01204211 Discrete Mathematics
Lecture 5a: Mathematical Induction 4

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Review: Mathematical Induction

Suppose that you want to prove that property $P(n)$ is true for every natural number n.

Suppose that we can prove the following two facts:
Base case: $P(1)$
Inductive step: For any $k \geq 1$, $P(k) \Rightarrow P(k+1)$

The **Principle of Mathematical Induction** states that $P(n)$ is true for every natural number n.

The assumption $P(k)$ in the inductive step is usually referred to as **the Induction Hypothesis**.

Review: Strengtening the Induction Hypothesis

To prove the following theorem with induction:

Theorem 1
For any integer $n \geq 1$, $\frac{1}{1^2} + \frac{1}{2^2} + \frac{1}{3^2} + \cdots + \frac{1}{n^2} < 2$.

You need to prove the following "stronger" version:

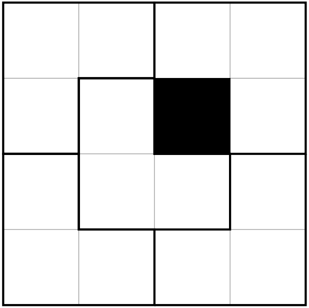
Theorem 2
For any integer $n \geq 1$, $\frac{1}{1^2} + \frac{1}{2^2} + \frac{1}{3^2} + \cdots + \frac{1}{n^2} \leq 2 - \frac{1}{n}$.

A Lesson learned

- Is a stronger statement easier to prove?
- In this case, the statement is indeed stronger, but the induction hypothesis gets stronger as well. Sometimes, this works out nicely.

L-shaped tiles (1)[1]

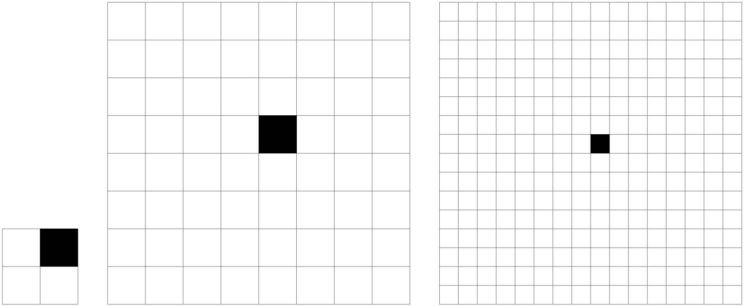
A 4x4 area with a hole in the middle can be tiled with L-shaped tiles.



[1] This section is from Berkeley CS70 lecture notes.

L-shaped tiles (2)

This is true for 2x2 area, 8x8 area, even 16x16 area.



This motivates us to try to prove that it is possible to use L-shaped tiles to tile a $2^n \times 2^n$ area.

Proving the fact?

Theorem 3

For integer $n \geq 1$, an area of size $2^n \times 2^n$ with one hole in the middle can be tiled with L-shaped tiles.

Proof: We prove by induction on n.

Base case: For $n = 1$, $2^1 \times 2^1$ area with a hole in the middle can be tiled.

Inductive step: Assume that for $k \geq 1$, an $2^k \times 2^k$ area with a hole in the middle can be tiled. We shall prove the statement for $n = k + 1$, i.e., that an $2^{k+1} \times 2^{k+1}$ area with one hole in the middle can be tiled.

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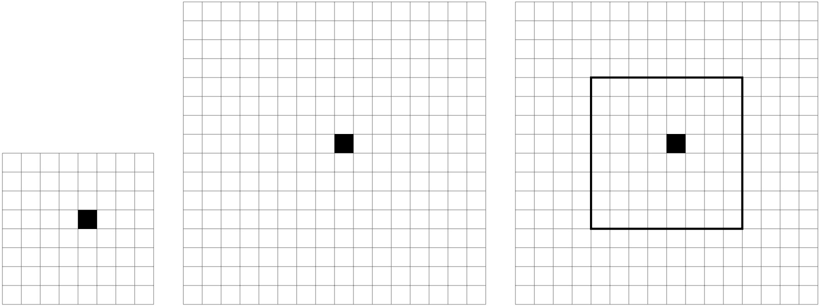
Proving the fact?

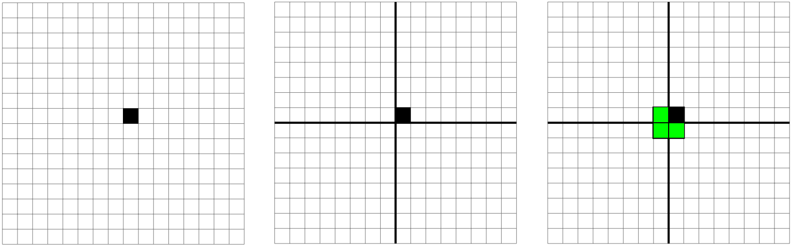
Proof: (cont.)

Let's see the Induction Hypothesis and the goal:



With the current form of the Induction Hypothesis, this is probably the way to use it. But it seems hard to go further with this approach....

Let's try a different approach



The last step seems nice, because it shows how we can solve the problem in the $2^{k+1} \times 2^{k+1}$ area with 4 problems in the $2^k \times 2^k$ areas. But do you see an issue with this approach regarding the Induction Hypothesis?

Current Inductive Hypothesis: Assume that for $k \geq 1$, an $2^k \times 2^k$ area with "a hole in the middle" can be tiled.

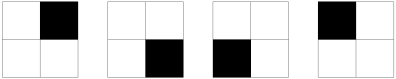
A Stronger Inductive Hypothesis: Assume that for $k \geq 1$, an $2^k \times 2^k$ area with one hole can be tiled.

A stronger statement

Theorem: For integer $n \geq 1$, an area of size $2^n \times 2^n$ with one hole can be tiled with L-shaped tiles.

Proof: We prove by induction on n.

Base case: For $n = 1$, $2^1 \times 2^1$ area with one hole can be tiled; there are 4 cases shown below.



Inductive step: Assume that for $k \geq 1$, an $2^k \times 2^k$ area with one hole can be tiled. We shall prove the statement for $n = k + 1$, i.e., that an $2^{k+1} \times 2^{k+1}$ area with one hole can be tiled.

(Try to finish it in homework.)

Proof of the Principle of Mathematical Induction[2]

Theorem 4

If $P(1)$ and for any integer $k \geq 1$, $P(k) \Rightarrow P(k+1)$, then $P(n)$ for all natural number n.

Proof.

We prove by contradiction. Assume that $P(n)$ is not true for some natural number n. Let m be the smallest positive integer such that $P(m)$ is false. If $m = 1$, we get a contradiction because we know that $P(1)$ is true; therefore, we know that $m > 1$.
Since m is smallest and $m > 1$, then $P(m-1)$ must be true.
However, because for any integer $k \geq 1$, $P(k) \Rightarrow P(k+1)$, we can conclude that $P(m)$ must be true. Again, we reach a contradiction.
Therefore, $P(n)$ is true for every positive integer n. □

Is this proof correct?

[2]This section is from Berkeley CS70 lecture notes.

The Well-Ordering Property

- The proof of the Principle of Mathematical Induction depends on the following axiom of natural numbers $\mathbb{N}$:

> **The Well-Ordering Property:** Any nonempty subset $S \subseteq \mathbb{N}$ contains the smallest element.

- Previously, we use the well-ordering property of natural numbers to prove the Principle of Mathematical Induction, but it turns out that we can use the induction to prove the well-ordering property as well. Therefore, we can take one as an axiom, and use it to prove the other.