Recap from Last Time
Ordered Dictionaries

• An ordered dictionary maintains a set $S$ drawn from an ordered universe $\mathcal{U}$ and supports these operations:
  • $\text{lookup}(x)$, which returns whether $x \in S$;
  • $\text{insert}(x)$, which adds $x$ to $S$;
  • $\text{delete}(x)$, which removes $x$ from $S$;
  • $\text{max}()$ / $\text{min}()$, which return the maximum or minimum element of $S$;
  • $\text{successor}(x)$, which returns the smallest element of $S$ greater than $x$; and
  • $\text{predecessor}(x)$, which returns the largest element of $S$ smaller than $x$.

• Reasoning by analogy:
  \[
  \text{Ordered Dictionary} : \text{BST} :: \text{Queue} : \text{Linked List}
  \]
Our Machine Model

• We will assume we’re working on a machine where memory is segmented into \( w \)-bit words.

• Although on any one fixed machine \( w \) is a constant, in general, don’t assume this is the case. 32-bit was the norm until fairly recently, and before that 16-bit was standard.

• We’ll assume that the C integer operators work in constant time, and will not assume we have access to operators beyond them.

\[
+ - * / \% \ll \gg \& | \wedge = \leq
\]

• This restriction is somewhat arbitrary and has been revisited / questioned / refined by future work in this area. Come talk to me after class if you’re curious about this!
Integer Ordered Dictionaries

• Suppose that \( \mathcal{U} = [U] = \{0, 1, \ldots, U - 1\} \).

• The **y-Fast Trie** is an ordered dictionary structure for the set \([U]\) where all operations run in expected, amortized time \(O(\log \log U)\).
  
  • Note that when \( n = \omega(\log U) \), this is exponentially better than a binary search tree!

• Space usage is \( \Theta(n) \), where \( n \) is the number of elements in the trie.
New Stuff!
A Key Technique: *Word-Level Parallelism*
Word-Level Parallelism

- On a standard computer, arithmetic and logical operations on a machine word take time $O(1)$.
- We can perform certain classes of operations (addition, shifts, etc.) on $\Theta(w)$ bits in time $O(1)$.
  - Think of this as a weak form of parallel computation, where we can work over multiple bits in parallel with a limited set of operations.
- With some creativity, we can harness these primitives to build operations that run in time $O(1)$ but work on $\omega(1)$ objects.
- Let’s see a quick example...
Word-Level Parallelism

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## Word-Level Parallelism

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Word-Level Parallelism

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We’ve performed eight logical additions with a single add instruction!
The Landscape

• Preprocessing/runtime tradeoffs:
  “Yes, we have to do a lot of work, but it’s a one-time cost and everything is cheaper after that.”

• Randomization:
  “We might have to do a lot of work, but it’s unlikely that we’ll do so.”

• Amortization:
  “Yes, we have to do a lot of work every once and a while, but only after a period of doing very little.”

• Word-level parallelism:
  “We have to do a lot of work, but we don’t have to perform many operations to do it.”
Where We’re Going

• Today is all about using word-level parallelism to speed up integer data structures.

• Today, we’ll see two techniques:
  
  • First, the sardine tree, a fast ordered dictionary for extremely small integers.
  
  • Next, a technique for finding the most-significant bit of an integer in $O(1)$ machine operations.

• When we come back next time, we’ll see how to adapt these techniques into the fusion tree, an ordered dictionary for integers that fit into a machine word.
These actually aren’t called sardine trees. I couldn’t find a name for them anywhere and thought that this title was appropriate. Let me know if there’s a more proper name to associate with them!
The Setup

• Let \( w \) denote the machine word size.
• Imagine you want to store a collection of \( s \)-bit integers, where \( s \) is small compared to \( w \).
  • For example, storing 7-bit integers on a 64-bit machine would have \( s = 7 \) and \( w = 64 \).
• Can we build an ordered dictionary that takes advantage of the small key size?
A Refresher: B-Trees

- A **B-tree** is a multiway tree with a tunable parameter $b$ called the **order** of the tree.
- Each node stores $\Theta(b)$ keys. The height of the tree is $\Theta(\log_b n)$.
- Most operations (**lookup**, **insert**, **delete**, **successor**, **predecessor**, etc.) perform a top-down search of the tree, doing some amount of work per node.
- Runtime of each operation is $O(f(b) \log_b n)$, where $f(b)$ is the amount of work done per node.
B-Tree Lookups

- When performing a *lookup* of a key $k$ in a B-tree node, we need to determine how many keys in the node are less than or equal to $k$.
  - This is called the *rank* of $k$.
- For example, in the top node:
  
  $\text{rank}(40) = 0 \quad \text{rank}(74) = 2 \quad \text{rank}(107) = 3$
B-Tree Lookups

- Knowing \textit{rank}(k) in a particular node tells us which key to compare against and which child to descend into.

