1.5 Case Study

- dynamic connectivity
- quick find
- quick union
- improvements
- applications
Subtext of today’s lecture (and this course)

Steps to developing a usable algorithm.
• Model the problem.
• Find an algorithm to solve it.
• Fast enough? Fits in memory?
• If not, figure out why.
• Find a way to address the problem.
• Iterate until satisfied.

The scientific method.

Mathematical analysis.
¬ dynamic connectivity
¬ quick find
¬ quick union
¬ improvements
¬ applications
Dynamic connectivity

Given a set of objects

- **Union**: connect two objects.
- **Find**: is there a path connecting the two objects?

union(3, 4)
union(8, 0)
union(2, 3)
union(5, 6)

find(0, 2)  no
find(2, 4)  yes

union(5, 1)
union(7, 3)
union(1, 6)
union(4, 8)

find(0, 2)  yes
find(2, 4)  yes
Network connectivity: larger example

Q. Is there a path from p to q?

A. Yes.

but finding the path is more difficult: stay tuned (Chapter 4)
Dynamic connectivity applications involve manipulating objects of all types.

- Variable name aliases.
- Pixels in a digital photo.
- Computers in a network.
- Web pages on the Internet.
- Transistors in a computer chip.
- Metallic sites in a composite system.

When programming, convenient to name objects 0 to N-1.

- Use integers as array index.
- Suppress details not relevant to union-find.

*can use symbol table to translate from object names to integers (stay tuned)*
Modeling the connections

Transitivity. If $p$ is connected to $q$ and $q$ is connected to $r$, then $p$ is connected to $r$.

Connected components. Maximal set of objects that are mutually connected.
Implementing the operations

Find query. Check if two objects are in the same set.

Union command. Replace sets containing two objects with their union.
**Goal.** Design efficient data structure for union-find.
- Number of objects $N$ can be huge.
- Number of operations $M$ can be huge.
- Find queries and union commands may be intermixed.

### Union-find data type (API)

```java
public class UnionFind {
    UnionFind(int N) {
        // create union-find data structure with N objects and no connections
    }

    boolean find(int p, int q) {
        // are p and q in the same set?
    }

    void union(int p, int q) {
        // replace sets containing p and q with their union
    }
}
```
dynamic connectivity
quick find
quick union
improvements
applications
Quick-find [eager approach]

Data structure.
• Integer array \texttt{id[]} of size \texttt{N}.
• Interpretation: \( p \) and \( q \) are connected if they have the same \texttt{id}.

<table>
<thead>
<tr>
<th>i</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{id}[i]</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

5 and 6 are connected
2, 3, 4, and 9 are connected
Quick-find [eager approach]

Data structure.
• Integer array \( id[] \) of size \( N \).
• Interpretation: \( p \) and \( q \) are connected if they have the same id.

<table>
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<tr>
<th>i</th>
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<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>( id[i] )</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

Find. Check if \( p \) and \( q \) have the same id.

5 and 6 are connected
2, 3, 4, and 9 are connected

3 and 6 not connected
Quick-find [eager approach]

Data structure.
• Integer array \( id[] \) of size \( N \).
• Interpretation: \( p \) and \( q \) are connected if they have the same id.

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<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>id[i]</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

Find. Check if \( p \) and \( q \) have the same id.

<table>
<thead>
<tr>
<th>i</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>id[i]</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

3 and 6 not connected

Union. To merge sets containing \( p \) and \( q \), change all entries with \( id[p] \) to \( id[q] \).

<table>
<thead>
<tr>
<th>i</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>id[i]</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

union of 3 and 6
2, 3, 4, 5, 6, and 9 are connected

problem: many values can change
### Quick-find example

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>3–4</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>4–9</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>9</td>
<td>9</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>8–0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>9</td>
<td>9</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>2–3</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>5–6</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>5–9</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>7</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>7–3</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>4–8</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6–1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

![Diagram with nodes labeled 0 to 9, highlighting changes in connectivity between iterations.]

**problem:** many values can change
Quick-find: Java implementation

```java
public class QuickFind {
    private int[] id;

    public QuickFind(int N) {
        id = new int[N];
        for (int i = 0; i < N; i++)
            id[i] = i;
    }

    private int find(int p) {
        return id[p];
    }

    public boolean find(int p, int q) {
        return find(p) == find(q);
    }

    public void union(int p, int q) {
        int pid = find(p);
        for (int i = 0; i < id.length; i++)
            if (id[i] == pid) id[i] = id[q];
    }
}
```

- **set id of each object to itself** (N array accesses)
- **return component id for p** (1 array access)
- **check whether p and q are in the same component**
- **change all entries with id[p] to id[q]** (N array accesses)

Quick-find: Java implementation

- check whether p and q are in the same component
- change all entries with id[p] to id[q] (N array accesses)
- set id of each object to itself (N array accesses)
- return component id for p (1 array access)
Quick-find is too slow

Quick-find defect.

