Basic info

- Dr. Maraist
  - My office: 209 Wing Tech. Center
  - Class web site: cs.uwlax.edu/~jmaraist/353-spring-18

Today

- Some problems
- Introduction

Next time

- Stable matching

Friday

- Asymptotic measure
- Problems due: (Ch. 1) 1, 2, 4

Contact information

- Web: cs.uwlax.edu/~jmaraist
- Email: jmaraist@uwlax.edu
  - Expect replies within a (business) day (but often faster) during the semester
- Office hours through spring break
  - Tuesdays 1:30-3:30pm
  - Wednesdays 4-5pm
  - Fridays 2-3:30pm
- Or by appointment
  - 15-minutes slots, email at least a day ahead
Chapter 1

Introduction: Some Representative Problems
Matching Residents to Hospitals

**Goal.** Given a set of preferences among hospitals and medical school students, design a *self-reinforcing* admissions process.

**Unstable pair:** applicant $x$ and hospital $y$ are *unstable* if:
- $x$ prefers $y$ to its assigned hospital.
- $y$ prefers $x$ to one of its admitted students.

**Stable assignment.** Assignment with no unstable pairs.
- Natural and desirable condition.
- Individual self-interest will prevent any applicant/hospital deal from being made.
Stable Matching Problem

**Goal.** Given n men and n women, find a "suitable" matching.
- Participants rate members of opposite sex.
- Each man lists women in order of preference from best to worst.
- Each woman lists men in order of preference from best to worst.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Women's Preference Profile</th>
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<tbody>
<tr>
<td>Xavier</td>
<td>Amy&lt;br&gt;Bertha&lt;br&gt;Clare</td>
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<tr>
<td>Yancey</td>
<td>Bertha&lt;br&gt;Amy&lt;br&gt;Clare</td>
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### Men's Preference Profile

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### Women's Preference Profile
Perfect matching: everyone is matched monogamously.
- Each man gets exactly one woman.
- Each woman gets exactly one man.

Stability: no incentive for some pair of participants to undermine assignment by joint action.
- In matching $M$, an unmatched pair $m-w$ is unstable if man $m$ and woman $w$ prefer each other to current partners.
- Unstable pair $m-w$ could each improve by eloping.

Stable matching: perfect matching with no unstable pairs.

Stable matching problem. Given the preference lists of $n$ men and $n$ women, find a stable matching if one exists.
Stable Matching Problem

Q. Is assignment X-C, Y-B, Z-A stable?

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<td>Zeus</td>
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**Women’s Preference Profile**
Stable Matching Problem

**Q.** Is assignment X-C, Y-B, Z-A stable?

**A.** No. Bertha and Xavier will hook up.
### Stable Matching Problem

**Q.** Is assignment X-A, Y-B, Z-C stable?

**A.** Yes.

**Men’s Preference Profile**

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<td>Yancey</td>
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Stable Roommate Problem

Q. Do stable matchings always exist?
A. Not obvious a priori.

Stable roommate problem.
- 2n people; each person ranks others from 1 to 2n-1.
- Assign roommate pairs so that no unstable pairs.

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<tbody>
<tr>
<td>Adam</td>
<td>B</td>
<td>C</td>
<td>D</td>
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<tr>
<td>Bob</td>
<td>C</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>Chris</td>
<td>A</td>
<td>B</td>
<td>D</td>
</tr>
<tr>
<td>Doofus</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
</tbody>
</table>

A-B, C-D $\Rightarrow$ B-C unstable
A-C, B-D $\Rightarrow$ A-B unstable
A-D, B-C $\Rightarrow$ A-C unstable

Observation. Stable matchings do not always exist for stable roommate problem.
For us, what is a "solution" to a problem like Stable Matching?
What is a solution?

For us, what is a "solution" to a problem like Stable Matching?

- First an \textit{algorithm}
  - Takes rankings tables
  - Returns a set of pairs
What is a solution?

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For us, what is a "solution" to a problem like Stable Matching?

- First an *algorithm*
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For us, what is a "solution" to a problem like Stable Matching?

- First an *algorithm*
  - Takes rankings tables
  - Returns a set of pairs
- *Proof* that the algorithm finds a (perfect) matching
- Proof that the matching is stable
- An *accounting* of the cost of the algorithm
Interval Scheduling

**Input.** Set of jobs with start times and finish times.

**Goal.** Find *maximum cardinality* subset of mutually compatible jobs.

Jobs don't overlap
Weighted Interval Scheduling

**Input.** Set of jobs with start times, finish times, and weights.

**Goal.** Find maximum weight subset of mutually compatible jobs.
Bipartite Matching

**Input.** Bipartite graph.

**Goal.** Find maximum cardinality matching.
Independent Set

**Input.** Graph.

**Goal.** Find maximum cardinality **independent set.**

subset of nodes such that no two joined by an edge
Input. Graph with weight on each node.

Game. Two competing players alternate in selecting nodes. Not allowed to select a node if any of its neighbors have been selected.

Goal. Select a maximum weight subset of nodes.

Second player can guarantee 20, but not 25.
Five Representative Problems

Variations on a theme: independent set.

Interval scheduling: \( n \log n \) greedy algorithm.
Weighted interval scheduling: \( n \log n \) dynamic programming algorithm.
Bipartite matching: \( n^k \) max-flow based algorithm.
Independent set: NP-complete.
Competitive facility location: PSPACE-complete.
Tentative schedule of topics

Weeks 1-2  Introduction (Chapters 1-2)
Weeks 2-3  Graphs (Chapter 3)
Weeks 4-5  Greedy algorithms (Chapter 4)
Weeks 6-7  Divide-and-conquer algorithms (Chapter 5)
Weeks 8-9  Dynamic programming (Chapter 6)
Weeks 10-14 To be decided (likely from Chapters 7-9)
Algorithms — January 26

Today
Asymptotic measure
Sec. 2.1-2.4

Monday
Stable matching
Read (re-read) Sec. 1.1

Wednesday
Priority queues and heaps
Read Sec. 2.5

Friday
Quiz on Sec. 2.1-2.4
Open-book (so bring the book)

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How do we quantify efficiency for programs?

- By the clock time that passes during execution?
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- CPU time?
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- By the clock time that passes during execution?
- CPU time?
- Statements?
  - Machine code statements?
How do we quantify efficiency for programs?

- By the clock time that passes during execution?
- CPU time?
- Statements?
  - Machine code statements?
- **Key operations**
  - Could be comparisons, assignments, etc.
**Polynomial-Time**

**Brute force.** For many non-trivial problems, there is a natural brute force search algorithm that checks every possible solution.
- Typically takes $2^N$ time or worse for inputs of size $N$.
- Unacceptable in practice.

**Desirable scaling property.** When the input size doubles, the algorithm should only slow down by some constant factor $C$.

There exists constants $c > 0$ and $d > 0$ such that on every input of size $N$, its running time is bounded by $cN^d$ steps.

**Def.** An algorithm is **poly-time** if the above scaling property holds.

$n!$ for stable matching with $n$ men and $n$ women

choose $C = 2^d$
Exercise 2.1

Suppose you have algorithms with these (exact) running times:

- $n^2$
- $n^3$
- $100n^2$
- $n \log n$
- $2^n$

How much slower do each get when you

- Double the input size?
- Increase the input size by one?
Worst-Case Analysis

**Worst case running time.** Obtain bound on largest possible running time of algorithm on input of a given size \( N \).
- Generally captures efficiency in practice.
- Draconian view, but hard to find effective alternative.

**Average case running time.** Obtain bound on running time of algorithm on random input as a function of input size \( N \).
- Hard (or impossible) to accurately model real instances by random distributions.
- Algorithm tuned for a certain distribution may perform poorly on other inputs.
Worst-Case Polynomial-Time

**Def.** An algorithm is **efficient** if its running time is polynomial.

**Justification:** It really works in practice!
- Although $6.02 \times 10^{23} \times N^{20}$ is technically poly-time, it would be useless in practice.
- In practice, the poly-time algorithms that people develop almost always have low constants and low exponents.
- Breaking through the exponential barrier of brute force typically exposes some crucial structure of the problem.

**Exceptions.**
- Some poly-time algorithms do have high constants and/or exponents, and are useless in practice.
- Some exponential-time (or worse) algorithms are widely used because the worst-case instances seem to be rare.

 simplex method
Unix grep
What is the smallest integer value for which the first expression becomes greater than the second function?