- \textit{Question:} How quickly can we determine \textit{rank}(k) in a B-tree node?
B-Tree Lookups

- We can determine \( \text{rank}(k) \) with a linear search in each B-tree node for a total lookup cost of \( O(b \cdot \log_b n) \).
- We can determine \( \text{rank}(k) \) with a binary search in each B-tree node for a total lookup cost of

\[
O(\log_b n \cdot \log b) = O(\log n).
\]
- **Claim:** If we can fit all the keys in a node into \( O(1) \) machine words, we can determine \( \text{rank}(k) \) in time \( O(1) \) for total lookup cost of \( O(\log_b n) \).
How is this possible?
Warmup: Comparing Two Values

- Imagine we have two $s$-bit integers $x$ and $y$ and want to determine whether $x \geq y$.
- How might we do this?

```
\begin{align*}
0 &\quad 1 \\
1 &\quad 1 &\quad 0 &\quad 0 \\
\underline{-} &\quad 0 &\quad 0 &\quad 1 &\quad 1 \\
1 &\quad 0 &\quad 0 &\quad 1
\end{align*}
```

```
\begin{align*}
? &\quad 0 &\quad 1 \\
0 &\quad 1 &\quad 0 &\quad 1 &\quad 1 \\
\underline{-} &\quad 1 &\quad 1 &\quad 0 &\quad 0 \\
 &\quad 1 &\quad 1
\end{align*}
```
Warmup: Comparing Two Values

- Imagine we have two $s$-bit integers $x$ and $y$ and want to determine whether $x \geq y$.
- How might we do this?

```
  1 1 1 0 0
- 0 0 0 1 1
  1 1 0 0 1
```

```
  1 0 1 1 1
- 0 1 1 0 0
  0 0 0 1 1
```
Warmup: Comparing Two Values

- Imagine we have two $s$-bit integers $x$ and $y$ and want to determine whether $x \geq y$.
- How might we do this?

This bit tells us whether the first number was at least as big as the second!
Comparing Multiple Values

- This technique can be extended to work on multiple values in parallel.
- For example, here’s how we’d compare eight pairs of 7-bit numbers by doing a single 64-bit subtraction:

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Comparing Multiple Values

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Comparing Multiple Values

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- For example, here’s how we’d compare eight pairs of 7-bit numbers by doing a single 64-bit subtraction:

```
11101110 10101110 11110000 11001101 10101111 10001101 11101111 11000001
- 00011010 01001011 00101000 00100000 01010000 00100010 01000100 00001000
  11010100 01101000 11100100 10101101 01011111 01011101 10110011 11011001
```
Comparing Multiple Values

- This technique can be extended to work on multiple values in parallel.
- For example, here's how we'd compare eight pairs of 7-bit numbers by doing a single 64-bit subtraction:

```
+-------------------+-------------------+-------------------+-------------------+-------------------+-------------------+-------------------+-------------------+
| 11101110 10101110 | 11111000 11001101 | 10101111 10001101 | 11101111 11000001 |
| 00011010 01001011  | 00010100 00100000  | 01010000 00100010  | 01001000 00010000  |
|-------------------+-------------------+-------------------+-------------------+-------------------+-------------------+-------------------+-------------------+
- 11010100 01101001 11100100 10101101 01011111 01101011 10110011 11011001
```
Comparing Multiple Values

- This technique can be extended to work on multiple values in parallel.
- For example, here’s how we’d compare eight pairs of 7-bit numbers by doing a single 64-bit subtraction:

```
 1101110 1010110 11111000 11001101 10101111 10001101 1110111 1100001
- 00011010 0100101 0010100 00100000 01010000 00100010 01000100 00001000
```

This technique is used in practice, including the glibc implementation of `strlen`. Thanks to former CS166 student Jane Lange for pointing this out!
Fundamental Primitive: *Parallel Compare*

1. Pack a list of values \( x_1, \ldots, x_k \) into a machine word \( X \), separated by 1s.

2. Pack a list of values \( y_1, \ldots, y_k \) into a machine word \( Y \), separated by 0s.

3. Compute \( X - Y \). The bit preceding \( x_i - y_i \) is 1 if \( x_i \geq y_i \) and 0 otherwise.

Assuming the packing can be done in \( O(1) \) time, this compares all the pairs is \( O(1) \) machine word operations.
Back to B-Trees

- **Recall:** The whole reason we’re interested in making these comparisons is so that we can find how many keys in a B-tree node are less than or equal to a query key \( k \).

- **Idea:** Store the (s-bit) keys in the B-tree node in a single (w-bit) machine word, with zeros interspersed:

<table>
<thead>
<tr>
<th>( y_1 )</th>
<th>( y_2 )</th>
<th>( y_3 )</th>
<th>( y_4 )</th>
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<td>41</td>
<td>93</td>
<td>103</td>
<td>106</td>
<td>107</td>
<td>109</td>
<td>110</td>
<td>127</td>
</tr>
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Back to B-Trees

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<tr>
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Rank in $O(1)$

- To perform a lookup for the key $k$, form a number by replicating $k$ multiple times with 1s interspersed.
### Rank in O(1)

- To perform a lookup for the key $k$, form a number by replicating $k$ multiple times with 1s interspersed.

<table>
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<tr>
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Rank in O(1)

- To perform a lookup for the key $k$, form a number by replicating $k$ multiple times with 1s interspersed.
- Subtract the B-tree key number from it to do a parallel comparison.
Rank in O(1)

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- Subtract the B-tree key number from it to do a parallel comparison.
Rank in $O(1)$

- To perform a lookup for the key $k$, form a number by replicating $k$ multiple times with 1s interspersed.
- Subtract the B-tree key number from it to do a parallel comparison.
- Count up how many of the sentinel bits in the resulting number are equal to 1. This is the number of keys in the node less than or equal to $k$.

```
1100111 1100111 1100111 1100111 1100111 1100111 1100111 1100111
- 00101001 01011101 01100111 01101010 01101011 01101101 01101110 01111111
```

Rank: 3
Back in Base Ten

• Suppose you have a one-digit number \( m \).

• You want to form this base-10 number:

\[
\text{mmm}
\]

• Is there a nice series of arithmetical operations that will produce this?

• \textbf{Answer:} Compute \( m \times 111 \).

• Why does this work?

\[
m \times 111 = m \times 100 + m \times 10 + m \times 1
\]

\[
= m00 + 0m0 + 00m
\]

\[
= \text{mmm}.
\]
Suppose you have a one-digit number \( m \).

