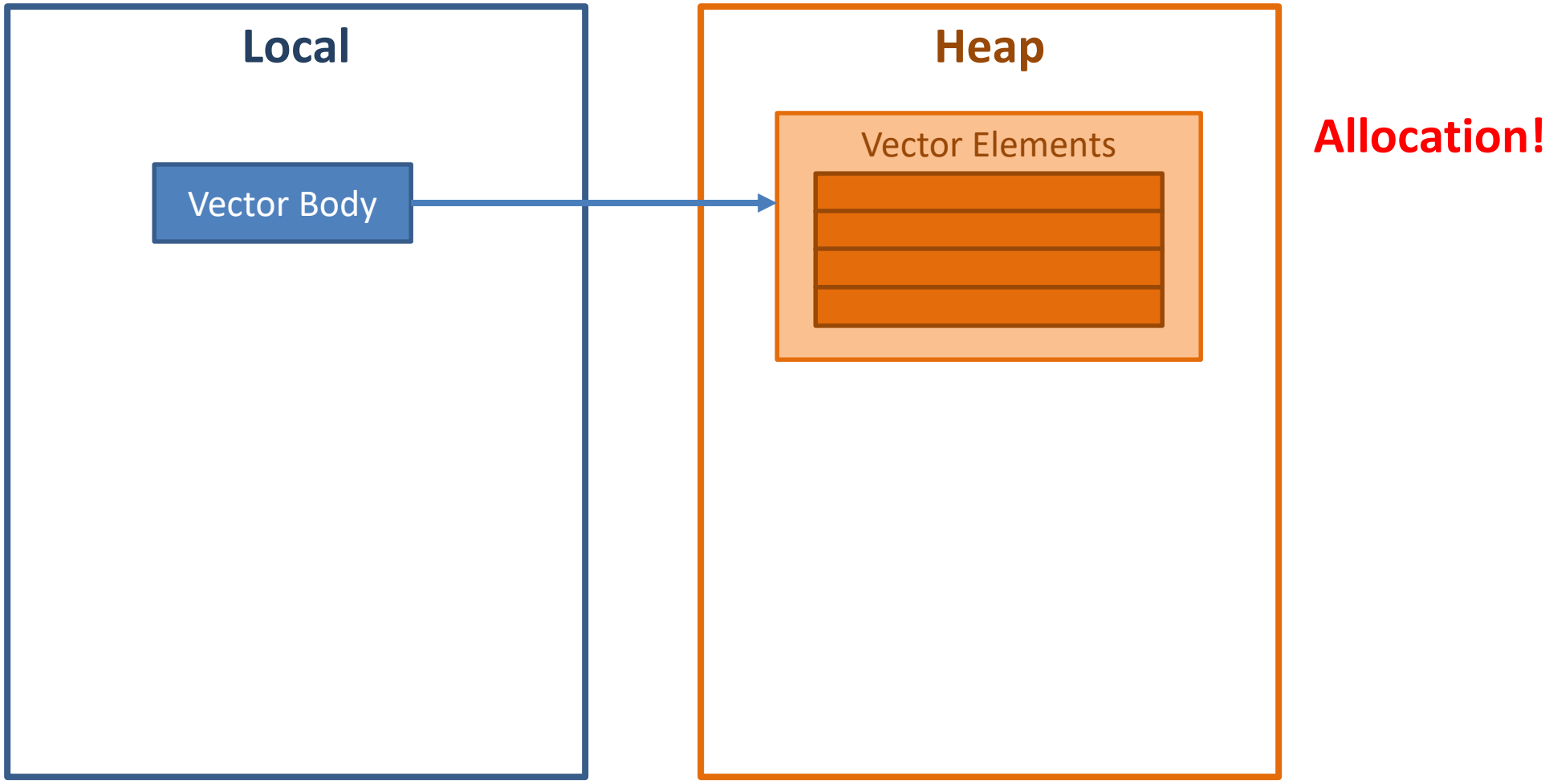
