CS1800 Day 17 (we'll get started at 9:55 so we ensure everybody is here)

Admin:
- HW6 due today
- HW7 (induction) released today (due next Friday)
    - slightly shorter than most:
        - more time to prep for exam2
        - will only count as 80% of other HWs with 100 points (HW7 has only 80 points)
- exam2 is next Friday in class
    - practice exam2 problems (and solution) available now
        - prep tip: don't peek at solutions before you've given a problem your best effort

Content:
- Summation Notation
- Strong induction
- Induction: inequality

We may end a few minutes early today. Please check in afterwards if you have any induction (or other) questions.

Exam2: outline

- ☐ one induction problem (equality or inequality)
- ☐ BFS / DFS orderings
- ☐ Dijkstra's Shortest Path Problem (show all steps, as shown in HW)
- ☐ Bayes Rule Problem
- ☐ Expected Value / Variance Problem
- ☐ Counting style probability (each outcome equally likely)

Summation Notation

$$1+2+4+8+16+32+64$$

$$= 2^0+2^1+2^2+2^3+2^4+2^5+2^6$$

LAST VALUE OF K

$$= \sum_{k=0}^{6} 2^k$$

→ BY PUTTING A PARTICULAR K INTO THIS TEMPLATE, YOU CAN PRODUCE ONE TERM

STARTING VALUE OF K

"The sum of 2^k where k goes from 0 to 6"

In Class Activity: Summation Notation

Express each sum below in summation notation

$9+11+13+15+17$

$\sum_{k=5}^{9} 2k-1 = \sum_{k=0}^{4} 9+2k$

$\sum_{k=1}^{n} k$

$1+2+3+4+5+\ldots+n$

$(9+2\cdot 0)+(9+2\cdot 1)+(9+2\cdot 2)+\ldots$

$9 \quad 11 \quad 13 \quad \ldots$

Compute each sum below (the second one has a pattern and simplifies)

$\sum_{k=10}^{12} 2k = 2\cdot 10+2\cdot 11+2\cdot 12$

$= 2\cdot(10+11+12)$

$= 66$

$\sum_{k=0}^{101} (-1)^k = 1 + -1 + \ldots$

$k=0 \quad k=1 \quad k=2$

$1 + -1 + 1 + -1$

1	-1
0	1
2	3
4	5
$\vdots$	$\vdots$
98	99
100	101

$$\sum_{k=0}^{101} (-1)^k = 0$$

Common Summation Notation Manipulation in Induction Proofs: trimming the last term

The black writing below if excerpt from last class's final ICA. The blue text says the same using summations.

Assume $1+2+3+4+\dots+n = \frac{n(n+1)}{2}$

$$\sum_{k=1}^{n} k = n(n+1)/2$$

THEN $1+2+3+4+\dots+n+(n+1) = \frac{n(n+1)}{2} + (n+1)$

$$\sum_{k=1}^{n+1} k = \left(\sum_{k=1}^{n} k\right) + (n+1) = \frac{n(n+1)}{2} + (n+1)$$

You can trim off last term (immediately above this text) from a summation notation.

Often helpful to apply inductive hypothesis (assumption)

Examining different induction structures: making change with 3 and 4 cent pieces

Claim: Using only 3 and 4 cent coins, one can produce any whole-number of cents greater than or equal to 6

Proof:

Statement n: there exists a way to produce exactly n cents using 3 and 4 cent coins

Base Cases (there are many):

6 cents = 3 + 3   7 cents = 3 + 4   8 cents = 4 + 4

Induction Step: If statement 6, 7, 8, 9, ..., n are all true, then statement n + 1 is true

Assume: some combo of 3 and 4 cent coins produce 6 cents, 7 cents, 8 cents, ... , n cents

Case 1: the combo of 3 and 4 cents to produce n cents includes a 3 cent coin

- replace this 3 cent coin with a 4 cent coin: new combo produces n + 1 cents

Case 2: the combo of 3 and 4 cents to produce n cents doesn't include a 3 cent coin

- it must contain at least two 4 cent coins (n is at least 8, see base cases above)
- replace these two 4 cent coins with three 3 cent coins: new combo produces n + 1 cents

Induction (Strong):

Induction allows us to prove a never-ending sequence of statements: S(1), S(2), S(3), S(4), ...