You want to form this base-10 number:

\[
mmm
\]

Is there a nice series of arithmetical operations that will produce this?

**Answer:** Compute \( m \times 111 \).

Why does this work?

\[
m \times 111 = m \ll 2 + m \ll 1 + m \ll 0
\]

\[
= m00 + 0m0 + 00m
\]

\[
= mmm.
\]
Back in Base Ten

• Suppose you have a two-digit number $mn$.
• You want to form this base-10 number:

$$mn,mn,mn,mn$$

• Is there a nice series of arithmetical operations that will produce this?
• **Answer:** Compute $mn \times 10,101$.
• Why does this work?

$$mn \times 10,101 = mn \times 10,000 + mn \times 100 + mn \times 1$$

$$= mn0000 + 00mn00 + 0000mn$$

$$= mnmnmnmn.$$
Back in Base Ten

• Suppose you have a two-digit number $mn$.
• You want to form this base-10 number:
  
  $\underbrace{mnmnmn}$

• Is there a nice series of arithmetical operations that will produce this?

• **Answer:** Compute $mn \times 10,101$.

• Why does this work?

  
  \[
  mn \times 10,101 = mn \ll 4 + mn \ll 2 + mn \ll 0
  \]

  \[
  = mn0000 + 00mn00 + 0000mn
  \]

  \[
  = mnmnmnmn.
  \]
Back in Base Ten

- **Answer:** Compute $mn \times 10,101$.
- Why does this work?

\[
mn \times 10,101 = mn \ll 4 + mn \ll 2 + mn \ll 0 = mn0000 + 00mn00 + 0000mn = mnmnmnmn.
\]
Suppose you have a three-digit number $mnp$. You want to form this base-10 number:

$$mnp000mnp0mnp$$

Is there a nice series of arithmetical operations that will produce this?

**Answer:** Compute $mnp \times */\text{something} */$. 

$$mnp000mnp0mnp$$

$$= mnp \ll 10 + mnp \ll 4 + mnp \ll 0$$

$$= mnp \times 10^{10} + mnp \times 10^4 + mnp \times 10^0$$

$$= mnp \times 10,000,010,001$$
Back in Base Ten

- Suppose you have a three-digit number $mnp$.
- You want to form this base-10 number:

$$mnp000mnp0mnp$$

- Is there a nice series of arithmetical operations that will produce this?

**Answer:** Compute $mnp \times 10,000,010,001$.

$$mnp000mnp0mnp$$

$$= mnp \ll 10 + mnp \ll 4 + mnp \ll 0$$

$$= mnp \times 10^{10} + mnp \times 10^4 + mnp \times 10^0$$

$$= mnp \times 10,000,010,001$$
Computing Rank in $O(1)$

```c
const uint64_t kMultiplier = 0b1000000010000000...100000001;

uint64_t tiledK = k * kMultiplier;
```
Computing Rank in O(1)

```cpp
const uint64_t kMultiplier = 0b1000000010000000...100000001;

uint64_t tiledK = k * kMultiplier;
```
Fundamental Primitive: *Parallel Tile*

1. Form a number $M$ with a 1 bit at the end of each location to tile $k$.

2. Compute $M \times k$.

Assuming step (1) can be done in time $O(1)$, this produces many copies of $k$ in time $O(1)$. 
Computing Rank in $O(1)$

```cpp
const uint64_t kMultiplier = 0b1000000010000000...100000001;

uint64_t tiledK = k * kMultiplier;
```
Computing Rank in O(1)

const uint64_t kMultiplier = 0b10000000010000000...100000001;
const uint64_t kOnesMask   = 0b10000000010000000...010000000;

uint64_t tiledK = k * kMultiplier;

\[
\begin{array}{ccccccccccc}
  k & k & k & k & k & k & k & k & k & k \\
1100111 & 1100111 & 1100111 & 1100111 & 1100111 & 1100111 & 1100111 & 1100111 & 1100111 \\
\end{array}
\]
Computing Rank in O(1)

```cpp
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask   = 0b1000000010000000...010000000;

uint64_t tiledK = (k * kMultiplier) | kOnesMask;
```
Computing Rank in O(1)

const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask   = 0b1000000010000000...010000000;

uint64_t tiledK     = (k * kMultiplier) | kOnesMask;

11100111 11100111 11100111 11100111 11100111 11100111 11100111 11100111
00101001 01011101 01100111 01101010 01101011 01101101 01101110 01111111
Computing Rank in O(1)

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const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask   = 0b1000000010000000...010000000;

uint64_t tiledK     = (k * kMultiplier) | kOnesMask;
uint64_t comparison =  tiledK - packedKeys;
```

```
11100111  11100111  11100111  11100111  11100111  11100111  11100111  11100111
-  00101001  0101101  01100111  01101010  01101011  01101101  01101110  01111111
  10111110  10001010  10000000  01111101  01111100  01111010  01111001  01101000
```
Computing Rank in O(1)