- Union too expensive (N array accesses).
- Trees are flat, but too expensive to keep them flat.

<table>
<thead>
<tr>
<th>algorithm</th>
<th>union</th>
<th>find</th>
</tr>
</thead>
<tbody>
<tr>
<td>quick-find</td>
<td>N</td>
<td>1</td>
</tr>
</tbody>
</table>

**Ex.** Takes $N^2$ array accesses to process sequence of N union commands on N objects.
Quadratic algorithms do not scale

Rough standard (for now).
• $10^9$ operations per second.
• $10^9$ words of main memory.
• Touch all words in approximately 1 second.

Ex. Huge problem for quick-find.
• $10^9$ union commands on $10^9$ objects.
• Quick-find takes more than $10^{18}$ operations.
• 30+ years of computer time!

Paradoxically, quadratic algorithms get worse with newer equipment.
• New computer may be 10x as fast.
• But, has 10x as much memory so problem may be 10x bigger.
• With quadratic algorithm, takes 10x as long!
dynamic connectivity
quick find
quick union
improvements
applications
Quick-union  [lazy approach]

Data structure.

- Integer array \( id[] \) of size \( N \).
- Interpretation: \( id[i] \) is parent of \( i \).
- Root of \( i \) is \( id[id[id[...id[i]...]]] \).

<table>
<thead>
<tr>
<th>i</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>id[i]</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>4</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

3's root is 9; 5's root is 6
Quick-union  [lazy approach]

Data structure.
• Integer array $\text{id}[]$ of size $N$.
• Interpretation: $\text{id}[i]$ is parent of $i$.
• Root of $i$ is $\text{id}[\text{id}[\text{id}[...\text{id}[i]...]]]$.

Find. Check if $p$ and $q$ have the same root.

<table>
<thead>
<tr>
<th>i</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{id}[i]$</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>4</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

3’s root is 9; 5’s root is 6
3 and 5 are not connected
Quick-union [lazy approach]

Data structure.
• Integer array \( \text{id[]} \) of size \( N \).
• Interpretation: \( \text{id}[i] \) is parent of \( i \).
• Root of \( i \) is \( \text{id}[\text{id}[\text{id}[\ldots\text{id}[i]\ldots]]] \).

Find. Check if \( p \) and \( q \) have the same root.

Union. To merge sets containing \( p \) and \( q \), set the id of \( p \)'s root to the id of \( q \)'s root.

```
i  0  1  2  3  4  5  6  7  8  9
id[i] 0  1  9  4  9  6  6  7  8  9
```

```
i  0  1  2  3  4  5  6  7  8  9
id[i] 0  1  9  4  9  6  6  7  8  6
```

3's root is 9; 5's root is 6
3 and 5 are not connected

```
i  0  1  2  3  4  5  6  7  8  9
id[i] 0  1  9  4  9  6  6  7  8  6
```

Only one value changes
Quick-union example

3–4  0 1 2 4 4 5 6 7 8 9
4–9  0 1 2 4 9 5 6 7 8 9
8–0  0 1 2 4 9 5 6 7 0 9
2–3  0 1 9 4 9 5 6 7 0 9
5–6  0 1 9 4 9 6 6 7 0 9
5–9  0 1 9 4 9 6 9 7 0 9
7–3  0 1 9 4 9 6 9 9 0 9
4–8  0 1 9 4 9 6 9 9 0 0
6–1  1 1 9 4 9 6 9 9 0 0

problem: trees can get tall
Quick-union: Java implementation

```java
public class QuickUnion
{
    private int[] id;

    public QuickUnion(int N)
    {
        id = new int[N];
        for (int i = 0; i < N; i++) id[i] = i;
    }

    private int find(int i)
    {
        while (i != id[i]) i = id[i];
        return i;
    }

    public boolean find(int p, int q)
    {
        return find(p) == find(q);
    }

    public void union(int p, int q)
    {
        int i = root(p), j = root(q);
        id[i] = j;
    }
}
```

- Set id of each object to itself (N array accesses)
- Chase parent pointers until reach root (depth of i array accesses)
- Check if p and q have same root (depth of p and q array accesses)
- Change root of p to point to root of q (depth of p and q array accesses)
Quick-union is also too slow

Quick-find defect.
• Union too expensive (N array accesses).
• Trees are flat, but too expensive to keep them flat.

Quick-union defect.
• Trees can get tall.
• Find too expensive (could be N array accesses).