1. $n^2$ and $10n$
2. $2^n$ and $2n^3$
3. $\frac{n^2}{\log n}$ and $n(\log n)^2$
4. $\frac{n^3}{2}$ and $n^{2.81}$
### Why It Matters

Table 2.1 The running times (rounded up) of different algorithms on inputs of increasing size, for a processor performing a million high-level instructions per second. In cases where the running time exceeds $10^{25}$ years, we simply record the algorithm as taking a very long time.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$n$</th>
<th>$n \log_2 n$</th>
<th>$n^2$</th>
<th>$n^3$</th>
<th>$1.5^n$</th>
<th>$2^n$</th>
<th>$n!$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 10$</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>4 sec</td>
</tr>
<tr>
<td>$n = 30$</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>18 min</td>
<td>$10^{25}$ years</td>
</tr>
<tr>
<td>$n = 50$</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>11 min</td>
<td>36 years</td>
<td>very long</td>
</tr>
<tr>
<td>$n = 100$</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>1 sec</td>
<td>12,892 years</td>
<td>$10^{17}$ years</td>
<td>very long</td>
</tr>
<tr>
<td>$n = 1,000$</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>1 sec</td>
<td>18 min</td>
<td>very long</td>
<td>very long</td>
<td>very long</td>
</tr>
<tr>
<td>$n = 10,000$</td>
<td>$&lt; 1$ sec</td>
<td>$&lt; 1$ sec</td>
<td>2 min</td>
<td>12 days</td>
<td>very long</td>
<td>very long</td>
<td>very long</td>
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<tr>
<td>$n = 100,000$</td>
<td>$&lt; 1$ sec</td>
<td>2 sec</td>
<td>3 hours</td>
<td>32 years</td>
<td>very long</td>
<td>very long</td>
<td>very long</td>
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<tr>
<td>$n = 1,000,000$</td>
<td>1 sec</td>
<td>20 sec</td>
<td>12 days</td>
<td>31,710 years</td>
<td>very long</td>
<td>very long</td>
<td>very long</td>
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</table>
Combining time scales

What about these running times?
- $n^3 + n^2$
- $n^3 + 200n^2$
- $2^n + n^2$
- $2n^2$
Asymptotic Order of Growth

**Upper bounds.** $T(n)$ is $O(f(n))$ if there exist constants $c > 0$ and $n_0 \geq 0$ such that for all $n \geq n_0$ we have $T(n) \leq c \cdot f(n)$.

**Lower bounds.** $T(n)$ is $\Omega(f(n))$ if there exist constants $c > 0$ and $n_0 \geq 0$ such that for all $n \geq n_0$ we have $T(n) \geq c \cdot f(n)$.

**Tight bounds.** $T(n)$ is $\Theta(f(n))$ if $T(n)$ is both $O(f(n))$ and $\Omega(f(n))$.

**Ex:** $T(n) = 32n^2 + 17n + 32$.

- $T(n)$ is $O(n^2)$, $O(n^3)$, $\Omega(n^2)$, $\Omega(n)$, and $\Theta(n^2)$.
- $T(n)$ is not $O(n)$, $\Omega(n^3)$, $\Theta(n)$, or $\Theta(n^3)$. 

Notation

Slight abuse of notation. \( T(n) = O(f(n)) \).

- Not transitive:
  - \( f(n) = 5n^3; \ g(n) = 3n^2 \)
  - \( f(n) = O(n^3) = g(n) \)
  - but \( f(n) \neq g(n) \).

- Better notation: \( T(n) \in O(f(n)) \).

Meaningless statement. Any comparison-based sorting algorithm requires at least \( O(n \log n) \) comparisons.

- Statement doesn't "type-check."
- Use \( \Omega \) for lower bounds.
Another notational issue

We are discussing the runtime of specific algorithms

- Not the runtime or needs of a problem
Another notational issue

We are discussing the runtime of *specific algorithms*

- Not the runtime or needs of a *problem*
- Later, we will consider more categorical statements about the possible algorithms for a problem
Properties

Transitivity.
- If $f = O(g)$ and $g = O(h)$ then $f = O(h)$.
- If $f = \Omega(g)$ and $g = \Omega(h)$ then $f = \Omega(h)$.
- If $f = \Theta(g)$ and $g = \Theta(h)$ then $f = \Theta(h)$.

Additivity.
- If $f = O(h)$ and $g = O(h)$ then $f + g = O(h)$.
- If $f = \Omega(h)$ and $g = \Omega(h)$ then $f + g = \Omega(h)$.
- If $f = \Theta(h)$ and $g = O(h)$ then $f + g = \Theta(h)$.
Asymptotic Bounds for Some Common Functions

Polynomials. $a_0 + a_1 n + \ldots + a_d n^d$ is $\Theta(n^d)$ if $a_d > 0$.

Polynomial time. Running time is $O(n^d)$ for some constant $d$ independent of the input size $n$.

Logarithms. $O(\log_a n) = O(\log_b n)$ for any constants $a, b > 0$.

Logarithms. For every $x > 0$, $\log n = O(n^x)$.

Exponentials. For every $r > 1$ and every $d > 0$, $n^d = O(r^n)$.
Linear Time: $O(n)$

**Linear time.** Running time is proportional to input size.

**Computing the maximum.** Compute maximum of $n$ numbers $a_1, \ldots, a_n$.

```
max ← a_1
for i = 2 to n {
    if (a_i > max)
        max ← a_i
}
```
**Merge.** Combine two sorted lists \( A = a_1, a_2, \ldots, a_n \) with \( B = b_1, b_2, \ldots, b_n \) into sorted whole.

\[
i = 1, \quad j = 1 \\
\text{while (both lists are nonempty) } \{ \\
\quad \text{if } (a_i \leq b_j) \text{ append } a_i \text{ to output list and increment } i \\
\quad \text{else } \text{ append } b_j \text{ to output list and increment } j \\
\}
\text{append remainder of nonempty list to output list}
\]

**Claim.** Merging two lists of size \( n \) takes \( O(n) \) time.

**Pf.** After each comparison, the length of output list increases by 1.
**O(n log n) Time**

*O(n log n) time.* Arises in divide-and-conquer algorithms.

also referred to as linearithmic time

**Sorting.** Mergesort and heapsort are sorting algorithms that perform \(O(n \log n)\) comparisons.

**Largest empty interval.** Given \(n\) time-stamps \(x_1, \ldots, x_n\) on which copies of a file arrive at a server, what is largest interval of time when no copies of the file arrive?

**O(n log n) solution.** Sort the time-stamps. Scan the sorted list in order, identifying the maximum gap between successive time-stamps.
Quadratic Time: \( O(n^2) \)

Quadratic time. Enumerate all pairs of elements.

Closest pair of points. Given a list of \( n \) points in the plane \((x_1, y_1), \ldots, (x_n, y_n)\), find the pair that is closest.

\( O(n^2) \) solution. Try all pairs of points.

\[
\text{min} \leftarrow (x_1 - x_2)^2 + (y_1 - y_2)^2 \\
\text{for } i = 1 \text{ to } n \{ \\
    \text{for } j = i+1 \text{ to } n \{ \\
        d \leftarrow (x_i - x_j)^2 + (y_i - y_j)^2 \\
        \text{if } (d < \text{min}) \\
        \quad \text{min} \leftarrow d \\
    \}
\}
\]

Remark. \( \Omega(n^2) \) seems inevitable, but this is just an illusion.  

---

\( \text{don't need to take square roots} \)
Cubic Time: $O(n^3)$

**Cubic time.** Enumerate all triples of elements.

**Set disjointness.** Given $n$ sets $S_1, \ldots, S_n$ each of which is a subset of $1, 2, \ldots, n$, is there some pair of these which are disjoint?

**$O(n^3)$ solution.** For each pairs of sets, determine if they are disjoint.

```plaintext
foreach set $S_i$ {
    foreach other set $S_j$ {
        foreach element $p$ of $S_i$ {
            determine whether $p$ also belongs to $S_j$
        }
        if (no element of $S_i$ belongs to $S_j$) {
            report that $S_i$ and $S_j$ are disjoint
        }
    }
}
```
Polynomial Time: $O(n^k)$ Time

Independent set of size $k$. Given a graph, are there $k$ nodes such that no two are joined by an edge?

$k$ is a constant

$O(n^k)$ solution. Enumerate all subsets of $k$ nodes.

```
foreach subset S of k nodes {
    check whether S in an independent set
    if (S is an independent set)
        report S is an independent set
}
```

- Check whether $S$ is an independent set = $O(k^2)$.
- Number of $k$ element subsets = $\binom{n}{k} = \frac{n (n-1) (n-2) \cdots (n-k+1)}{k (k-1) (k-2) \cdots (2) (1)} \leq \frac{n^k}{k!}$
- $O(k^2 n^k / k!) = O(n^k)$.

poly-time for $k=17$, but not practical
Exponential Time

**Independent set.** Given a graph, what is maximum size of an independent set?

**$O(n^2 2^n)$ solution.** Enumerate all subsets.

```plaintext
S* ← φ
foreach subset S of nodes {
    check whether S in an independent set
    if (S is largest independent set seen so far)
        update S* ← S
}
```
Algorithms — January 29

Today

Wednesday
Priority queues and heaps (Sec. 2.5)

Friday
Quiz on Sec. 2.1-2.4
Open-book (so bring the book)

Monday
Graphs
Ch. 3

Events

- CS120 tutoring, Mo./We./Th. 6-9pm, Wing 231
- CODERS, community service via CS
  - Regular meeting, Wednesdays 3:15pm, 231 Wing
  - Weekly study group, to be scheduled
- CS Club, student ACM chapter
  - Regular meeting, every other Monday (from January 29), 6pm, 3214 Centennial
  - Womyn's group, Tuesday 4pm

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How to do the problems

(In this or any advanced concepts course)
How to do the problems

(In this or any advanced concepts course)

Do them all
▶ In a decent text, the authors develop skills across the problem set
▶ They’re walking you through a story
▶ In a perfect world, my grading staff would go over each problem as you do them
▶ We do not live in a perfect world
▶ I’m going to assign you all the homework (quizzes, etc.) that I’m confident I can grade and return quickly
▶ Still: the best practice is to do them all
▶ This isn’t your only class
▶ And even if it is, that amount of homework may still not be feasible
▶ Not necessarily each of you, individually, alone, separately
▶ Group work is great here
▶ Especially in this size of class
▶ Come see me when you are blocked
How to do the problems

(In this or any advanced concepts course)

Do them all

▶ In an decent text, the authors develop skills across the problem set
▶ They’re walking you through a story
▶ In a perfect world, my grading staff would go over each problem as you do them

▶ We do not live in a perfect world
▶ I’m going to assign you all the homework (quizzes, etc.) that I’m confident I can grade and return quickly
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  ▶ Come see me when you are blocked
Properties

Transitivity.
- If \( f = O(g) \) and \( g = O(h) \) then \( f = O(h) \).
- If \( f = \Omega(g) \) and \( g = \Omega(h) \) then \( f = \Omega(h) \).
- If \( f = \Theta(g) \) and \( g = \Theta(h) \) then \( f = \Theta(h) \).