```cpp
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask   = 0b1000000010000000...010000000;

uint64_t tiledK = (k * kMultiplier) | kOnesMask;
uint64_t comparison = (tiledK - packedKeys) & kOnesMask;
```

How do we count how many of these bits are set?
Summing Up Flags

- After performing our subtraction, we’re left with a number like this one, where the highlighted bits are “interesting” to us.

- **Goal:** Add up these “interesting” values using $O(1)$ word operations.
An Initial Idea

- To sum up the flags, we could extract each bit individually and add the result.

- **The catch:** This takes time $\Theta(r)$, where $r$ is the number of times we tiled our value.

- Can we do better?

  a00000000  b00000000  c00000000  d00000000
A Shifty Solution

• Given this number:

\[ a0000000 \quad b0000000 \quad c0000000 \quad d0000000 \]

we want to compute \( a + b + c + d \).

• We can’t efficiently isolate \( a, b, c, \) and \( d \).

• \textbf{Claim:} We don’t have to!

\[ + \quad a \]

\[ + \quad b \]

\[ + \quad c \]

\[ + \quad d \]
A Shifty Solution

• Given this number:
  \[ a0000000 \quad b0000000 \quad c0000000 \quad d0000000 \]
  we want to compute \( a + b + c + d \).

• We can’t efficiently isolate \( a, b, c, \) and \( d \).

• **Claim:** We don’t have to!

\[
\begin{array}{c}
  d \\
  c \\
  b \\
  + \\
  \hline \\
  a \\
\end{array}
\]
A Shifty Solution

• Given this number:

\[
\begin{array}{cccc}
  a & 0 & 0 & 0 \\
  b & 0 & 0 & 0 \\
  c & 0 & 0 & 0 \\
  d & 0 & 0 & 0 \\
\end{array}
\]

we want to compute \( a + b + c + d \).

• We can’t efficiently isolate \( a, b, c, \) and \( d \).

• **Claim:** We don’t have to!

\[
\begin{array}{cccc}
  & d \\
  c \\
  b \\
  + \quad a & 0 & 0 & 0 \\
  b & 0 & 0 & 0 \\
  c & 0 & 0 & 0 \\
  d & 0 & 0 & 0 \\
\end{array}
\]

\[
\begin{array}{cccc}
  a & 0 & 0 & 0 \\
  b & 0 & 0 & 0 \\
  c & 0 & 0 & 0 \\
  d & 0 & 0 & 0 \\
\end{array}
\]
A Shifty Solution

• Given this number:

\[ \begin{array}{cccc}
a & b & c & d \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{array} \]

we want to compute \( a + b + c + d \).

• We can’t efficiently isolate \( a, b, c, \) and \( d \).

• Claim: We don’t have to!

\[ \begin{array}{cccc}
a & b & c & d \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{array} \]

\[ \begin{array}{cccc}
a & b & c & d \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{array} \]

\[ + \]

\[ \begin{array}{cccc}
a & b & c & d \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{array} \]

\[ \begin{array}{cccc}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{array} \]
A Shifty Solution

• Given this number:

\[
\begin{array}{cccc}
  a & b & c & d \\
\end{array}
\]

we want to compute \( a + b + c + d \).

• We can’t efficiently isolate \( a, b, c, \) and \( d \).

• **Claim:** We don’t have to!

\[
\begin{array}{cccc}
  d \\
  a & b & c & d \\
  a & b & c & d \\
  + & a & b & c & d \\
\end{array}
\]
A Shifty Solution

• Given this number:

    a0000000 b0000000 c0000000 d0000000

    we want to compute a + b + c + d.

• We can’t efficiently isolate a, b, c, and d.

• **Claim:** We don’t have to!

    a0000000 b0000000 c0000000 d0000000 00000000 00000000 00000000

    a0000000 b0000000 c0000000 d0000000 00000000 00000000

    a0000000 b0000000 c0000000 d0000000 00000000

    + a0000000 b0000000 c0000000 d0000000

    ___________________________

    a0000000 b0000000 c0000000 d0000000
A Shifty Solution

• Given this number:

\[\begin{array}{cccc}
a & b & c & d \\
0 & 0 & 0 & 0 \\
\end{array}\]

we want to compute \(a + b + c + d\).

• We can’t efficiently isolate \(a\), \(b\), \(c\), and \(d\).

• \textit{Claim:} We don’t have to!

\[\begin{array}{cccc}
a & b & c & d \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{array}\]

\[\begin{array}{cccc}
a & b & c & d \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{array}\]
A Shifty Solution

• Given this number:

\[
\begin{align*}
\text{a0000000} & \quad \text{b0000000} & \quad \text{c0000000} & \quad \text{d0000000} \\
\text{a0000000} & \quad \text{b0000000} & \quad \text{c0000000} & \quad \text{d0000000} \\
\text{a0000000} & \quad \text{b0000000} & \quad \text{c0000000} & \quad \text{d0000000} \\
\text{a0000000} & \quad \text{b0000000} & \quad \text{c0000000} & \quad \text{d0000000} \\
\end{align*}
\]

we want to compute \(a + b + c + d\).

• We can’t efficiently isolate \(a, b, c,\) and \(d\).

• **Claim:** We don’t have to!

\[
\begin{align*}
\text{a0000000} & \quad \text{b0000000} & \quad \text{c0000000} & \quad \text{d0000000} \\
\text{a0000000} & \quad \text{b0000000} & \quad \text{c0000000} & \quad \text{d0000000} \\
\text{a0000000} & \quad \text{b0000000} & \quad \text{c0000000} & \quad \text{d0000000} \\
\text{a0000000} & \quad \text{b0000000} & \quad \text{c0000000} & \quad \text{d0000000} \\
\end{align*}
\]

This is a series of shifts and adds. It’s equivalent to multiplying our original number by some well-chosen spreader!
Fundamental Primitive: **Parallel Add**

1. Perform a *parallel tile* with an appropriate multiplier to place all leading bits on top of one another.

2. Use a bitmask and bitshift to isolate those bits.

Assuming the multiplier for part (1) and the mask and shift for part (2) can be computed in time $O(1)$, this takes time $O(1)$. 
Computing Rank in O(1)

```
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask = 0b1000000010000000...010000000;

uint64_t tiledK = (k * kMultiplier) | kOnesMask;
uint64_t comparison = (tiledK - packedKeys) & kOnesMask;
```
Computing Rank in O(1)