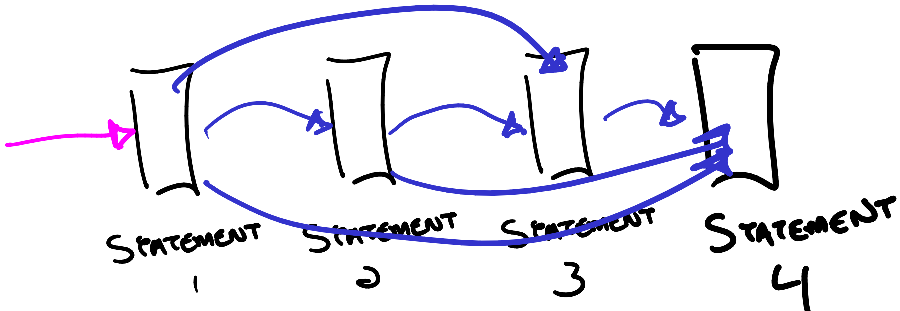
Process:

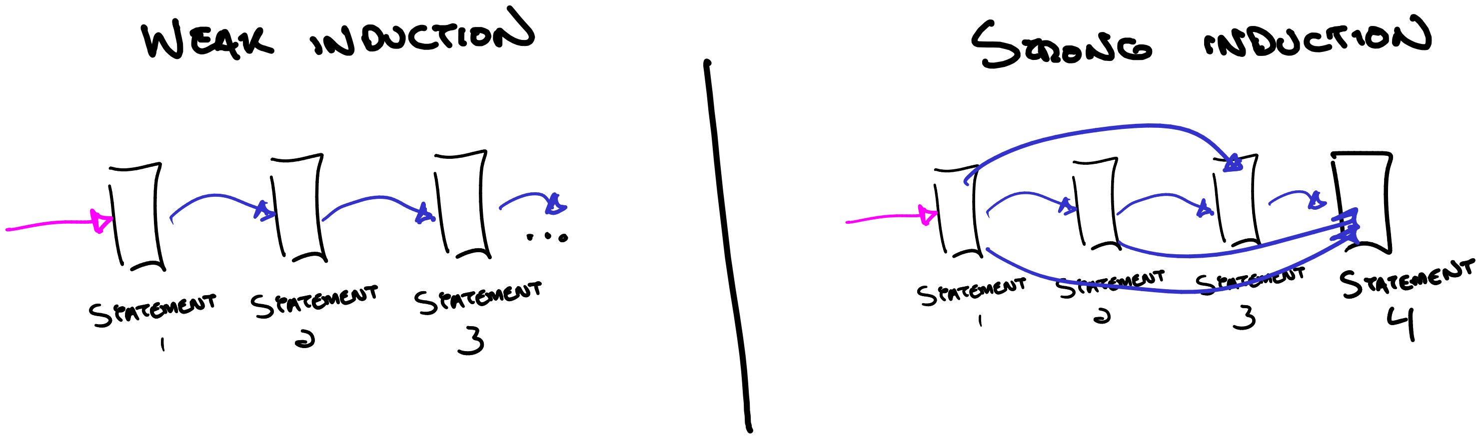
- Prove the first statement, S(n) for some n
- Show that S(1), S(2), ... S(n) implies S(n+1)

Metaphor (Dominos):

To knock over all the dominos

- Push over the first one
- Place each other domino so that if ALL dominos behind it falls, it too will fall





When should I use weak vs strong induction?

Both are always available to you, you may find one method produces a simpler proof (usually weak induction, if it can get the job done).

In Class Activity: Why do we study Induction with inequalities?

Suppose two algorithms both accomplish the same task but take a different number of "computes" to do so.

For an input of size N:

- Algorithm 1 takes: 2^N computes 2^N
- Algorithm 2 takes: N! computes $N!$

Input Size	1	2	3	4	5	6
Algorithm 1 Compute Operations	2	4	8	16	32	64
Algorithm 2 Compute Operations	1	2	6	24	120	720

- Complete the table above
- which algorithm would you prefer for a list of size n=2?

ALG 2 (N!) HAS FEWER COMPUTES

- which algorithm would you prefer for a list of size n=5?

ALG 1 (2^N) HAS FEWER COMPUTES

- if you had to pick one algorithm for lists of any size, which would you choose, why?

- for small inputs, difference in computes isn't all that significant. for big inputs, alg 1 is faster

ALG 1 (2^N) IS PREFERRED

Induction with inequalities:

$S(n) = \text{"} 2^N < N! \text{"}$

Prove that 2^N < N! for all N above some threshold.