Additivity.
- If \( f = O(h) \) and \( g = O(h) \) then \( f + g = O(h) \).
- If \( f = \Omega(h) \) and \( g = \Omega(h) \) then \( f + g = \Omega(h) \).
- If \( f = \Theta(h) \) and \( g = O(h) \) then \( f + g = \Theta(h) \).
Asymptotic Bounds for Some Common Functions

**Polynomials.** $a_0 + a_1 n + \ldots + a_d n^d$ is $\Theta(n^d)$ if $a_d > 0$.

**Polynomial time.** Running time is $O(n^d)$ for some constant $d$ independent of the input size $n$.

**Logarithms.** $O(\log_a n) = O(\log_b n)$ for any constants $a, b > 0$.

Logarithms. For every $x > 0$, $\log n = O(n^x)$.

**Exponentials.** For every $r > 1$ and every $d > 0$, $n^d = O(r^n)$.

---

12
So let’s turn back to stable matching

Initialize each person to be free.

while (some man is free and hasn't proposed to every woman) {
    Choose such a man m
    w = 1st woman on m's list to whom m has not yet proposed
    if (w is free)
        assign m and w to be engaged
    else if (w prefers m to her fiancé m')
        assign m and w to be engaged, and m' to be free
    else
        w rejects m
}
Proof of Correctness: Termination

Observation 1. Men propose to women in decreasing order of preference.

Observation 2. Once a woman is matched, she never becomes unmatched; she only "trades up."

Claim. Algorithm terminates after at most \( n^2 \) iterations of while loop.

Pf. Each time through the while loop a man proposes to a new woman. There are only \( n^2 \) possible proposals. □

\[
\begin{array}{c|ccccc}
\text{1st} & \text{2nd} & \text{3rd} & \text{4th} & \text{5th} \\
\hline
\text{Victor} & A & B & C & D & E \\
\text{Wyatt} & B & C & D & A & E \\
\text{Xavier} & C & D & A & B & E \\
\text{Yancey} & D & A & B & C & E \\
\text{Zeus} & A & B & C & D & E \\
\end{array}
\]

\[
\begin{array}{c|ccccc}
\text{1st} & \text{2nd} & \text{3rd} & \text{4th} & \text{5th} \\
\hline
\text{Amy} & W & X & Y & Z & V \\
\text{Bertha} & X & Y & Z & V & W \\
\text{Clare} & Y & Z & V & W & X \\
\text{Diane} & Z & V & W & X & Y \\
\text{Erika} & V & W & X & Y & Z \\
\end{array}
\]

\( n(n-1) + 1 \) proposals required
Proof of Correctness: Perfection

Claim. All men and women get matched.
Pf. (by contradiction)

- Suppose, for sake of contradiction, that Zeus is not matched upon termination of algorithm.
- Then some woman, say Amy, is not matched upon termination.
- By Observation 2, Amy was never proposed to.
- But, Zeus proposes to everyone, since he ends up unmatched.
Proof of Correctness: Stability

**Claim.** No unstable pairs.

**Pf.** (by contradiction)

- Suppose A-Z is an unstable pair: each prefers each other to partner in Gale-Shapley matching $S^*$.

- **Case 1:** Z never proposed to A.
  - $\Rightarrow$ Z prefers his GS partner to A.
  - $\Rightarrow$ A-Z is stable.

- **Case 2:** Z proposed to A.
  - $\Rightarrow$ A rejected Z (right away or later)
  - $\Rightarrow$ A prefers her GS partner to Z.
  - $\Rightarrow$ A-Z is stable.

- In either case A-Z is stable, a contradiction.
Summary

**Stable matching problem.** Given n men and n women, and their preferences, find a stable matching if one exists.

**Gale-Shapley algorithm.** Guarantees to find a stable matching for any problem instance.

**Q.** How to implement GS algorithm efficiently?

**Q.** If there are multiple stable matchings, which one does GS find?
Efficient Implementation

Efficient implementation. We describe $O(n^2)$ time implementation.

Representing men and women.
- Assume men are named 1, …, n.
- Assume women are named 1’, …, n’.

Engagements.
- Maintain a list of free men, e.g., in a queue.
- Maintain two arrays $\text{wife}[m]$, and $\text{husband}[w]$.
  - set entry to 0 if unmatched
  - if $m$ matched to $w$ then $\text{wife}[m]=w$ and $\text{husband}[w]=m$

Men proposing.
- For each man, maintain a list of women, ordered by preference.
- Maintain an array $\text{count}[m]$ that counts the number of proposals made by man $m$. 
Women rejecting/accepting.

- Does woman $w$ prefer man $m$ to man $m'$?
- For each woman, create inverse of preference list of men.
- Constant time access for each query after $O(n)$ preprocessing.

```
for i = 1 to n
    inverse[pref[i]] = i
```

Amy prefers man 3 to 6 since $\text{inverse}[3] < \text{inverse}[6]$

<table>
<thead>
<tr>
<th>Pref</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amy</td>
<td>8</td>
<td>3</td>
<td>7</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inverse</th>
<th>4th</th>
<th>8th</th>
<th>2nd</th>
<th>5th</th>
<th>6th</th>
<th>7th</th>
<th>3rd</th>
<th>1st</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amy</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>
Understanding the Solution

**Q.** For a given problem instance, there may be several stable matchings. Do all executions of Gale-Shapley yield the same stable matching? If so, which one?

An instance with two stable matchings.
- A-X, B-Y, C-Z.
- A-Y, B-X, C-Z.

<table>
<thead>
<tr>
<th></th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xavier</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>Yancey</td>
<td>B</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>Zeus</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Amy</td>
<td>Y</td>
<td>X</td>
<td>Z</td>
</tr>
<tr>
<td>Bertha</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>Clare</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
</tbody>
</table>
Understanding the Solution

**Q.** For a given problem instance, there may be several stable matchings. Do all executions of Gale-Shapley yield the same stable matching? If so, which one?

**Def.** Man $m$ is a valid partner of woman $w$ if there exists some stable matching in which they are matched.

**Man-optimal assignment.** Each man receives best valid partner.

**Claim.** All executions of GS yield man-optimal assignment, which is a stable matching!
- No reason a priori to believe that man-optimal assignment is perfect, let alone stable.
- Simultaneously best for each and every man.
Man Optimality

Claim. GS matching S* is man-optimal.
Pf. (by contradiction)

- Suppose some man is paired with someone other than best partner. Men propose in decreasing order of preference ⇒ some man is rejected by valid partner.
- Let Y be first such man, and let A be first valid woman that rejects him.
- Let S be a stable matching where A and Y are matched.
- When Y is rejected, A forms (or reaffirms) engagement with a man, say Z, whom she prefers to Y.
- Let B be Z's partner in S.
- Z not rejected by any valid partner at the point when Y is rejected by A. Thus, Z prefers A to B.
- But A prefers Z to Y.
- Thus A-Z is unstable in S. □

since this is first rejection by a valid partner
Stable Matching Summary

**Stable matching problem.** Given preference profiles of $n$ men and $n$ women, find a stable matching.

- no man and woman prefer to be with each other than assigned partner

**Gale-Shapley algorithm.** Finds a stable matching in $O(n^2)$ time.

**Man-optimality.** In version of GS where men propose, each man receives best valid partner.

- $w$ is a valid partner of $m$ if there exist some stable matching where $m$ and $w$ are paired

**Q.** Does man-optimality come at the expense of the women?
**Woman Pessimality**

**Woman-pessimal assignment.** Each woman receives worst valid partner.

**Claim.** GS finds **woman-pessimal** stable matching $S^*$. 

**Pf.**
- Suppose $A-Z$ matched in $S^*$, but $Z$ is not worst valid partner for $A$.
- There exists stable matching $S$ in which $A$ is paired with a man, say $Y$, whom she likes less than $Z$.
- Let $B$ be $Z$'s partner in $S$.
- $Z$ prefers $A$ to $B$. $\leftarrow \text{man-optimality}$
- Thus, $A-Z$ is an unstable in $S$. □

<table>
<thead>
<tr>
<th>$S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amy-Yancey</td>
</tr>
<tr>
<td>Bertha-Zeus</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>
Lessons Learned

Powerful ideas learned in course.
- Isolate underlying structure of problem.
- Create useful and efficient algorithms.

