

## Remarks about $\text{cf}(\kappa^{\text{card}})$

# $\text{cf}(\kappa)$ without ordinals

## $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

## $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals,

## $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

*Let  $\kappa$  be an infinite cardinal.*



# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

*Let  $\kappa$  be an infinite cardinal.*

- (1) (Sums)  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which it is possible to express  $\kappa$  as a sum of  $\chi$  cardinals, all smaller than  $\kappa$ . ( $\kappa = \sum_{i < \chi} \lambda_i$ , each  $\lambda_i < \kappa$ .)

# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

*Let  $\kappa$  be an infinite cardinal.*

- (1) (Sums)  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which it is possible to express  $\kappa$  as a sum of  $\chi$  cardinals, all smaller than  $\kappa$ . ( $\kappa = \sum_{i < \chi} \lambda_i$ , each  $\lambda_i < \kappa$ .)
- (2) (Successor versus limit  $\kappa$ )

# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

*Let  $\kappa$  be an infinite cardinal.*

- (1) *(Sums)  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which it is possible to express  $\kappa$  as a sum of  $\chi$  cardinals, all smaller than  $\kappa$ . ( $\kappa = \sum_{i < \chi} \lambda_i$ , each  $\lambda_i < \kappa$ .)*
- (2) *(Successor versus limit  $\kappa$ )*
  - (a) *If  $\kappa = \aleph_{\alpha+1}$  is a successor cardinal, then  $\text{cf}(\kappa) = \kappa$ . (Successor cardinals are regular.)*

# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

*Let  $\kappa$  be an infinite cardinal.*

- (1) (Sums)  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which it is possible to express  $\kappa$  as a sum of  $\chi$  cardinals, all smaller than  $\kappa$ . ( $\kappa = \sum_{i < \chi} \lambda_i$ , each  $\lambda_i < \kappa$ .)
- (2) (Successor versus limit  $\kappa$ )
  - (a) If  $\kappa = \aleph_{\alpha+1}$  is a successor cardinal, then  $\text{cf}(\kappa) = \kappa$ . (Successor cardinals are regular.)
  - (b) If  $\kappa = \aleph_\lambda$  is a limit cardinal, then  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ . (I.e.,  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

*Let  $\kappa$  be an infinite cardinal.*

- (1) (Sums)  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which it is possible to express  $\kappa$  as a sum of  $\chi$  cardinals, all smaller than  $\kappa$ . ( $\kappa = \sum_{i < \chi} \lambda_i$ , each  $\lambda_i < \kappa$ .)
- (2) (Successor versus limit  $\kappa$ )
  - (a) If  $\kappa = \aleph_{\alpha+1}$  is a successor cardinal, then  $\text{cf}(\kappa) = \kappa$ . (Successor cardinals are regular.)
  - (b) If  $\kappa = \aleph_\lambda$  is a limit cardinal, then  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ . (I.e.,  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

*Let  $\kappa$  be an infinite cardinal.*

- (1) (Sums)  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which it is possible to express  $\kappa$  as a sum of  $\chi$  cardinals, all smaller than  $\kappa$ . ( $\kappa = \sum_{i < \chi} \lambda_i$ , each  $\lambda_i < \kappa$ .)
- (2) (Successor versus limit  $\kappa$ )
  - (a) If  $\kappa = \aleph_{\alpha+1}$  is a successor cardinal, then  $\text{cf}(\kappa) = \kappa$ . (Successor cardinals are regular.)
  - (b) If  $\kappa = \aleph_\lambda$  is a limit cardinal, then  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ . (I.e.,  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

## Discussion.

# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

*Let  $\kappa$  be an infinite cardinal.*

- (1) (Sums)  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which it is possible to express  $\kappa$  as a sum of  $\chi$  cardinals, all smaller than  $\kappa$ . ( $\kappa = \sum_{i < \chi} \lambda_i$ , each  $\lambda_i < \kappa$ .)
- (2) (Successor versus limit  $\kappa$ )
  - (a) If  $\kappa = \aleph_{\alpha+1}$  is a successor cardinal, then  $\text{cf}(\kappa) = \kappa$ . (Successor cardinals are regular.)
  - (b) If  $\kappa = \aleph_\lambda$  is a limit cardinal, then  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ . (I.e.,  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

**Discussion.**  $\kappa = \aleph_1$ .

# $\text{cf}(\kappa)$ without ordinals

Q: Can we speak about the cofinality of cardinals without mentioning ordinals?

A: The DEFINITION of  $\text{cf}(\kappa)$  involves ordinals, but we can find equivalent conditions that involve cardinals only.