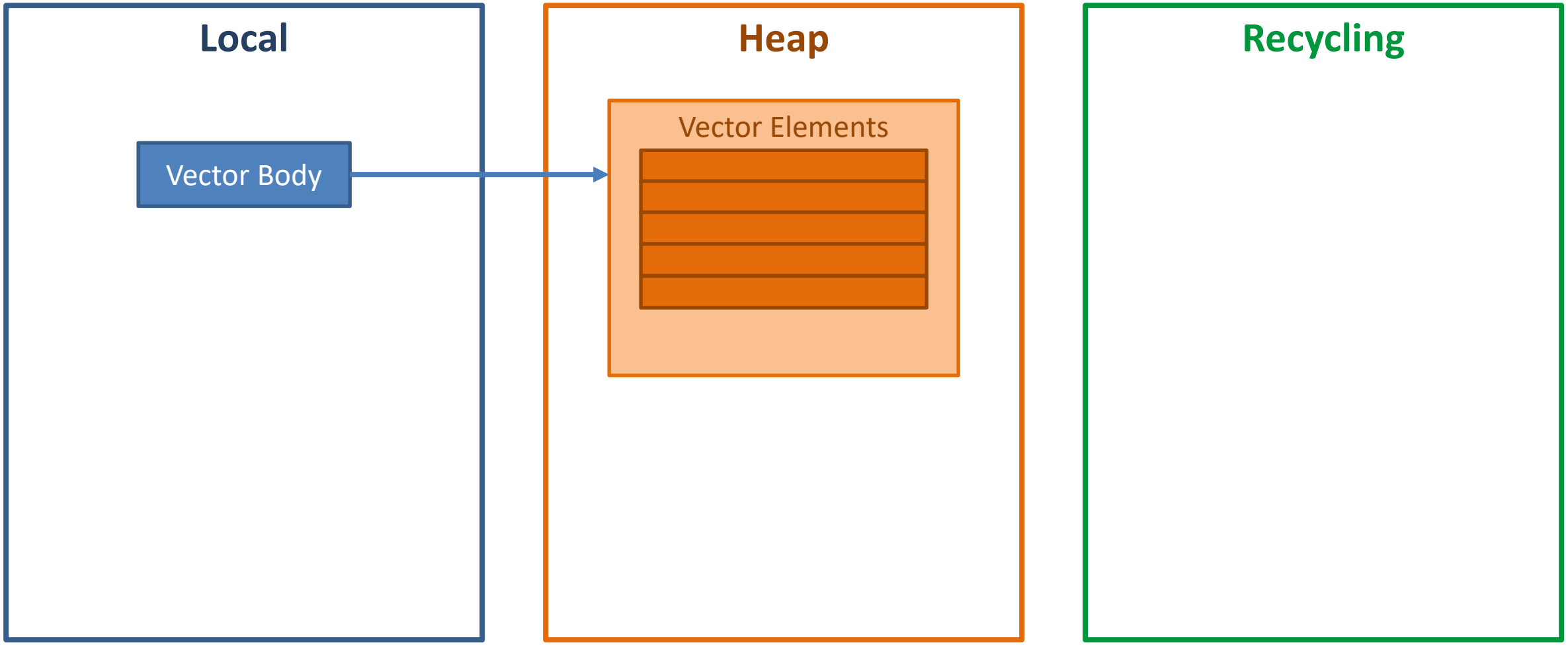