Potentially deep social ramifications. [legal disclaimer]
Today
Priority queues and heaps (Sec. 2.5)

Friday
Quiz on Sec. 2.1-2.4
  ▶ Let’s also revisit Exercise 1.4 on the quiz
Open-book (so bring the book)

Contact information
  ▶ Web: cs.uwlax.edu/~jmaraist
  ▶ Email: jmaraist@uwlax.edu
    ▶ Expect replies within a (business) day (but often faster) during the semester
  ▶ Office hours through spring break
    ▶ Tuesdays 1:30-3:30pm
    ▶ Wednesdays 4-5pm
    ▶ Fridays 2-3:30pm
  ▶ Or by appointment
    ▶ 15-minutes slots, email at least a day ahead
Designing priority queues

Simple implementations of priority queues
- One queue, with the first of highest priority marked
- Multiple queues, one for each priority
- Single array or linked list

What is the time cost for
- Insertion of a new element
  - Remember that we must find the right queue
- Finding the minimum element
- Deletion of the minimum element
- Deletion of an arbitrary element

Can we do better than linear time for all of them?
Heap implementation

A tree implemented as an array

- The parent of node \( n \) is \( n/2 \) (rounding down)
- The children of node \( n \) are nodes \( 2n \) and \( 2n+1 \)
- We are assuming a fixed maximum size
Each node’s key is at least as large as its parent’s.

Figure 2.3 Values in a heap shown as a binary tree on the left, and represented as an array on the right. The arrows show the children for the top three nodes in the tree.
Figure 2.4 The Heapify-up process. Key 3 (at position 16) is too small (on the left). After swapping keys 3 and 11, the heap violation moves one step closer to the root of the tree (on the right).
Algorithm 2.8, page 61

Heapify-up(H,i):
    If $i > 1$ then
        let $j = \text{parent}(i) = \lfloor i/2 \rfloor$
        If key[H[i]] < key[H[j]] then
            swap the array entries H[i] and H[j]
            Heapify-up(H,j)
        Endif
    Endif
Endif
The Heapify-down process is moving element \( w \) down, toward the leaves.

**Figure 2.5** The Heapify-down process: Key 21 (at position 3) is too big (on the left). After swapping keys 21 and 7, the heap violation moves one step closer to the bottom of the tree (on the right).
Algorithm 2.9, page 63

Heapify-down(H,i):
    Let n = length(H)
    If 2i > n then
        Terminate with H unchanged
    Else if 2i < n then
        Let left = 2i, and right = 2i + 1
        Let j be the index that minimizes key[H[left]] and key[H[right]]
    Else if 2i = n then
        Let j = 2i
    Endif
    If key[H[j]] < key[H[i]] then
        swap the array entries H[i] and H[j]
    Endif
    Heapify-down(H,j)

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So what are the costs?

- Insertion of a new element
- Finding the minimum element
- Deletion of an arbitrary (possibly the minimum) element
So what are the costs?

- Insertion of a new element
  - Add it to the end, then heapify-up, then down
  - $O(\log n)$
- Finding the minimum element
- Deletion of an arbitrary (possibly the minimum) element
So what are the costs?

- Insertion of a new element
  - Add it to the end, then heapify-up, then down
  - $O(\log n)$
- Finding the minimum element
  - Always at the top — constant
- Deletion of an arbitrary (possibly the minimum) element
So what are the costs?

- Insertion of a new element
  - Add it to the end, then heapify-up, then down
  - $O(\log n)$
- Finding the minimum element
  - Always at the top — constant
- Deletion of an arbitrary (possibly the minimum) element
  - Move element at maximum position to point to be deleted, then heapify-up, then down
  - $O(\log n)$
Today
Graphs (Ch. 3)

Wednesday
More graphs

Friday

- Problems due: from Chapter 2, exercise 7; from Chapter 3, exercises 1-2.

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Undirected Graphs

Undirected graph. \( G = (V, E) \)

- \( V = \) nodes.
- \( E = \) edges between pairs of nodes.
- Captures pairwise relationship between objects.
- Graph size parameters: \( n = |V|, m = |E| \).

\[ V = \{ 1, 2, 3, 4, 5, 6, 7, 8 \} \]
\[ E = \{ 1-2, 1-3, 2-3, 2-4, 2-5, 3-5, 3-7, 3-8, 4-5, 5-6 \} \]
\( n = 8 \)
\( m = 11 \)
World Wide Web

Web graph.
- Node: web page.
- Edge: hyperlink from one page to another.
9-11 Terrorist Network

Social network graph.
- Node: people.
- Edge: relationship between two people.

Paths and Connectivity

Def. A path in an undirected graph $G = (V, E)$ is a sequence $P$ of nodes $v_1, v_2, \ldots, v_{k-1}, v_k$ with the property that each consecutive pair $v_i, v_{i+1}$ is joined by an edge in $E$.

Def. A path is simple if all nodes are distinct.

Def. An undirected graph is connected if for every pair of nodes $u$ and $v$, there is a path between $u$ and $v$. 

![Graph Diagram]
Cycles

Def. A cycle is a path $v_1, v_2, ..., v_{k-1}, v_k$ in which $v_1 = v_k$, $k > 2$, and the first $k-1$ nodes are all distinct.

cycle $C = 1-2-4-5-3-1$
Trees

Def. An undirected graph is a tree if it is connected and does not contain a cycle.

Theorem. Let $G$ be an undirected graph on $n$ nodes. Any two of the following statements imply the third.
- $G$ is connected.
- $G$ does not contain a cycle.
- $G$ has $n-1$ edges.
Rooted Trees

**Rooted tree.** Given a tree $T$, choose a root node $r$ and orient each edge away from $r$.

**Importance.** Models hierarchical structure.
Phylogeny Trees

Phylogeny trees. Describe evolutionary history of species.
GUI Containment Hierarchy

GUI containment hierarchy. Describe organization of GUI widgets.

Reference: http://java.sun.com/docs/books/tutorial/uiswing/overview/anatomy.html
Connectivity

\textbf{s-t connectivity problem.} Given two node }s\text{ and }t\text{, is there a path between }s\text{ and }t\text{?}

\textbf{s-t shortest path problem.} Given two node }s\text{ and }t\text{, what is the length of the shortest path between }s\text{ and }t\text{?}

\textbf{Applications.}
- Friendster.
- Maze traversal.
- Kevin Bacon number.
- Fewest number of hops in a communication network.
Graph Representation: Adjacency Matrix

**Adjacency matrix.** n-by-n matrix with $A_{uv} = 1$ if (u, v) is an edge.

- Two representations of each edge.
- Space proportional to $n^2$.
- Checking if (u, v) is an edge takes $\Theta(1)$ time.
- Identifying all edges takes $\Theta(n^2)$ time.

![Graph representation with adjacency matrix](image)
**Graph Representation: Adjacency List**

**Adjacency list.** Node indexed array of lists.
- Two representations of each edge.
- Space proportional to $m + n$.
- Checking if $(u, v)$ is an edge takes $O(\text{deg}(u))$ time.
- Identifying all edges takes $\Theta(m + n)$ time.
Breadth First Search

**BFS intuition.** Explore outward from $s$ in all possible directions, adding nodes one "layer" at a time.

**BFS algorithm.**
- $L_0 = \{ s \}$.
- $L_1 =$ all neighbors of $L_0$.
- $L_2 =$ all nodes that do not belong to $L_0$ or $L_1$, and that have an edge to a node in $L_1$.
- $L_{i+1} =$ all nodes that do not belong to an earlier layer, and that have an edge to a node in $L_i$.

**Theorem.** For each $i$, $L_i$ consists of all nodes at distance exactly $i$ from $s$. There is a path from $s$ to $t$ iff $t$ appears in some layer.
**Breadth First Search**

**Property.** Let $T$ be a BFS tree of $G = (V, E)$, and let $(x, y)$ be an edge of $G$. Then the level of $x$ and $y$ differ by at most 1.
Theorem. The above implementation of BFS runs in $O(m + n)$ time if the graph is given by its adjacency representation.

Pf.

- Easy to prove $O(n^2)$ running time:
  - at most $n$ lists $L[i]$
  - each node occurs on at most one list; for loop runs $\leq n$ times
  - when we consider node $u$, there are $\leq n$ incident edges $(u, v)$, and we spend $O(1)$ processing each edge

- Actually runs in $O(m + n)$ time:
  - when we consider node $u$, there are $\text{deg}(u)$ incident edges $(u, v)$
  - total time processing edges is $\sum_{u \in V} \text{deg}(u) = 2m$

$\downarrow$

Each edge $(u, v)$ is counted exactly twice in sum: once in $\text{deg}(u)$ and once in $\text{deg}(v)$
Connected Component

Connected component. Find all nodes reachable from $s$.

