Homework Logistics

- HW1 is due this Friday 09/02.
- Login to Gradescope “TODAY” to see if you have access to CS 70. If you still do not have access, read https://piazza.com/class/irwxcmgdofp2uz?cid=6.
- Homework must be submitted electronically to Gradescope as pdf but it may be prepared by hand, in LaTeX, or using Microsoft Word. Make sure the uploaded PDF is readable!!!

Lecture Outline

- Strengthening Induction Hypothesis.
- Strong Induction
- Well ordered principle.

Theorem: The sum of the first $n$ odd numbers is a perfect square.

Proof: Each tile covers 3 squares. The remainder of $2^{2n}$ divided by 3 is 1.

Base case: true for $n = 0$, $2^0 = 1$

Ind Hyp: $n = k$, $2^{2k} = 3a + 1$ for integer $a$.

$$2^{2(k+1)} = 2^{2k} + 2^2 = 4 + 2^{2k} = 4 + (3a + 1) = 4a + 3 + 1 = 3(4a + 1) + 1$$

$a$ integer $\implies (4a + 1)$ is an integer.

Hole have to be there? Maybe just one?

Theorem: Can tile the $2^n \times 2^n$ square to leave a hole adjacent to the center.

Proof: Each tile covers 3 squares. The remainder of $2^{2n}$ divided by 3 is 1.

Base case: true for $n = 0$, $2^0 = 1$

Ind Hyp: $n = k$, $2^{2k} = 3a + 1$ for integer $a$.

$$2^{2(k+1)} = 2^{2k} + 2^2 = 4 + 2^{2k} = 4 + (3a + 1) = 4a + 3 + 1 = 3(4a + 1) + 1$$

$a$ integer $\implies (4a + 1)$ is an integer.

Hole in center?

Theorem: Can tile the $2^n \times 2^n$ square to leave a hole adjacent to the center.

Proof: Each tile covers 3 squares. The remainder of $2^{2n}$ divided by 3 is 1.

Base case: true for $n = 0$, $2^0 = 1$

Ind Hyp: $n = k$, $2^{2k} = 3a + 1$ for integer $a$.

$$2^{2(k+1)} = 2^{2k} + 2^2 = 4 + 2^{2k} = 4 + (3a + 1) = 4a + 3 + 1 = 3(4a + 1) + 1$$

$a$ integer $\implies (4a + 1)$ is an integer.
Hole can be anywhere!

**Theorem:** Can tile the $2^n \times 2^n$ to leave a hole adjacent anywhere.

Better theorem ... stronger induction hypothesis!

Base case: Sure. A tile is fine.

Flipping the orientation can leave hole anywhere.

Induction Hypothesis:
"Any $2^n \times 2^n$ square can be tiled with a hole anywhere."

Consider $2^{n+1} \times 2^{n+1}$ square.

Use induction hypothesis in each.

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**Strong Induction: Example**

**Theorem:** Every natural number $n > 1$ is either a prime or can be written as a product of primes.

**Fact:** A prime $n$ has exactly 2 factors 1 and $n$.

**Base Case:** $n = 2$.

**Induction Step:**
$P(n) = \neg \exists a, b (1 < a, b < n$ and $n = a \cdot b$).

Either $n = 1$ is a prime or $n = a \cdot b$ where $1 < a, b < n + 1$.

$P(n)$ says nothing about $a, b$!

**Strong Induction Principle:** If $P(0)$ and
$\left( \forall k \in \mathbb{N} \right) ((P(0) \land \ldots \land P(k)) \implies P(k + 1)),$

then $\left( \forall k \in \mathbb{N} \right)(P(k)).$

$P(0) \implies P(1) \implies P(2) \implies P(3) \implies \ldots$

Strong induction hypothesis: "a and b are products of primes"

$n + 1 = a \cdot b = (\text{factorization of } a)(\text{factorization of } b)$

$n + 1$ can be written as the product of the prime factors!

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**Well Ordering Principle and Induction.**

If $(\forall n)P(n)$ is not true, then $(\exists n)\neg P(n)$.