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<th>union</th>
<th>find</th>
</tr>
</thead>
<tbody>
<tr>
<td>quick-find</td>
<td>N</td>
<td>1</td>
</tr>
<tr>
<td>quick-union</td>
<td>N†</td>
<td>N</td>
</tr>
</tbody>
</table>

† includes cost of finding root

worst case
dynamic connectivity
quick find
quick union
improvements
applications
Improvement 1: weighting

Weighted quick-union.
- Modify quick-union to avoid tall trees.
- Keep track of size of each set.
- Balance by linking small tree below large one.

Ex. Union of 3 and 5.
- Quick union: link 9 to 6.
- Weighted quick union: link 6 to 9.
Weighted quick-union example

3–4  0 1 2 3 3 5 6 7 8 9
4–9  0 1 2 3 3 5 6 7 8 3
8–0  8 1 2 3 3 5 6 7 8 3
2–3  8 1 3 3 3 5 6 7 8 3
5–6  8 1 3 3 3 5 5 7 8 3
5–9  8 1 3 3 3 3 5 7 8 3
7–3  8 1 3 3 3 3 5 3 8 3
4–8  8 1 3 3 3 3 5 3 3 3
6–1  8 3 3 3 3 3 5 3 3 3

no problem: trees stay flat
Weighted quick-union: Java implementation

**Data structure.** Same as quick-union, but maintain extra array \( sz[i] \) to count number of objects in the tree rooted at \( i \).

**Find.** Identical to quick-union.

```java
return find(p) == find(q);
```

**Union.** Modify quick-union to:
- Merge smaller tree into larger tree.
- Update the \( sz[] \) array.

```java
int i = find(p);
int j = find(q);
if (sz[i] < sz[j]) { id[i] = j; sz[j] += sz[i]; }
else { id[j] = i; sz[i] += sz[j]; }
```
Weighted quick-union analysis

Analysis.
• Find: takes time proportional to depth of p and q.
• Union: takes constant time, given roots.

Proposition. Depth of any node x is at most lg N.

\[
N = 10 \\
\text{depth}(x) = 3 \leq \lg N
\]
Weighted quick-union analysis

Analysis.
• Find: takes time proportional to depth of p and q.
• Union: takes constant time, given roots.

Proposition. Depth of any node x is at most lg N.
Pf. When does depth of x increase?
Increases by 1 when tree T_1 containing x is merged into another tree T_2.
• The size of the tree containing x at least doubles since |T_2| ≥ |T_1|.
• Size of tree containing x can double at most lg N times. Why?
Weighted quick-union analysis

Analysis.
- **Find**: takes time proportional to depth of p and q.
- **Union**: takes constant time, given roots.

**Proposition.** Depth of any node \( x \) is at most \( \lg N \).

### Table: Algorithm Comparison

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Union</th>
<th>Find</th>
</tr>
</thead>
<tbody>
<tr>
<td>quick-find</td>
<td>( N )</td>
<td>1</td>
</tr>
<tr>
<td>quick-union</td>
<td>( N^\dagger )</td>
<td>( N )</td>
</tr>
<tr>
<td>weighted QU</td>
<td>( \lg N^\dagger )</td>
<td>( \lg N )</td>
</tr>
</tbody>
</table>

\( \dagger \) includes cost of finding root

**Q.** Stop at guaranteed acceptable performance?

**A.** No, easy to improve further.
Improvement 2: path compression

Quick union with path compression. Just after computing the root of $p$, set the id of each examined node to point to that root.
Path compression: Java implementation

Standard implementation: add second loop to `find()` to set the `id[]` of each examined node to the root.

Simpler one-pass variant: halve the path length by making every other node in path point to its grandparent.

```
public int find(int i)
{
   while (i != id[i])
   {
      id[i] = id[id[i]];
      i = id[i];
   }
   return i;
}
```

In practice. No reason not to! Keeps tree almost completely flat.
Weighted quick-union with path compression example

3–4  0 1 2 3 3 5 6 7 8 9
4–9  0 1 2 3 3 5 6 7 8 3
8–0  8 1 2 3 3 5 6 7 8 3
2–3  8 1 3 3 3 5 6 7 8 3
5–6  8 1 3 3 3 5 5 7 8 3
5–9  8 1 3 3 3 3 5 7 8 3
7–3  8 1 3 3 3 3 5 3 8 3
4–8  8 1 3 3 3 3 5 3 3 3
6–1  8 3 3 3 3 3 3 3 3
**Proposition.** [Tarjan 1975] Starting from an empty data structure, any sequence of $M$ union and find ops on $N$ objects takes $O(N + M \lg^* N)$ time.

- Proof is very difficult.
- But the algorithm is still simple!

**Linear algorithm?**

- Cost within constant factor of reading in the data.
- In theory, WQUPC is not quite linear.
- In practice, WQUPC is linear.