Connected component containing node 1 = $\{1, 2, 3, 4, 5, 6, 7, 8\}$. 
Flood Fill

**Flood fill.** Given lime green pixel in an image, change color of entire blob of neighboring lime pixels to blue.

- **Node:** pixel.
- **Edge:** two neighboring lime pixels.
- **Blob:** connected component of lime pixels.

![Image of Tux Paint software with a green blob filled with blue]

*recolor lime green blob to blue*
Flood Fill

Flood fill. Given lime green pixel in an image, change color of entire blob of neighboring lime pixels to blue.

- **Node:** pixel.
- **Edge:** two neighboring lime pixels.
- **Blob:** connected component of lime pixels.

recolor lime green blob to blue
Connected Component

**Connected component.** Find all nodes reachable from s.

---

R will consist of nodes to which s has a path
Initially $R = \{s\}$
While there is an edge $(u, v)$ where $u \in R$ and $v \notin R$
    Add $v$ to $R$
Endwhile

---

**Theorem.** Upon termination, R is the connected component containing s.
- BFS = explore in order of distance from s.
- DFS = explore in a different way.
Bipartite Graphs

**Def.** An undirected graph $G = (V, E)$ is *bipartite* if the nodes can be colored red or blue such that every edge has one red and one blue end.

**Applications.**
- Stable marriage: men = red, women = blue.
- Scheduling: machines = red, jobs = blue.
More formal version of the definition:

An undirected graph $G = (V, E)$ is bipartite if there exist sets $V_1$ and $V_2$ such that

- $V_1 \cup V_2 = V$
- $V_1 \cap V_2 = \emptyset$
- For every edge $(v_1, v_2) \in E$, either
  - $v_1 \in V_1$ and $v_2 \in V_2$, or
  - $v_1 \in V_2$ and $v_2 \in V_1$
Testing bipartiteness. Given a graph $G$, is it bipartite?

- Many graph problems become:
  - easier if the underlying graph is bipartite (matching)
  - tractable if the underlying graph is bipartite (independent set)
- Before attempting to design an algorithm, we need to understand structure of bipartite graphs.
Lemma. If a graph $G$ is bipartite, it cannot contain an odd length cycle.

Pf. Not possible to 2-color the odd cycle, let alone $G$. 
Lemma. Let $G$ be a connected graph, and let $L_0, \ldots, L_k$ be the layers produced by BFS starting at node $s$. Exactly one of the following holds.

(i) No edge of $G$ joins two nodes of the same layer, and $G$ is bipartite.
(ii) An edge of $G$ joins two nodes of the same layer, and $G$ contains an odd-length cycle (and hence is not bipartite).
**Bipartite Graphs**

**Lemma.** Let $G$ be a connected graph, and let $L_0, \ldots, L_k$ be the layers produced by BFS starting at node $s$. Exactly one of the following holds.

(i) No edge of $G$ joins two nodes of the same layer, and $G$ is bipartite.

(ii) An edge of $G$ joins two nodes of the same layer, and $G$ contains an odd-length cycle (and hence is not bipartite).

**Pf.** (i)

- Suppose no edge joins two nodes in adjacent layers.
- By previous lemma, this implies all edges join nodes on same level.
- Bipartition: red = nodes on odd levels, blue = nodes on even levels.

![Diagram](image)

CASE (i)

$L_1$  $L_2$  $L_3$
Lemma. Let $G$ be a connected graph, and let $L_0, \ldots, L_k$ be the layers produced by BFS starting at node $s$. Exactly one of the following holds.

(i) No edge of $G$ joins two nodes of the same layer, and $G$ is bipartite.
(ii) An edge of $G$ joins two nodes of the same layer, and $G$ contains an odd-length cycle (and hence is not bipartite).

Pf. (ii)

- Suppose $(x, y)$ is an edge with $x, y$ in same level $L_j$.
- Let $z = \text{lca}(x, y) = \text{lowest common ancestor}$.
- Let $L_i$ be level containing $z$.
- Consider cycle that takes edge from $x$ to $y$, then path from $y$ to $z$, then path from $z$ to $x$.
- Its length is $1 + (j-i) + (j-i)$, which is odd. □

\[ (x, y) \quad \text{path from} \quad y \text{ to } z \quad \text{path from} \quad z \text{ to } x \]
Corollary. A graph $G$ is bipartite iff it contain no odd length cycle.
Directed Graphs

**Directed graph.** $G = (V, E)$
- Edge $(u, v)$ goes from node $u$ to node $v$.

**Ex.** Web graph - hyperlink points from one web page to another.
- Directedness of graph is crucial.
- Modern web search engines exploit hyperlink structure to rank web pages by importance.
Ecological Food Web

Food web graph.
- Node = species.
- Edge = from prey to predator.

Graph Search

Directed reachability. Given a node $s$, find all nodes reachable from $s$.

Directed $s$-$t$ shortest path problem. Given two node $s$ and $t$, what is the length of the shortest path between $s$ and $t$?

Graph search. BFS extends naturally to directed graphs.

Web crawler. Start from web page $s$. Find all web pages linked from $s$, either directly or indirectly.
Strong Connectivity

Def. Node u and v are **mutually reachable** if there is a path from u to v and also a path from v to u.

Def. A graph is **strongly connected** if every pair of nodes is mutually reachable.

Lemma. Let s be any node. G is strongly connected iff every node is reachable from s, and s is reachable from every node.

Pf. ⇒ Follows from definition.
Pf. ⇐ Path from u to v: concatenate u-s path with s-v path. Path from v to u: concatenate v-s path with s-u path. □

\[ \text{ok if paths overlap} \]
Theorem. Can determine if $G$ is strongly connected in $O(m + n)$ time.

Pf.

- Pick any node $s$.
- Run BFS from $s$ in $G$.
- Run BFS from $s$ in $G^\text{rev}$.
- Return true iff all nodes reached in both BFS executions.
- Correctness follows immediately from previous lemma.

![Diagram of strongly connected and not strongly connected graphs]
Directed Acyclic Graphs

Def. An **DAG** is a directed graph that contains no directed cycles.

Ex. Precedence constraints: edge \((v_i, v_j)\) means \(v_i\) must precede \(v_j\).

Def. A topological order of a directed graph \(G = (V, E)\) is an ordering of its nodes as \(v_1, v_2, ..., v_n\) so that for every edge \((v_i, v_j)\) we have \(i < j\).

\[ a \text{ DAG} \]

\[ a \text{ topological ordering} \]
Precedence Constraints

Precedence constraints. Edge \((v_i, v_j)\) means task \(v_i\) must occur before \(v_j\).

Applications.

- Course prerequisite graph: course \(v_i\) must be taken before \(v_j\).
- Compilation: module \(v_i\) must be compiled before \(v_j\). Pipeline of computing jobs: output of job \(v_i\) needed to determine input of job \(v_j\).
Directed Acyclic Graphs

**Lemma.** If $G$ has a topological order, then $G$ is a DAG.

**Pf.** (by contradiction)
- Suppose that $G$ has a topological order $v_1, \ldots, v_n$ and that $G$ also has a directed cycle $C$. Let's see what happens.
- Let $v_i$ be the lowest-indexed node in $C$, and let $v_j$ be the node just before $v_i$; thus $(v_j, v_i)$ is an edge.
- By our choice of $i$, we have $i < j$.
- On the other hand, since $(v_j, v_i)$ is an edge and $v_1, \ldots, v_n$ is a topological order, we must have $j < i$, a contradiction. □
Directed Acyclic Graphs

Lemma. If $G$ has a topological order, then $G$ is a DAG.

Q. Does every DAG have a topological ordering?

Q. If so, how do we compute one?
Lemma. If $G$ is a DAG, then $G$ has a node with no incoming edges.

Pf. (by contradiction)
- Suppose that $G$ is a DAG and every node has at least one incoming edge. Let's see what happens.
- Pick any node $v$, and begin following edges backward from $v$. Since $v$ has at least one incoming edge $(u, v)$ we can walk backward to $u$.
- Then, since $u$ has at least one incoming edge $(x, u)$, we can walk backward to $x$.
- Repeat until we visit a node, say $w$, twice.
- Let $C$ denote the sequence of nodes encountered between successive visits to $w$. $C$ is a cycle.
Lemma. If $G$ is a DAG, then $G$ has a topological ordering.

Pf. (by induction on $n$)

- Base case: true if $n = 1$.
- Given DAG on $n > 1$ nodes, find a node $v$ with no incoming edges.
- $G - \{ v \}$ is a DAG, since deleting $v$ cannot create cycles.
- By inductive hypothesis, $G - \{ v \}$ has a topological ordering.
- Place $v$ first in topological ordering; then append nodes of $G - \{ v \}$ in topological order. This is valid since $v$ has no incoming edges.

To compute a topological ordering of $G$:
Find a node $v$ with no incoming edges and order it first
Delete $v$ from $G$
Recursively compute a topological ordering of $G - \{ v \}$ and append this order after $v$
**Theorem.** Algorithm finds a topological order in $O(m + n)$ time.