Consider smallest $m$, with $\neg P(m)$.

$P(m) \implies P(m)$ must be false (assuming $P(0)$ holds.)

This is a proof of the induction principle!

i.e., $(\forall n)\neg P(n) \implies (\exists m)(\neg P(m) \implies P(n))$.

(Contrapositive of induction principle (assuming $P(0)$)

It assumes that there is a smallest $m$ where $P(m)$ does not hold.

The **Well ordering principle** states that for any subset of the natural numbers there is a smallest element.

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**Strong Induction is a form of (regular) Induction.**

Let $Q(k) = P(0) \land P(1) \land \ldots \land P(k)$.

By the induction principle:
"If $Q(0)$, and $\left( \forall k \in \mathbb{N} \right)(Q(k) \implies Q(k + 1))$ then $\left( \forall k \in \mathbb{N} \right)(Q(k))$".

Also, $Q(0) \equiv P(0)$, and $\left( \forall k \in \mathbb{N} \right)(Q(k) \equiv Q(k + 1))$

$\equiv \left( \forall k \in \mathbb{N} \right)((P(0) \land \ldots \land P(k)) \implies (P(0) \land \ldots \land P(k) \land P(k + 1)))$

$\equiv \left( \forall k \in \mathbb{N} \right)((P(0) \land \ldots \land P(k)) \implies P(k + 1)).$

**Strong Induction Principle:** If $P(0)$ and
$\left( \forall k \in \mathbb{N} \right)((P(0) \land \ldots \land P(k)) \implies P(k + 1))$,

then $\left( \forall k \in \mathbb{N} \right)(P(0) \land \ldots \land P(k)) \implies P(k + 1))$.

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**Horses of the same color...**

**Theorem:** All horses have the same color.

Base Case: $P(1)$ - trivially true.

New Base Case: $P(2)$: there are two horses with same color.

Induction Hypothesis: $P(k)$ - Any $k$ horses have the same color.

Induction step $P(k + 1)$?

First $k$ have same color by $P(k)$.

1122: 3, ... , $k + 1$

Second $k$ have same color by $P(k)$.

1122: 3, ... , $k + 1$

A horse in the middle in common!

1122: 122, ... , $k + 1$

All k must have the same color!!

How about $P(1)$ implying $P(2)$?

Fix base case.

...Still doesn't work!!

(There are two horses is $\not\equiv$ For all two horses!!!)

Of course it doesn't work.

As we will see, it is more subtle to catch errors in proofs of correct theorems!!

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**Strong Induction and Recursion.**

Thm: For every natural number $n \geq 12$, $n = 4x + 5y$.

Instead of proof, let's write some code!

```python
def find-x-y(n):
    if (n==12): return (3,0)
    elif (n==13): return (2,1)
    elif (n==14): return (1,2)
    elif (n==15): return (0,3)
    else:
        (x,y) = find-x-y(n-4)
        return (x+1,y)
```


**Strong Induction step:**

Recursive call is correct: $P(n - 4) \implies P(n)$.

Slight differences: showed for all $n \geq 16$ that $\wedge_{i=4}^{n-1}P(i) \implies P(n)$.
Summary: principle of induction.

Today: More induction.

\[(P(0) \land (\forall k \in \mathbb{N})(P(k) \implies P(k + 1)))) \implies (\forall n \in \mathbb{N})(P(n))\]

Statement to prove: \(P(n)\) for \(n\) starting from \(n_0\)
Base Case: Prove \(P(n_0)\).
Ind. Step: Prove. For all values, \(n \geq n_0\), \(P(n) \implies P(n + 1)\).
Statement is proven!

Strong Induction:
\[(P(0) \land (\forall n \leq k P(n)) \implies P(k + 1)))) \implies (\forall n \in \mathbb{N})(P(n))\]

Also Today: strengthened induction hypothesis.
n-Strengthen theorem statement.
Sum of first \(n\) odds is \(n^2\).
Hole anywhere.
Not same as strong induction.

Induction \equiv Recursion.