Vector – Creating Another



Vector – Recycling



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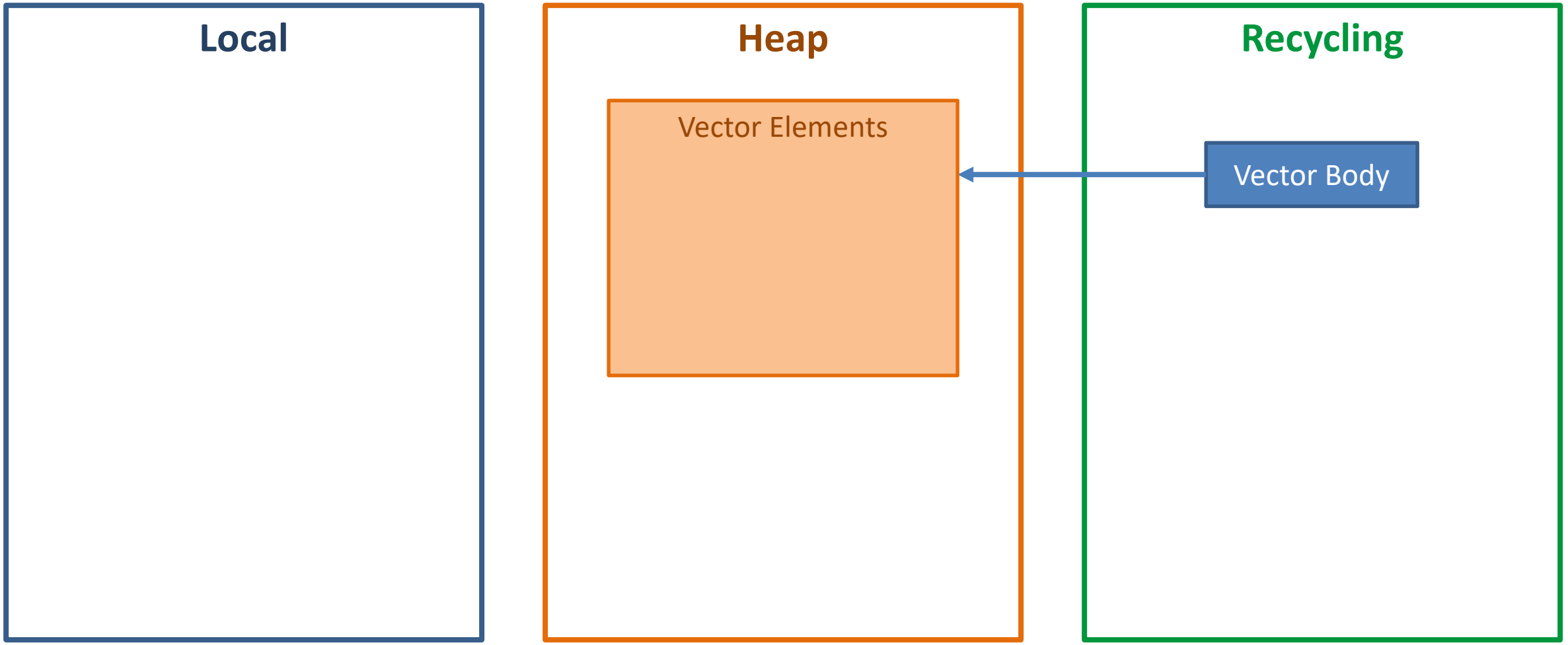