**Pf.**

- **Maintain the following information:**
  - $\text{count}[w] =$ remaining number of incoming edges
  - $S =$ set of remaining nodes with no incoming edges
- **Initialization:** $O(m + n)$ via single scan through graph.
- **Update:** to delete $v$
  - remove $v$ from $S$
  - decrement $\text{count}[w]$ for all edges from $v$ to $w$, and add $w$ to $S$ if $c_{\text{count}[w]}$ hits 0
  - this is $O(1)$ per edge
Algorithms — February 7

Today
Graphs (Ch. 3)
▶ You should find the collected slides online now

Friday
▶ Graphs, greedy algorithms
▶ Problems due: from Chapter 2, exercise 7; from Chapter 3, exercises 1-2

Contact information
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  ▶ Expect replies within a (business) day (but often faster) during the semester
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  ▶ Fridays 2-3:30pm
▶ Or by appointment
  ▶ 15-minutes slots, email at least a day ahead
Trees

**Def.** An undirected graph is a tree if it is connected and does not contain a cycle.

**Theorem.** Let $G$ be an undirected graph on $n$ nodes. Any two of the following statements imply the third.
- $G$ is connected.
- $G$ does not contain a cycle.
- $G$ has $n-1$ edges.
Proof (part 1)
Given: $G$ has $n$ nodes, is connected and acyclic
Prove: $G$ has $n - 1$ edges
Proof (part 1)
Given: $G$ has $n$ nodes, is connected and acyclic
Prove: $G$ has $n - 1$ edges

Lemma: If $G$ is acyclic and connected, then $G$ has at least one vertex which connects to only one edge
  ▶ Assume the contrary
Proof (part 1)
Given: \( G \) has \( n \) nodes, is connected and acyclic
Prove: \( G \) has \( n - 1 \) edges

Lemma: If \( G \) is acyclic and connected, then \( G \) has at least one vertex which connects to only one edge

- Assume the contrary
- Let \( v_a \) one endpoint of the longest simple path \( p \) in \( G \)
  - (Or if there is more than one simple path with the same maximum length, pick any one of them)
Proof (part 1)
Given: $G$ has $n$ nodes, is connected and acyclic
Prove: $G$ has $n - 1$ edges

Lemma: If $G$ is acyclic and connected, then $G$ has at least one vertex which connects to only one edge

- Assume the contrary
- Let $v_a$ one endpoint of the longest simple path $p$ in $G$
  - (Or if there is more than one simple path with the same maximum length, pick any one of them)
- But $v$ must have another edge attached to it. Does that edge lead to a vertex which is in $p$?

Main result: by induction on the number $n$ of nodes

- Case $n = 2$: construct directly
- For $n > 2$: by the lemma, there is some vertex $v$ attached only to edge $e$ in $G = (V, E)$
  - Consider the graph $G' = (V \setminus \{v\}, E \setminus \{e\})$
  - $G'$ is still connected, still acyclic, and has $n - 1$ nodes
  - So by the induction hypothesis, $G'$ has $n - 2$ edges
  - $G$ has one more edge than $G'$, so $n - 1$ edges — QED
Proof (part 1)
Given: $G$ has $n$ nodes, is connected and acyclic
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  - If yes, then $G$ has a cycle

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  - If yes, then $G$ has a cycle
  - If no, then $p$ was not the longest simple path

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  - If yes, then $G$ has a cycle
  - If no, then $p$ was not the longest simple path
- Either way, we reach a contradiction, so we reject the assumption, and conclude that $G$ does have at least one vertex which connects to only one edge

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$\quad\quad$ If yes, then $G$ has a cycle

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$\quad$ For $n > 2$: by the lemma, there is some vertex $v$ attached only to edge $e$ in $G = (V, E)$

$\quad\quad$ Consider the graph $G' = (V \setminus \{v\}, E \setminus \{e\})$

$\quad\quad$ $G'$ is still connected, still acyclic, and has $n - 1$ nodes

$\quad\quad$ So by the induction hypothesis, $G'$ has $n - 2$ edges

$G$ has one more edge than $G'$, so $n - 1$ edges — QED
Proof (part 1)

Given: G has $n$ nodes, is connected and acyclic
Prove: G has $n - 1$ edges

Lemma: If G is acyclic and connected, then G has at least one vertex which connects to only one edge

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- Let $v_a$ one endpoint of the longest simple path $p$ in G
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Proof (part 2)

Given: $G = (\{v_1, \cdots, v_n\}, \{e_1, \cdots, e_{n-1}\})$ is connected,
Prove: $G$ does not contain a cycle
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Given: \( G = (\{v_1, \cdots, v_n\}, \{e_1, \cdots, e_{n-1}\}) \) is connected,
Prove: \( G \) does not contain a cycle

- Assume the contrary: that \( G \) does contain a cycle
  - Moreover we can assume without loss of generality that the largest cycle
    - Has \( h \) edges, and
    - Runs from \( v_1 \) through \( v_h \) and back to \( v_1 \)
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  - Thus there are $n - h$ vertices not in the cycle

- But this contradicts the assumption that $G$ has $n-1$ edges
- So we reject the assumption, and conclude that $G$ is acyclic — QED
Given: $G = (\{v_1, \cdots, v_n\}, \{e_1, \cdots, e_{n-1}\})$ is connected,
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  ▷ Moreover we can assume without loss of generality that the largest cycle
    ▷ Has $h$ edges, and
    ▷ Runs from $v_1$ through $v_h$ and back to $v_1$
  ▷ Thus there are $n - h$ vertices not in the cycle
    ▷ Since $G$ is connected, we can order them so that for every $v_j$ with $j > h$, there is at least one link from $v_j$ to some $v_i$ with $i < j$
    ▷ This means that there are (at least) $n - h$ edges attached to these vertices
Proof (part 2)

Given: \( G = (\{v_1, \cdots, v_n\}, \{e_1, \cdots, e_{n-1}\}) \) is connected,
Prove: \( G \) does not contain a cycle

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  - Moreover we can assume without loss of generality that the largest cycle
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  - Thus there are \( n - h \) vertices not in the cycle
    - Since \( G \) is connected, we can order them so that for every \( v_j \) with \( j > h \), there is at least one link from \( v_j \) to some \( v_i \) with \( i < j \)
    - This means that there are (at least) \( n - h \) edges attached to these vertices
  - So there must be at least \( h + n - h = n \) edges in \( G \)
    - But this contradicts the assumption that \( G \) has \( n - 1 \) edges
    - So we reject the assumption, and conclude that \( G \) is acyclic — QED
Given: $G = (\{v_1, \cdots, v_n\}, \{e_1, \cdots, e_{n-1}\})$ is acyclic
Prove: $G$ is connected
Proof (part 3)

Given: $G = (\{v_1, \cdots, v_n\}, \{e_1, \cdots, e_{n-1}\})$ is acyclic
Prove: $G$ is connected

By induction on the number $n$ of nodes
Proof (part 3)

Given: $G = (\{v_1, \cdots, v_n\}, \{e_1, \cdots, e_{n-1}\})$ is acyclic
Prove: $G$ is connected

By induction on the number $n$ of nodes
  ▶ Base case $n = 3$, observing the construction directly
Given: $G = (\{v_1, \cdots, v_n\}, \{e_1, \cdots, e_{n-1}\})$ is acyclic
Prove: $G$ is connected

By induction on the number $n$ of nodes

- Base case $n = 3$, observing the construction directly
- For $n > 3$, rely again on the lemma to remove one vertex $v$ and its sole edge $e$ for $G'$
  - Now $G'$ is acyclic, and connected
  - And $G$ is also connected, since $v$ has a path to any other node via $e$ — QED
Rooted Trees

**Rooted tree.** Given a tree $T$, choose a root node $r$ and orient each edge away from $r$.

**Importance.** Models hierarchical structure.
Phylogeny Trees

Phylogeny trees. Describe evolutionary history of species.
GUI Containment Hierarchy

GUI containment hierarchy. Describe organization of GUI widgets.

Reference: http://java.sun.com/docs/books/tutorial/uiswing/overview/anatomy.html
Connectivity

**s-t connectivity problem.** Given two node $s$ and $t$, is there a path between $s$ and $t$?

**s-t shortest path problem.** Given two node $s$ and $t$, what is the length of the shortest path between $s$ and $t$?

**Applications.**
- Friendster.
- Maze traversal.
- Kevin Bacon number.
- Fewest number of hops in a communication network.
**Graph Representation: Adjacency Matrix**

**Adjacency matrix.** n-by-n matrix with $A_{uv} = 1$ if (u, v) is an edge.

- Two representations of each edge.
- Space proportional to $n^2$.
- Checking if (u, v) is an edge takes $\Theta(1)$ time.
- Identifying all edges takes $\Theta(n^2)$ time.

$$
\begin{bmatrix}
0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\
0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 & 0 & 0 & 1 & 0
\end{bmatrix}
$$
Graph Representation: Adjacency List

**Adjacency list.** Node indexed array of lists.

- Two representations of each edge.
- Space proportional to $m + n$.
- Checking if $(u, v)$ is an edge takes $O(\text{deg}(u))$ time.
- Identifying all edges takes $\Theta(m + n)$ time.
Breadth First Search

**BFS intuition.** Explore outward from s in all possible directions, adding nodes one "layer" at a time.

**BFS algorithm.**
- $L_0 = \{ s \}$.
- $L_1$ = all neighbors of $L_0$.
- $L_2$ = all nodes that do not belong to $L_0$ or $L_1$, and that have an edge to a node in $L_1$.
- $L_{i+1}$ = all nodes that do not belong to an earlier layer, and that have an edge to a node in $L_i$.