```c
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask   = 0b1000000010000000...010000000;

uint64_t tiledK     = (k * kMultiplier) | kOnesMask;
uint64_t comparison = (tiledK – packedKeys) & kOnesMask;

const uint64_t kStacker = 0b10000001000000...10000001;
const uint8_t  kShift   = 31;
const uint64_t kMask    = 0b111;

uint64_t rank = comparison * kStacker;
```
Computing Rank in O(1)

```c
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask   = 0b1000000010000000...010000000;
uint64_t tiledK     = (k * kMultiplier) | kOnesMask;
uint64_t comparison = (tiledK – packedKeys) & kOnesMask;
const uint64_t kStacker = 0b1000000010000000...100000001;

uint64_t rank = comparison * kStacker;
```

```
 a0000000 b0000000 c0000000 d0000000 00000000 00000000 00000000
+ a0000000 b0000000 c0000000 d0000000 00000000 00000000 00000000
---------------------------
 a0000000 b0000000 c0000000 d0000000 00000000 00000000 00000000
```
Computing Rank in $O(1)$

```c
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask   = 0b1000000010000000...010000000;

uint64_t tiledK     = (k * kMultiplier) | kOnesMask;
uint64_t comparison = (tiledK – packedKeys) & kOnesMask;

const uint64_t kStacker = 0b1000000010000000...100000001;

const uint8_t kShift   = 31;
const uint64_t kMask    = 0b111;

uint64_t rank =   comparison * kStacker;
```

```

```
```
Computing Rank in O(1)

```c
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask = 0b1000000010000000...010000000;

uint64_t tiledK = (k * kMultiplier) | kOnesMask;
uint64_t comparison = (tiledK - packedKeys) & kOnesMask;

const uint64_t kStacker = 0b10000001000000...10000001;
const uint8_t kShift = 31;

uint64_t rank = comparison * kStacker;
```

```plaintext

```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
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```
```
```
```
```
```
```

```c
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask = 0b1000000010000000...010000000;

uint64_t tiledK = (k * kMultiplier) | kOnesMask;
uint64_t comparison = (tiledK - packedKeys) & kOnesMask;

const uint64_t kStacker = 0b10000001000000...10000001;
const uint8_t kShift = 31;

uint64_t rank = comparison * kStacker;
```
**Computing Rank in O(1)**

```c
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask   = 0b1000000010000000...010000000;

uint64_t tiledK     = (k * kMultiplier) | kOnesMask;
uint64_t comparison = (tiledK - packedKeys) & kOnesMask;

const uint64_t kStacker = 0b10000001000000...10000001;
const uint8_t kShift   = 31;

uint64_t rank = (comparison * kStacker) >> kShift;
```

```
a00000000 b00000000 c00000000 d00000000 00000000 00000000 00000000 00000000
  a00000000 b00000000 c00000000 d00000000 00000000 00000000 00000000 00000000
  a00000000 b00000000 c00000000 d00000000 00000000 00000000 00000000 00000000
  a00000000 b00000000 c00000000 d00000000 00000000 00000000 00000000 00000000
  a00000000 b00000000 c00000000 d00000000 00000000 00000000 00000000 00000000
+   a00000000 b00000000 c00000000 d00000000 00000000 00000000 00000000 00000000
  ????????? ????????? ????????? ????????? ????????? ????????? ??????sum
```
Computing Rank in O(1)

```c
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask   = 0b1000000010000000...010000000;

uint64_t tiledK     = (k * kMultiplier) | kOnesMask;
uint64_t comparison = (tiledK - packedKeys) & kOnesMask;

const uint64_t kStacker = 0b10000001000000...10000001;
const uint8_t  kShift   = 31;
const uint64_t kMask    = 0b111;

uint64_t rank = (comparison * kStacker) >> kShift;
```

```
+  a0000000 b0000000 c0000000 d0000000 00000000 00000000 00000000 00000000
   a0000000 b0000000 c0000000 d0000000 00000000 00000000 00000000 00000000
   a0000000 b0000000 c0000000 d0000000 00000000 00000000 00000000 00000000

???????? ????????? ????????? ????????? ????????? ????????? sum
```
Computing Rank in O(1)

```c
const uint64_t kMultiplier = 0b1000000010000000...100000001;
const uint64_t kOnesMask   = 0b1000000010000000...010000000;

uint64_t tiledK = (k * kMultiplier) | kOnesMask;
uint64_t comparison = (tiledK – packedKeys) & kOnesMask;

const uint64_t kStacker = 0b10000001000000...10000001;
const uint8_t  kShift   = 31;
const uint64_t kMask    = 0b111;

uint64_t rank = ((comparison * kStacker) >> kShift) & kMask;
```

```
+  a0000000 b0000000 c0000000 d0000000
  a0000000 b0000000 c0000000 d0000000
  a0000000 b0000000 c0000000 d0000000
  a0000000 b0000000 c0000000 d0000000
  a0000000 b0000000 c0000000 d0000000

sum
```
Fundamental Primitive: *Parallel Rank*

1. Perform a *parallel tile* to create \( n \) copies of the key \( k \), prefixed by 1’s.

2. Perform a *parallel compare* of the key \( k \) against values \( x_1, \ldots, x_n \).

3. Perform a *parallel add* to sum those values into some total \( t \).

4. Return \( t \).

Assuming the parallel compare and parallel have their internal constants computed in advance, this runs in time \( O(1) \).
The Sardine Tree

- Let $w$ be the word size and $s$ be some (much) smaller number of bits.