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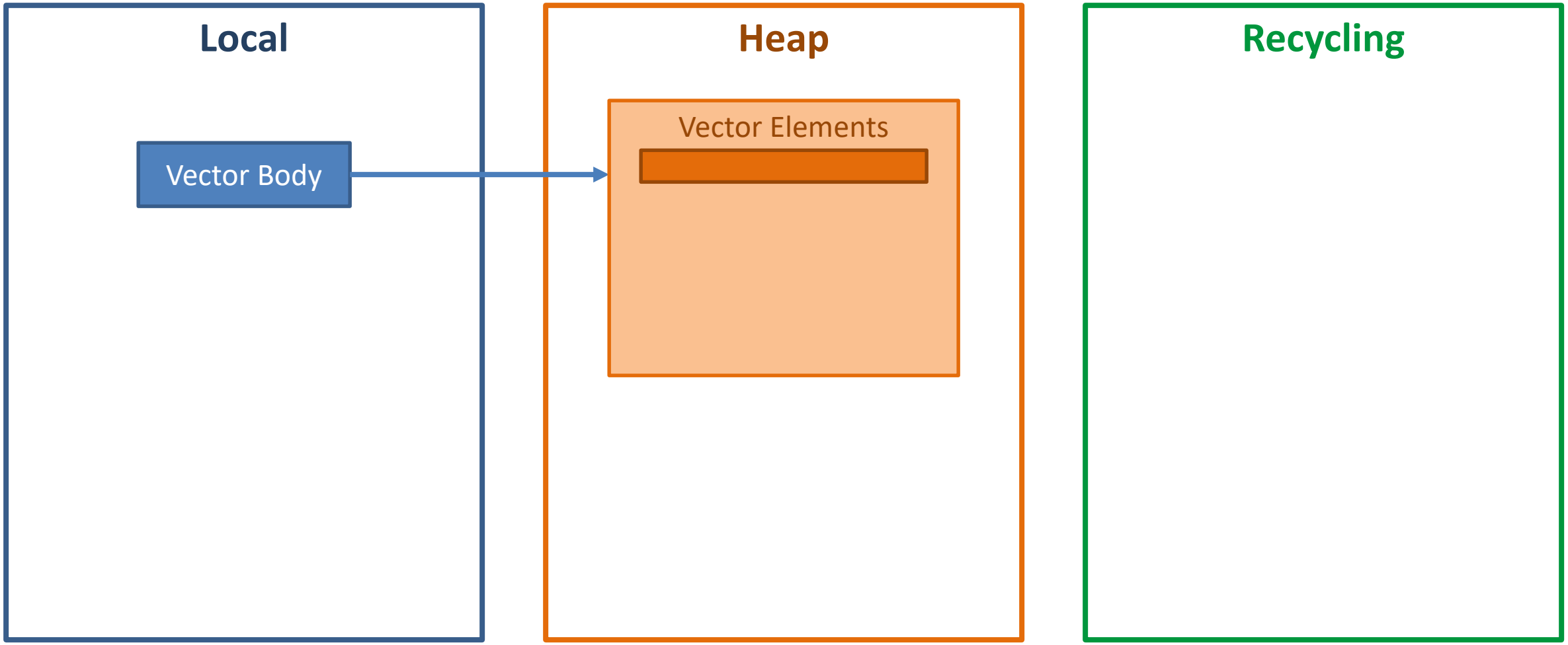

Vector – Recycling

```
struct number_list {
    number_list()
    {
        if (recycling.empty())
            numbers.reserve(X);
        else
        {
            numbers = move(recycling.back());
            recycling.pop_back();
        }
    }
    ~number_list()
    {
        numbers.clear();
        recycling.push_back(move(numbers));
    }
    vector<int> numbers;
    static vector<vector<int>> recycling;
};
```

```
number_list(const number_list& rhs)
: number_list()
{
    numbers = rhs.numbers;
}
```

Program Runs Slow

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  - It was a lot slower on the customer's laptop
- Ran 100 times slower at 0.1 sec time step than at 1.0 sec
  - That's exactly 10 times the work and 10 times the data generated
- Profiling revealed lots of time spent in **vector** allocation
  - But I was doing all the right things: reserving, using move semantics
- Ran fine at 1.0 sec with electrical system, or at 0.1 without
  - Electrical system generates lots more data per time step
- With **vector** recycling, simulation took 35 min (instead of 435)
  - **A speed up of over 12 times**

Lessons

- Don’t make assumptions - measure
  - Rules of thumb may not apply to pinkies
  - Results on a server may be very different than on a laptop
  - You may want to try several different approaches
- Know your containers
  - Basic complexity is not the whole story
  - Learn how all the standard containers work
  - Other containers may offer significant improvements
- Know what’s going on in memory
  - Heap allocations are expensive
  - Locality of reference is critical
  - Random access of main memory can be much slower than sliding things in cache

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