**Amazing fact.** No linear-time algorithm exists.

### WQUPC performance

<table>
<thead>
<tr>
<th>$N$</th>
<th>$\lg^* N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>65536</td>
<td>4</td>
</tr>
<tr>
<td>$2^{65536}$</td>
<td>5</td>
</tr>
</tbody>
</table>

$\lg^*$ function refers to the number of times needed to take the $\lg$ of a number until reaching 1.
Bottom line. WQUPC makes it possible to solve problems that could not otherwise be addressed.

<table>
<thead>
<tr>
<th>algorithm</th>
<th>worst-case time</th>
</tr>
</thead>
<tbody>
<tr>
<td>quick-find</td>
<td>$M N$</td>
</tr>
<tr>
<td>quick-union</td>
<td>$M N$</td>
</tr>
<tr>
<td>weighted QU</td>
<td>$N + M \log N$</td>
</tr>
<tr>
<td>QU + path compression</td>
<td>$N + M \log N$</td>
</tr>
<tr>
<td>weighted QU + path compression</td>
<td>$N + M \lg^* N$</td>
</tr>
</tbody>
</table>

*M union-find operations on a set of N objects*

Ex. [10⁹ unions and finds with 10⁹ objects]
- WQUPC reduces time from 30 years to 6 seconds.
- Supercomputer won't help much; good algorithm enables solution.
- dynamic connectivity
- quick find
- quick union
- improvements
- applications
Union-find applications

- Percolation.
- Games (Go, Hex).
- Network connectivity.
- Least common ancestor.
- Equivalence of finite state automata.
- Hoshen-Kopelmann algorithm in physics.
- Hinley-Milner polymorphic type inference.
- Kruskal's minimum spanning tree algorithm.
- Compiling equivalence statements in Fortran.
- Morphological attribute openings and closings.
- Matlab's `bwlabel()` function in image processing.
A model for many physical systems:
• N-by-N grid of sites.
• Each site is open with probability p (or blocked with probability 1-p).
• System percolates if top and bottom are connected by open sites.
Percolation

A model for many physical systems:
• N-by-N grid of sites.
• Each site is open with probability $p$ (or blocked with probability $1-p$).
• System **percolates** if top and bottom are connected by open sites.

<table>
<thead>
<tr>
<th>model</th>
<th>system</th>
<th>vacant site</th>
<th>occupied site</th>
<th>percolates</th>
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<tbody>
<tr>
<td>electricity</td>
<td>material</td>
<td>conductor</td>
<td>insulated</td>
<td>conducts</td>
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<tr>
<td>fluid flow</td>
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<td>empty</td>
<td>blocked</td>
<td>porous</td>
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<td>social interaction</td>
<td>population</td>
<td>person</td>
<td>empty</td>
<td>communicates</td>
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Likelihood of percolation

Depends on site vacancy probability $p$.

$p$ low
does not percolate

$p$ medium
percolates? 

$p$ high
percolates

$N = 20$
When $N$ is large, theory guarantees a sharp threshold $p^*$. 

- $p > p^*$: almost certainly percolates.
- $p < p^*$: almost certainly does not percolate.

Q. What is the value of $p^*$?
Monte Carlo simulation

- Initialize N-by-N whole grid to be blocked.
- Declare random sites open until top connected to bottom.
- Vacancy percentage estimates $p^*$.
How to check whether system percolates?

- Create an object for each site.
- Sites are in same set if connected by open sites.
- Percolates if any site in top row is in same set as any site in bottom row.

UF solution to find percolation threshold

brute force algorithm needs to check $N^2$ pairs

\[ N = 8 \]
**Question:** How to declare a new site open?

*UF solution to find percolation threshold*

A block diagram or matrix illustrates different states of sites, including:
- **Open sites:**
  - Full open site (connected to top) indicated by blue
  - Empty open site (not connected to top) indicated by white
- **Blocked site** indicated by black

The number of sites, $N = 8$, is shown at the bottom of the diagram.
Q. How to declare a new site open?
A. Take union of new site and all adjacent open sites.

UF solution to find percolation threshold

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N = 8
UF solution: a critical optimization

Q. How to avoid checking all pairs of top and bottom sites?

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- **Blue**: full open site (connected to top)
- **White**: empty open site (not connected to top)
- **Black**: blocked site

*N = 8*
UF solution: a critical optimization

Q. How to avoid checking all pairs of top and bottom sites?
A. Create a virtual top and bottom objects;
   system percolates when virtual top and bottom objects are in same set.
Percolation threshold

Q. What is percolation threshold $p^*$?
A. About 0.592746 for large square lattices.

Fast algorithm enables accurate answer to scientific question.
Steps to developing a usable algorithm.

- Model the problem.
- Find an algorithm to solve it.
- Fast enough? Fits in memory?
- If not, figure out why.
- Find a way to address the problem.
- Iterate until satisfied.

The scientific method.

Mathematical analysis.