BASE CASE N=4 $\quad 2^N = 2^4 = 16 < 24 = 4! = N!$

INDUCTIVE STEP $S(n) \rightarrow S(n+1)$

ASSUME $2^N < N!$

$$\begin{aligned} 2^{N+1} &= 2^N \cdot 2 \\ &< N! \cdot 2 \\ &< N! \cdot (N+1) \\ &= (N+1)! \end{aligned}$$

MAKING BIG SIDE BIGGER

Induction Recipe (from previous lesson)

1. define & remind: statement n
2. choose base case n & show it
3. write "inductive step: if S(n) then S(n+1)
4. Prove inductive step:
    - a. assume statement n (inductive hypothesis)
    - b. write statement n + 1 in two halves
      (tip: start at sum side, work to other side)
    - c. apply assumption to get from one half to other

Induction with inequalities: sol

$S(n) = $ " $2^N < N!$ "

Prove that 2^N < N! for all N above some threshold.

STATEMENT N: $2^N < N!$

BASE CASE $N = 4$

$2^N = 16 < 24 = N!$

INDUCTIVE STEP $S(N) \to S(N+1)$

ASSUME $2^N < N!$

$$2^{N+1} = 2^N \cdot 2$$
$$< N! \cdot 2$$
$$< N! \cdot (N+1) = (N+1)!$$

Induction Recipe (from previous lesson)

1. define & remind: statement n
2. choose base case n & show it
3. write "inductive step: if S(n) then S(n+1)
4. Prove inductive step:
    a. assume statement n (inductive hypothesis)
    b. write statement n + 1 in two halves
        (tip: start at sum side, work to other side)
    c. apply assumption to get from one half to other

Algebra: Working with inequalities (1 of 4)

Move 1: add the same things to both sides, it preserves the inequality

IF $3 < 4$ THEN $3+10 < 4+10$

$$x < y \Rightarrow x+c < y+c \quad \forall c \in \mathbb{R}$$

Algebra: Working with inequalities (2 of 4)

Move 2: multiply by a positive value, it preserves the inequality

IF $3 < 4$ THEN $3 \cdot 10 < 4 \cdot 10$

IF $x < y$ THEN $xc < yc$ $\forall c \in \mathbb{R}$ WITH $c > 0$

Move 3: multiply by a negative value, it swaps the inequality direction

IF $3 < 4$ THEN $3 \cdot -1 > 4 \cdot -1$

IF $x < y$ THEN $xc > yc$ $\forall x, y \in \mathbb{R}$ WITH $c < 0$

Algebra: Working with inequalities (3 of 4)

Move 4: sum two inequalities (large side together & small side together)

if $3 < 4$ AND $5 < 6$ THEN $3+5 < 4+6$

if $x < y$ AND $w < z$ THEN $x + w < y + z$

Algebra: Working with inequalities (4 of 4)

Move 5 (another view of move 4 really):

- you can replace a term in smaller side of inequality with something smaller

$$3 < 7 \quad \text{AND} \quad 1 < 3 \quad \Rightarrow \quad 1 < 7$$

$$y < z \quad \text{AND} \quad x < y \quad \Rightarrow \quad x < y$$

- you can also replace a term in larger side of inequality with something larger

Tip: This is one of the most common manipulations in inequality induction problems

In Class Activity:

Complete the table:

Input Size	1	2	3	4	5	6
N^2	1	4	9	16	25	36
N + 10	11	12	13	14	15	16

Show that N^2 > N + 10 for all N above some value

$S(N) = N^2 > N+10$

BASE CASE $N=4$

$N^2 = 16 > 14 = N+10$

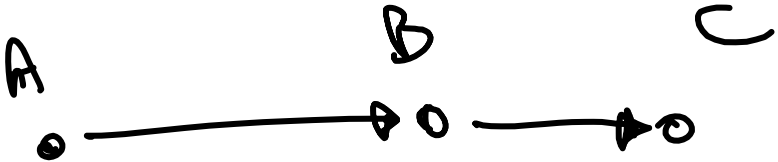
INDUCTIVE STEP $S(n) \to S(n+1)$

ASSUME $N^2 > N+10$

$(N+1)^2 = N^2 + 2N + 1$

$> N+10 + 2N + 1 = N+11 + \underline{2N}$

$> N + 11$


A
B
C

In Class Activity: sol

Complete the table:

Input Size	1	2	3	4	5	6
N^2	2	4	9	16	25	36
N + 10	11	12	13	14	15	16

Show that N^2 > N + 10 for all N above some value

STATEMENT N : $N+10 < N^2$

BASE CASE $N=4$

$N+10 = 14 < 16 = N^2$

INDUCTIVE STEP: $S(N) \to S(N+1)$

ASSUME $N+10 < N^2$

$$(N+1)+10 < N^2+1$$
$$< N^2+2N+1$$
$$= (N+1)^2$$

WE ADD A POSITIVE VALUE ($2N$) TO LARGER SIDE (MOVE 5)