**Theorem.** For each $i$, $L_i$ consists of all nodes at distance exactly $i$ from $s$. There is a path from $s$ to $t$ iff $t$ appears in some layer.
Algorithms — February 9

Today

- Graphs
- Problems due: from Chapter 2, exercise 7; from Chapter 3, exercises 1-2

Monday

- Greedy algorithms

Next Friday

- Problems due: from Chapter 2, exercise 7; from Chapter 3, exercises 1-2

Contact information

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Theorem. For each $i$, $L_i$ consists of all nodes at distance exactly $i$ from $s$. There is a path from $s$ to $t$ iff $t$ appears in some layer.
Breadth First Search

**Property.** Let $T$ be a BFS tree of $G = (V, E)$, and let $(x, y)$ be an edge of $G$. Then the level of $x$ and $y$ differ by at most 1.

![Diagram of BFS tree](image)
Graph Representation: Adjacency List

**Adjacency list.** Node indexed array of lists.
- Two representations of each edge.
- Space proportional to $m + n$.
- Checking if $(u, v)$ is an edge takes $O(\text{deg}(u))$ time.
- Identifying all edges takes $\Theta(m + n)$ time.
Breadth First Search: Analysis

**Theorem.** The above implementation of BFS runs in $O(m + n)$ time if the graph is given by its adjacency representation.

**Pf.**
- Easy to prove $O(n^2)$ running time:
  - at most $n$ lists $L[i]$
  - each node occurs on at most one list; for loop runs $\leq n$ times
  - when we consider node $u$, there are $\leq n$ incident edges $(u, v)$, and we spend $O(1)$ processing each edge

- Actually runs in $O(m + n)$ time:
  - when we consider node $u$, there are $\text{deg}(u)$ incident edges $(u, v)$
  - total time processing edges is $\Sigma_{u \in V} \text{deg}(u) = 2m$
    - each edge $(u, v)$ is counted exactly twice in sum: once in $\text{deg}(u)$ and once in $\text{deg}(v)$
Connected Component

Connected component. Find all nodes reachable from s.

Connected component containing node 1 = \{ 1, 2, 3, 4, 5, 6, 7, 8 \}.
**Flood Fill**

**Flood fill.** Given lime green pixel in an image, change color of entire blob of neighboring lime pixels to blue.

- **Node:** pixel.
- **Edge:** two neighboring lime pixels.
- **Blob:** connected component of lime pixels.

![Diagram of Flood Fill](image)

recolor lime green blob to blue
**Flood Fill**

**Flood fill.** Given lime green pixel in an image, change color of entire blob of neighboring lime pixels to blue.

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**Connected Component**

**Connected component.** Find all nodes reachable from s.

---

\[ R \text{ will consist of nodes to which s has a path} \]

Initially \( R = \{s\} \)

While there is an edge \((u, v)\) where \( u \in R \) and \( v \notin R \)
    Add \( v \) to \( R \)
Endwhile

---

**Theorem.** Upon termination, \( R \) is the connected component containing \( s \).

- **BFS** = explore in order of distance from \( s \).
- **DFS** = explore in a different way.
Bipartite Graphs

**Def.** An undirected graph $G = (V, E)$ is **bipartite** if the nodes can be colored red or blue such that every edge has one red and one blue end.

**Applications.**
- Stable marriage: men = red, women = blue.
- Scheduling: machines = red, jobs = blue.

![A bipartite graph](image-url)
Bipartite graph

More formal version of the definition:

An undirected graph $G = (V, E)$ is bipartite if there exist sets $V_1$ and $V_2$ such that

- $V_1 \cup V_2 = V$
- $V_1 \cap V_2 = \emptyset$
- For every edge $(v_1, v_2) \in E$, either
  - $v_1 \in V_1$ and $v_2 \in V_2$, or
  - $v_1 \in V_2$ and $v_2 \in V_1$
Testing bipartiteness. Given a graph $G$, is it bipartite?

- Many graph problems become:
  - easier if the underlying graph is bipartite (matching)
  - tractable if the underlying graph is bipartite (independent set)
- Before attempting to design an algorithm, we need to understand structure of bipartite graphs.

![a bipartite graph $G$](image1)

![another drawing of $G$](image2)
Lemma. If a graph $G$ is bipartite, it cannot contain an odd length cycle.

Pf. Not possible to 2-color the odd cycle, let alone $G$. 
Lemma. Let $G$ be a connected graph, and let $L_0, \ldots, L_k$ be the layers produced by BFS starting at node $s$. Exactly one of the following holds.

(i) No edge of $G$ joins two nodes of the same layer, and $G$ is bipartite.
(ii) An edge of $G$ joins two nodes of the same layer, and $G$ contains an odd-length cycle (and hence is not bipartite).
Corollary. A graph $G$ is bipartite iff it contain no odd length cycle.
Directed Graphs

Directed graph. $G = (V, E)$
- Edge $(u, v)$ goes from node $u$ to node $v$.

Ex. Web graph - hyperlink points from one web page to another.
- Directedness of graph is crucial.
- Modern web search engines exploit hyperlink structure to rank web pages by importance.
Ecological Food Web

Food web graph.
- **Node** = species.
- **Edge** = from prey to predator.

Graph Search

Directed reachability. Given a node $s$, find all nodes reachable from $s$.

Directed $s$-$t$ shortest path problem. Given two node $s$ and $t$, what is the length of the shortest path between $s$ and $t$?

Graph search. BFS extends naturally to directed graphs.

Web crawler. Start from web page $s$. Find all web pages linked from $s$, either directly or indirectly.
Strong Connectivity

**Def.** Node \( u \) and \( v \) are **mutually reachable** if there is a path from \( u \) to \( v \) and also a path from \( v \) to \( u \).

**Def.** A graph is **strongly connected** if every pair of nodes is mutually reachable.

**Lemma.** Let \( s \) be any node. \( G \) is strongly connected iff every node is reachable from \( s \), and \( s \) is reachable from every node.

**Pf.** \( \Rightarrow \) Follows from definition.

**Pf.** \( \Leftarrow \) Path from \( u \) to \( v \): concatenate \( u-s \) path with \( s-v \) path.
Path from \( v \) to \( u \): concatenate \( v-s \) path with \( s-u \) path. \( \blacksquare \)

ok if paths overlap
Strong Connectivity: Algorithm

**Theorem.** Can determine if \( G \) is strongly connected in \( O(m + n) \) time.

**Pf.**

- Pick any node \( s \).
- Run BFS from \( s \) in \( G \).
- Run BFS from \( s \) in \( G^{rev} \).
- Return true iff all nodes reached in both BFS executions.
- Correctness follows immediately from previous lemma. □

![Diagram](image-url)
Directed Acyclic Graphs

Def. An DAG is a directed graph that contains no directed cycles.

Ex. Precedence constraints: edge $(v_i, v_j)$ means $v_i$ must precede $v_j$.

Def. A topological order of a directed graph $G = (V, E)$ is an ordering of its nodes as $v_1, v_2, ..., v_n$ so that for every edge $(v_i, v_j)$ we have $i < j$. 
Precedence Constraints

Precedence constraints. Edge \((v_i, v_j)\) means task \(v_i\) must occur before \(v_j\).

Applications.
- Course prerequisite graph: course \(v_i\) must be taken before \(v_j\).
- Compilation: module \(v_i\) must be compiled before \(v_j\). Pipeline of computing jobs: output of job \(v_i\) needed to determine input of job \(v_j\).
Today
▶ Graphs, Greedy algorithms

Wednesday
▶ Greedy algorithms

Friday
▶ Greedy algorithms
▶ Problems due: from Chapter 3, exercises 5, 6, 10

Contact information
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    ▶ Expect replies within a (business) day (but often faster) during the semester
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    ▶ Fridays 2-3:30pm
▶ Or by appointment
    ▶ 15-minutes slots, email at least a day ahead
Exercise 3.2

Note the difference between what we can do in an *algorithm* and in a *proof*

- In a proof we can assert the existence of things, maybe with maximum/minimum or other bounds/properties
- In an algorithm, we must give the steps to produce such artifacts (or refer to previous algorithms and their cost)
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- When modifying an algorithm we have already analyzed, we can just give the difference
  - But we must be mindful of non-constant-time changes — they may change the overall cost of the algorithm
  - For example, if we add an *inner* loop
Exercise 3.2

Note the difference between what we can do in an \textit{algorithm} and in a \textit{proof}

- In a proof we can assert the existence of things, maybe with maximum/minimum or other bounds/properties
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  - For example, if we add an \textit{inner} loop

Here: Use a BFS

- Two arrays, indexed by the node number
  - \texttt{visited} contains booleans — usual for BFS
  - Additional array \texttt{via} to contain node numbers, but initially all -1
- When visiting any node
  - Set its \texttt{visited} entry to true as usual
- When enqueuing the neighbor \texttt{j} of node \texttt{i}
  - If \texttt{visited}[j] then we have found a cycle, can stop
    - To retrieve cycle, start from \texttt{via}[i] and \texttt{via}[j]
  - Else set \texttt{via}[j] to \texttt{i}
Lemma. If $G$ has a topological order, then $G$ is a DAG.