- A **sardine tree** is a B-tree of order $\Theta(w/s)$ where the keys in a node are packed into a single machine word.
  - Get it? The keys are “packed” tightly into a machine word! I’m funny.

- Each node is annotated with several values (the masks and multipliers from the preceding slide), which are updated in time $O(1)$ whenever a key is added or removed.

- Supports all ordered dictionary operations in time $O(\log_b n) = O(\log_{w/s} n)$. 
The Scorecard

● Here’s the performance breakdown for the sardine tree.

● Notice that the runtime performance is strictly better than that of a BST!

● Notice that the space usage is sublinear, since each node stores multiple keys!

The Sardine Tree

- **lookup**: $O(\log_{w/s} n)$
- **insert**: $O(\log_{w/s} n)$
- **delete**: $O(\log_{w/s} n)$
- **max**: $O(\log_{w/s} n)$
- **succ**: $O(\log_{w/s} n)$
- Space: $\Theta(n \cdot s/w)$
For Comparison

• Here’s what that would look like if we used a y-fast trie instead.

• Since our keys range from 0 to $2^s - 1$ and the y-fast trie operations take time $O(\log \log U)$, each operation takes time $O(\log s)$.

The y-Fast Trie

• **lookup**: $O(\log s)$
• **insert**: $O(\log s)^*$
• **delete**: $O(\log s)^*$
• **max**: $O(\log s)$
• **succ**: $O(\log s)$
• Space: $\Theta(n)$

* Expected, amortized
Time-Out for Announcements!
Problem Sets

- Problem Set Five was due at 2:30PM today.
  - Using late days, you can submit it up until Thursday at 2:30PM.
- **Congrats! You’re done with the CS166 problem sets!**
Take-Home Exam

• The take-home midterm is now available online, and hardcopies are available up front.

• It’s due Thursday at 2:30PM on GradeScope.

• **Best of luck on the exam!** Seriously, we hope you all knock this one out of the park.
Back to CS166!
Word-Level Parallelism Tricks #2: Most-Significant Bits
Most-Significant Bits

• The most-significant bit function, denoted $\text{msb}(n)$, outputs the index of the highest 1 bit set in the binary representation of number $n$.

• Some examples:

\[
\text{msb}(0110) = 2 \quad \text{msb}(010100) = 4 \quad \text{msb}(1111) = 3
\]

• Note that $\text{msb}(0)$ is undefined.

• Mathematically, $\text{msb}(n)$ is the largest value of $k$ such that $2^k \leq n$. (Do you see why?)
Most-Significant Bits

• Although we didn’t have this name earlier in the quarter, you’ve seen a place where we needed to efficiently compute $\text{msb}(n)$.

• Do you remember where?

• **Answer:** In the sparse table RMQ structure, where computing $\text{RMQ}(i, j)$ requires computing the largest number $k$ where $2^k \leq j - i + 1$.

• That’s exactly the value of $\text{msb}(j - i + 1)$!
Most-Significant Bits

- On many architectures, there’s a single assembly instruction that computes $\text{msb}(n)$.
  - on x86, it’s `BSR (bit scan reverse)).
- On others, nothing like this exists.
  - MIPS, for example.
- **Question:** How would we compute $\text{msb}(n)$ assuming we only have access to the regular C operators?

  ```plaintext
  +  -  *  /  %  <<  >>  &  |  ^  ==  <=
  ```
Computing $\text{msb}$

- In Problem Set 1, you (probably) computed $\text{msb}(n)$ by building a lookup table mapping each value of $n$ to $\text{msb}(n)$.

- **The Good:** This takes time $O(1)$ to evaluate.

- **The Bad:** The preprocessing time, and space usage, is $\Theta(U)$, where $U$ is the maximum value we’ll be querying for.

- **The Ugly:** In the worst case $U = 2^w$.

- Can we do better?
Most-Significant Bits

• There’s a simple $O(w)$-time algorithm for computing \( \text{msb}(n) \) that just checks all the bits until a 1 is found:

```c
for (uint8_t bit = 64; bit > 0; bit--)
{
    if (n & (uint64_t(1) << (bit - 1)))
    {
        return bit;
    }
}
flailAndPanic();
```

• Can we do better?
Computing `msb`

- We can improve this runtime to $O(\log w)$ by using a binary search:
  - Check if any bits in the bottom half of the bits of $n$ are set.
  - If so, recursively explore the upper half of $n$.
  - If not, recursively explore the lower half of $n$.
- We can test whether any bit in a range is set by ANDing with a mask of 1s and seeing if the result is nonzero:

```
  11011100 10110111 11000100 11010101 11100110 11110111 11000010 00110010
^ 11111111 11111111 11111111 11111111 00000000 00000000 00000000 00000000
```

- Can we do better?
**Claim:** For any machine word size $w$, there is an algorithm that uses $O(1)$ machine operations and $O(1)$ space – independently of $w$ – and computes $\text{msb}(n)$.

*This is not obvious!*

---

This is not obvious!
How is this possible?
Not Starting from Scratch

• We’re not going into this problem blind. We’ve seen a bunch of useful techniques so far:
  
  • **Parallel compare:** We can compare a bunch of small numbers in parallel in O(1) machine word operations.
  
  • **Parallel tile:** We can take a small number and “tile” it multiple times in O(1) machine word operations.
  
  • **Parallel add:** If we have a bunch of “flag” bits spread out evenly, we can add them all up in O(1) machine word operations.
  
  • **Parallel rank:** We can find the rank of a small number in an array of small numbers in O(1) machine word operations.