Pf. (by contradiction)

- Suppose that $G$ has a topological order $v_1, \ldots, v_n$ and that $G$ also has a directed cycle $C$. Let's see what happens.
- Let $v_i$ be the lowest-indexed node in $C$, and let $v_j$ be the node just before $v_i$; thus $(v_j, v_i)$ is an edge.
- By our choice of $i$, we have $i < j$.
- On the other hand, since $(v_j, v_i)$ is an edge and $v_1, \ldots, v_n$ is a topological order, we must have $j < i$, a contradiction. □
Directed Acyclic Graphs

**Lemma.** If $G$ has a topological order, then $G$ is a DAG.

**Q.** Does every DAG have a topological ordering?

**Q.** If so, how do we compute one?
Directed Acyclic Graphs

Lemma. If $G$ is a DAG, then $G$ has a node with no incoming edges.

Pf. (by contradiction)
- Suppose that $G$ is a DAG and every node has at least one incoming edge. Let's see what happens.
- Pick any node $v$, and begin following edges backward from $v$. Since $v$ has at least one incoming edge $(u, v)$ we can walk backward to $u$.
- Then, since $u$ has at least one incoming edge $(x, u)$, we can walk backward to $x$.
- Repeat until we visit a node, say $w$, twice.
- Let $C$ denote the sequence of nodes encountered between successive visits to $w$. $C$ is a cycle. □

![Directed Acyclic Graph Diagram]
Lemma. If $G$ is a DAG, then $G$ has a topological ordering.

Pf. (by induction on $n$)
- Base case: true if $n = 1$.
- Given DAG on $n > 1$ nodes, find a node $v$ with no incoming edges.
- $G - \{v\}$ is a DAG, since deleting $v$ cannot create cycles.
- By inductive hypothesis, $G - \{v\}$ has a topological ordering.
- Place $v$ first in topological ordering; then append nodes of $G - \{v\}$ in topological order. This is valid since $v$ has no incoming edges.

To compute a topological ordering of $G$:
Find a node $v$ with no incoming edges and order it first
Delete $v$ from $G$
Recursively compute a topological ordering of $G - \{v\}$ and append this order after $v$
Topological Sorting Algorithm: Running Time

**Theorem.** Algorithm finds a topological order in $O(m + n)$ time.

**Pf.**

- Maintain the following information:
  - $\text{count}[w] = \text{remaining number of incoming edges}$
  - $S = \text{set of remaining nodes with no incoming edges}$
- Initialization: $O(m + n)$ via single scan through graph.
- Update: to delete $v$
  - remove $v$ from $S$
  - decrement $\text{count}[w]$ for all edges from $v$ to $w$, and add $w$ to $S$ if $\text{count}[w]$ hits 0
  - this is $O(1)$ per edge
Chapter 4

Greedy Algorithms
Interval scheduling.

- Job $j$ starts at $s_j$ and finishes at $f_j$.
- Two jobs compatible if they don't overlap.
- Goal: find maximum subset of mutually compatible jobs.
Greedy template. Consider jobs in some natural order.
Take each job provided it's compatible with the ones already taken.

- [Earliest start time] Consider jobs in ascending order of $s_j$.
- [Earliest finish time] Consider jobs in ascending order of $f_j$.
- [Shortest interval] Consider jobs in ascending order of $f_j - s_j$.
- [Fewest conflicts] For each job $j$, count the number of conflicting jobs $c_j$. Schedule in ascending order of $c_j$. 
Interval Scheduling: Greedy Algorithms

**Greedy template.** Consider jobs in some natural order. Take each job provided it's compatible with the ones already taken.

- counterexample for earliest start time
- counterexample for shortest interval
- counterexample for fewest conflicts
Interval Scheduling: Greedy Algorithm

Greedy algorithm. Consider jobs in increasing order of finish time. Take each job provided it's compatible with the ones already taken.

Sort jobs by finish times so that \( f_1 \leq f_2 \leq \ldots \leq f_n \).

\[
\begin{align*}
A &\leftarrow \emptyset \\
\text{for } j = 1 \text{ to } n \{ \\
\quad \text{if (job } j \text{ compatible with } A) \\
\quad \quad A &\leftarrow A \cup \{j\} \\
\} \\
\text{return } A
\end{align*}
\]

Implementation. \( O(n \log n) \).
- Remember job \( j^* \) that was added last to \( A \).
- Job \( j \) is compatible with \( A \) if \( s_j \geq f_{j^*} \).
Theorem. Greedy algorithm is optimal.

Pf. (by contradiction)

- Assume greedy is not optimal, and let's see what happens.
- Let $i_1, i_2, \ldots, i_k$ denote set of jobs selected by greedy.
- Let $j_1, j_2, \ldots, j_m$ denote set of jobs in the optimal solution with $i_1 = j_1, i_2 = j_2, \ldots, i_r = j_r$ for the largest possible value of $r$.

![Diagram showing the difference between Greedy and OPT solutions with job $i_{r+1}$ finishing before $j_{r+1}$ and the potential replacement of $j_{r+1}$ with $i_{r+1}$.]
Theorem. Greedy algorithm is optimal.

Pf. (by contradiction)
- Assume greedy is not optimal, and let's see what happens.
- Let $i_1, i_2, \ldots i_k$ denote set of jobs selected by greedy.
- Let $j_1, j_2, \ldots j_m$ denote set of jobs in the optimal solution with $i_1 = j_1, i_2 = j_2, \ldots, i_r = j_r$ for the largest possible value of $r$.

The greedy algorithm solution is still feasible and optimal, but contradicts maximality of $r$. Job $i_{r+1}$ finishes before $j_{r+1}$. Solution still feasible and optimal, but contradicts maximality of $r$. 
Is greed good?

- Very often, it produces inferior solutions
- But sometime it does give the best possible answer
  - And sometimes, it gives *good enough* results
- The skill of using greedy algorithms is in
  1. Picking the order in which we search
  2. Characterizing an "optimal solution"
  3. Demonstrating that an algorithm is optimal
Interval Partitioning

Interval partitioning.
- Lecture $j$ starts at $s_j$ and finishes at $f_j$.
- Goal: find minimum number of classrooms to schedule all lectures so that no two occur at the same time in the same room.

Ex: This schedule uses 4 classrooms to schedule 10 lectures.
Interval Partitioning

Interval partitioning.

- Lecture $j$ starts at $s_j$ and finishes at $f_j$.
- Goal: find minimum number of classrooms to schedule all lectures so that no two occur at the same time in the same room.

Ex: This schedule uses only 3.
Interval Partitioning: Lower Bound on Optimal Solution

**Def.** The depth of a set of open intervals is the maximum number that contain any given time.

**Key observation.** Number of classrooms needed $\geq$ depth.

**Ex:** Depth of schedule below $= 3 \Rightarrow$ schedule below is optimal.

\[
\begin{array}{ccccccccc}
9 & 9:30 & 10 & 10:30 & 11 & 11:30 & 12 & 12:30 & 1 & 1:30 \\
\hline
1 & a & b & c & d & e & f & g & h & i & j
\end{array}
\]

$a, b, c$ all contain 9:30

**Q.** Does there always exist a schedule equal to depth of intervals?
Interval Partitioning: Greedy Algorithm

Greedy algorithm. Consider lectures in increasing order of start time: assign lecture to any compatible classroom.

Sort intervals by starting time so that \( s_1 \leq s_2 \leq \ldots \leq s_n \).
\[
d \leftarrow 0 \quad \text{number of allocated classrooms}
\]

for \( j = 1 \) to \( n \) {
    if (lecture \( j \) is compatible with some classroom \( k \))
        schedule lecture \( j \) in classroom \( k \)
    else
        allocate a new classroom \( d + 1 \)
        schedule lecture \( j \) in classroom \( d + 1 \)
        \( d \leftarrow d + 1 \)
}

Implementation. \( O(n \log n) \).
- For each classroom \( k \), maintain the finish time of the last job added.
- Keep the classrooms in a priority queue.
Interval Partitioning: Greedy Analysis

Observation. Greedy algorithm never schedules two incompatible lectures in the same classroom.

Theorem. Greedy algorithm is optimal.

Pf.

- Let $d = \text{number of classrooms that the greedy algorithm allocates}$.
- Classroom $d$ is opened because we needed to schedule a job, say $j$, that is incompatible with all $d-1$ other classrooms.
- These $d$ jobs each end after $s_j$.
- Since we sorted by start time, all these incompatibilities are caused by lectures that start no later than $s_j$.
- Thus, we have $d$ lectures overlapping at time $s_j + \varepsilon$.
- Key observation $\Rightarrow$ all schedules use $\geq d$ classrooms. □