• This is an impressive array of techniques. Let’s see if we can reuse or adapt them.
We’re not going into this problem blind. We’ve seen a bunch of useful techniques so far:

- **Parallel compare:** We can compare a bunch of small numbers in parallel in $O(1)$ machine word operations.
- **Parallel tile:** We can take a small number and “tile” it multiple times in $O(1)$ machine word operations.
- **Parallel add:** If we have a bunch of “flag” bits spread out evenly, we can add them all up in $O(1)$ machine word operations.
- **Parallel rank:** We can find the rank of a small number in an array of small numbers in $O(1)$ machine word operations.

This is an impressive array of techniques. Let’s see if we can reuse or adapt them.
MSBs as Ranks

• **Recall:** $\text{msb}(n)$ is the largest value of $k$ for which $2^k \leq n$.

• **Idea:** Imagine we have an array of all the powers of two that we can represent in a machine word. Then $\text{msb}(n)$ is the rank of $n$ in that array!

\[ \begin{array}{cccccccccccccccc}
  00000000 & 00000000 & 00100000 & 00000010 & 00000000 & 00100000 & 00100001 & 00101111 \\
\end{array} \]

\[ \begin{array}{cccccccccccccccc}
  2^0 & 2^1 & 2^2 & 2^3 & 2^4 & 2^5 & 2^6 & \ldots & 2^{50} & 2^{51} & 2^{52} & 2^{53} & 2^{54} & 2^{55} & 2^{56} & 2^{57} & 2^{58} & \ldots & 2^{61} & 2^{62} & 2^{63} \\
\end{array} \]
The Problem

- We can compute the rank of a value in an array assuming that
  - all the array entries fit into a single machine word, and
  - the value in question is the same size as the array entries.
- Neither of these requirements hold here.
- **Question:** Can we reduce the size of our number?
Imagine we want to compute the most-significant bit of a \( w \)-bit integer.

- In what follows, we’ll pick \( w = 64 \), but this works for any \( w \).
- We ultimately want to be finding the MSB of numbers with way fewer than \( w \) bits.

**Idea:** Split \( w \) into some number of blocks of size \( b \). Then,

- find the index of the highest block with at least one 1 bit set, then
- find the index of the highest bit within that block.
A Nice Decomposition

- Imagine we want to compute the most-significant bit of a $w$-bit integer.
  - In what follows, we’ll pick $w = 64$, but this works for any $w$.
- We ultimately want to be finding the MSB of numbers with way fewer than $w$ bits.
- **Idea:** Split $w$ into some number of blocks of size $b$. Then,
  - find the index of the highest block with at least one 1 bit set, then
  - find the index of the highest bit within that block.

Compute $\text{msb}$ for a $w/b$-bit number.

0111

000000000000000000110000100110100101110000110101110111011101110111011000010
A Nice Decomposition

- Imagine we want to compute the most-significant bit of a $w$-bit integer.
  - In what follows, we’ll pick $w = 64$, but this works for any $w$.
  - We ultimately want to be finding the MSB of numbers with way fewer than $w$ bits.
- **Idea:** Split $w$ into some number of blocks of size $b$. Then,
  - find the index of the highest block with at least one 1 bit set, then
  - find the index of the highest bit within that block.
A Nice Decomposition

- Imagine we want to compute the most-significant bit of a $w$-bit integer.
  - In what follows, we’ll pick $w = 64$, but this works for any $w$.
- We ultimately want to be finding the MSB of numbers with way fewer than $w$ bits.
- **Idea:** Split $w$ into some number of blocks of size $b$. Then,
  - find the index of the highest block with at least one 1 bit set, then
  - find the index of the highest bit within that block.

---

Compute $\text{msb}$ for a $b$-bit number.
A Nice Decomposition

- We will compute the MSB for $w$-bit integers by solving MSB for $b$ and $w/b$-bit integers.
- What choice of $b$ minimizes max{$b$, $w/b$}? 
  - **Answer:** Pick $b = w^{1/2}$.
- So now we need to see how to
  - solve $\text{msb}(n)$ for integers with $w^{1/2}$ bits, and
  - replace each block with a bit indicating whether that block contains a 1.
A Nice Decomposition

- We will compute the MSB for $w$-bit integers by solving MSB for $b$ and $w/b$-bit integers.
- What choice of $b$ minimizes $\max\{b, w/b\}$?
- **Answer:** Pick $b = w^{1/2}$.

So now we need to see how to

- solve $\text{msb}(n)$ for integers with $w^{1/2}$ bits, and
- replace each block with a bit indicating whether that block contains a 1.
A Nice Decomposition

- We will compute the MSB for \( w \)-bit integers by solving MSB for \( b \) and \( w/b \)-bit integers.
- What choice of \( b \) minimizes \( \max\{b, \frac{w}{b}\} \)?
- \textbf{Answer:} Pick \( b = w^{\frac{1}{2}} \).
- So now we need to see how to
  - solve \( \text{msb}(n) \) for integers with \( w^{\frac{1}{2}} \) bits, and
  - replace each block with a bit indicating whether that block contains a 1.
A Nice Decomposition

- We will compute the MSB for $w$-bit integers by solving MSB for $b$ and $w/b$-bit integers.
- What choice of $b$ minimizes $\max\{b, w/b\}$?
- **Answer:** Pick $b = w^{\frac{1}{2}}$.
- So now we need to see how to
  - solve $\text{msb}(n)$ for integers with $w^{\frac{1}{2}}$ bits, and
  - replace each block with a bit indicating whether that block contains a 1.
MSB for $w^{1/2}$ Bits

- **Recall:** We can compute $\text{msb}(n)$ by counting how many powers of two are less than or equal to $n$.
- If our numbers have size $w^{1/2}$, there are $w^{1/2}$ powers of two to compare against.
- Each of those powers of two has $w^{1/2}$ bits, so all of those powers of two can be packed into a single machine word!
- **Idea:** Use our $O(1)$-time rank algorithm!

\[ \begin{array}{cccccccc}
\texttt{1} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{1} & \texttt{0} & \texttt{0} \\
\texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{1} & \texttt{0} & \texttt{0} & \texttt{1} \\
\texttt{0} & \texttt{0} & \texttt{0} & \texttt{1} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{1} \\
\texttt{0} & \texttt{0} & \texttt{1} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{1} \\
\texttt{0} & \texttt{1} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} \\
\texttt{0} & \texttt{1} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} \\
\texttt{0} & \texttt{1} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} \\
\texttt{1} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} & \texttt{0} \\
\end{array} \]
MSB for $w^{1/2}$ Bits

- If our numbers have size $w^{1/2}$, there are $w^{1/2}$ powers of two to compare against, each of which has $w^{1/2}$ bits.
- Our parallel comparison prepends an extra bit to each number to compare.
MSB for $w^{1/2}$ Bits

- If our numbers have size $w^{1/2}$, there are $w^{1/2}$ powers of two to compare against, each of which has $w^{1/2}$ bits.
- Our parallel comparison prepends an extra bit to each number to compare.
- That’s barely – just barely – too many bits to fit into a machine word.
MSB for $w^{1/2}$ Bits

- **Claim:** This is an engineering problem at this point.
- **Option 1:** Split the powers of two into two different machine words and do two rank calculations.
- **Option 2:** Special-case the most-significant bit to reduce the number of bits to check.
- Either way, we find that the work done here is $O(1)$ machine operations, with no dependency on the word size $w$!
A Nice Decomposition

- We need to see how to
  - solve $\text{msb}(n)$ for integers with $w^{\frac{1}{2}}$ bits, and
  - replace each block with a bit indicating whether that block contains a 1.
A Nice Decomposition

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Identifying Active Blocks

<table>
<thead>
<tr>
<th>$b_1$</th>
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<th>$b_3$</th>
<th>$b_4$</th>
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<tbody>
<tr>
<td>00000000</td>
<td>00011001</td>
<td>11110000</td>
<td>10011010</td>
<td>10000000</td>
<td>00011010</td>
<td>11101110</td>
<td>11000010</td>
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</tbody>
</table>

**Observation:** A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.
Identifying Active Blocks

\[
\begin{align*}
 b_1 & \quad b_2 & \quad b_3 & \quad b_4 & \quad b_5 & \quad b_6 & \quad b_7 & \quad b_8 \\
00000000 & \quad 00011001 & \quad 11110000 & \quad 10011010 & \quad 10000000 & \quad 00011010 & \quad 11101110 & \quad 11000010 \\
\end{align*}
\]

**Observation:** A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.
## Identifying Active Blocks

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**Observation:** A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.
# Identifying Active Blocks

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Observation: A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.

High bit set?
Identifying Active Blocks

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High bit set?

**Observation:** A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.
Identifying Active Blocks

A number’s lower 7 bits contain a 1 if and only if the numeric value of those bits is at least 1.

**Observation:** A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.
# Identifying Active Blocks

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<tr>
<th>b₁</th>
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*Observation:* A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.

*High bit set?*
Identifying Active Blocks

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High bit set?

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$\textit{High bit set?}$

**Observation:** A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.
## Identifying Active Blocks

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### Observation:
A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.
Identifying Active Blocks

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Observation: A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.
**Identifying Active Blocks**

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**Observation:** A block contains a 1 bit if its first bit is 1 or its lower 7 bits contain a 1.

**Any bits set?**

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**Low bits set?**

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**High bit set?**

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</table>
Identifying Active Blocks

• We now have a word holding flags telling us which blocks have a 1 bit set.

• We need to find the highest set flag.

• There are only $w^{\frac{1}{2}}$ flags. If we could compact them into $w^{\frac{1}{2}}$ adjacent bits, we could use our earlier algorithm to find the highest one set!

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Identifying Active Blocks

• **Idea:** Adapt the shifting technique we used to compute ranks.

• Instead of shifting the bits on top of one another, shift the bits next to one another:

```plaintext
a00000000b00000000c00000000d00000000
```
Identifying Active Blocks

• **Idea:** Adapt the shifting technique we used to compute ranks.

• Instead of shifting the bits on top of one another, shift the bits next to one another:

```
a0000000b0000000c0000000d0000000
```

```
a0000000b0000000c0000000d0000000
  a0000000b0000000c0000000d0000000
  a0000000b0000000c0000000d0000000
```

```
+ a0000000b0000000c0000000d0000000

????????????????????????????????????aabcd?????????????????????????????????????????
Fundamental Primitive: **Parallel Pack**

1. Perform a *parallel tile* with an appropriate multiplier to place all leading bits adjacent to one another.

2. Use a bitmask and bitshift to isolate those bits.

Assuming the multiplier for part (1) and the mask and shift for part (2) can be computed in time $O(1)$, this takes time $O(1)$. 
Putting It All Together

- Use a bitmask to identify all blocks whose high bit is set.
- Use a parallel tile and a parallel compare to identify all blocks with a 1 bit aside from the first.
- Use a parallel pack to pack those bits together.
- Use a parallel rank to determine the highest of those bits set, which gives the block index.
- Use a parallel rank to determine the highest bit set within that block.
The Finished Product

• I’ve posted a link to a working implementation of this algorithm for 64-bit integers on the course website.

• Feel free to check it out – it’s really magical seeing all the techniques come together!
Next Time

• **Patricia Codes**
  • Compressing a small number of big integers into a small number of small integers.

• **Fusion Trees**
  • Combining all these techniques together!