## Theorem

*Let  $\kappa$  be an infinite cardinal.*

- (1) (Sums)  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which it is possible to express  $\kappa$  as a sum of  $\chi$  cardinals, all smaller than  $\kappa$ . ( $\kappa = \sum_{i < \chi} \lambda_i$ , each  $\lambda_i < \kappa$ .)
- (2) (Successor versus limit  $\kappa$ )
  - (a) If  $\kappa = \aleph_{\alpha+1}$  is a successor cardinal, then  $\text{cf}(\kappa) = \kappa$ . (Successor cardinals are regular.)
  - (b) If  $\kappa = \aleph_\lambda$  is a limit cardinal, then  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ . (I.e.,  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

**Discussion.**  $\kappa = \aleph_1$ .  $\lambda_i \in \{0, 1, 2, \dots, \aleph_0\}$ .



# Proof of one direction of (1)

# Proof of one direction of (1)

**Assumptions:**

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Choose a  $\chi$ -sequence of ordinals  $(\alpha_i)_{i < \chi} \nearrow \kappa$  such that  $\kappa = \bigcup_{i < \chi} \alpha_i$ .

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Choose a  $\chi$ -sequence of ordinals  $(\alpha_i)_{i < \chi} \nearrow \kappa$  such that  $\kappa = \bigcup_{i < \chi} \alpha_i$ .

$\kappa$   
 $\uparrow$

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Choose a  $\chi$ -sequence of ordinals  $(\alpha_i)_{i < \chi} \nearrow \kappa$  such that  $\kappa = \bigcup_{i < \chi} \alpha_i$ .

$$\underset{\uparrow}{\kappa} = \left| \bigcup_{i < \chi} \alpha_i \right|$$



# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Choose a  $\chi$ -sequence of ordinals  $(\alpha_i)_{i < \chi} \nearrow \kappa$  such that  $\kappa = \bigcup_{i < \chi} \alpha_i$ .

$$\underset{\uparrow}{\kappa} = \left| \bigcup_{i < \chi} \alpha_i \right| \leq \sum_{i < \chi} |\alpha_i|$$

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Choose a  $\chi$ -sequence of ordinals  $(\alpha_i)_{i < \chi} \nearrow \kappa$  such that  $\kappa = \bigcup_{i < \chi} \alpha_i$ .

$$\underset{\uparrow}{\kappa} = \left| \bigcup_{i < \chi} \alpha_i \right| \leq \sum_{i < \chi} |\alpha_i| = \sum_{\underset{\uparrow}{i < \chi}} \lambda_i$$

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Choose a  $\chi$ -sequence of ordinals  $(\alpha_i)_{i < \chi} \nearrow \kappa$  such that  $\kappa = \bigcup_{i < \chi} \alpha_i$ .

$$\begin{array}{c} \kappa \\ \uparrow \end{array} = \left| \bigcup_{i < \chi} \alpha_i \right| \leq \sum_{i < \chi} |\alpha_i| = \sum_{i < \chi} \lambda_i \leq \sum_{i < \chi} \kappa$$

$\uparrow$

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Choose a  $\chi$ -sequence of ordinals  $(\alpha_i)_{i < \chi} \nearrow \kappa$  such that  $\kappa = \bigcup_{i < \chi} \alpha_i$ .

$$\begin{array}{c} \kappa \\ \uparrow \end{array} = \left| \bigcup_{i < \chi} \alpha_i \right| \leq \sum_{i < \chi} |\alpha_i| = \sum_{i < \chi} \lambda_i \leq \sum_{i < \chi} \kappa \leq \kappa \cdot \text{cf}(\kappa)$$

$\uparrow$

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Choose a  $\chi$ -sequence of ordinals  $(\alpha_i)_{i < \chi} \nearrow \kappa$  such that  $\kappa = \bigcup_{i < \chi} \alpha_i$ .

$$\underset{\uparrow}{\kappa} = \left| \bigcup_{i < \chi} \alpha_i \right| \leq \sum_{i < \chi} |\alpha_i| = \sum_{\substack{i < \chi \\ \uparrow}} \lambda_i \leq \sum_{i < \chi} \kappa \leq \kappa \cdot \text{cf}(\kappa) = \underset{\uparrow}{\kappa}$$

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Choose a  $\chi$ -sequence of ordinals  $(\alpha_i)_{i < \chi} \nearrow \kappa$  such that  $\kappa = \bigcup_{i < \chi} \alpha_i$ .

$$\underset{\uparrow}{\kappa} = \left| \bigcup_{i < \chi} \alpha_i \right| \leq \sum_{i < \chi} |\alpha_i| = \sum_{i < \chi} \underset{\uparrow}{\lambda_i} \leq \sum_{i < \chi} \kappa \leq \kappa \cdot \text{cf}(\kappa) = \underset{\uparrow}{\kappa}$$

where  $\lambda_i := |\alpha_i|$ .

# Proof of one direction of (1)

**Assumptions:**  $\chi = \text{cf}(\kappa)$ .

**Conclusion:**  $\kappa = \sum_{i < \chi} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Choose a  $\chi$ -sequence of ordinals  $(\alpha_i)_{i < \chi} \nearrow \kappa$  such that  $\kappa = \bigcup_{i < \chi} \alpha_i$ .

$$\underset{\uparrow}{\kappa} = \left| \bigcup_{i < \chi} \alpha_i \right| \leq \sum_{i < \chi} |\alpha_i| = \sum_{i < \chi} \underset{\uparrow}{\lambda_i} \leq \sum_{i < \chi} \kappa \leq \kappa \cdot \text{cf}(\kappa) = \underset{\uparrow}{\kappa}$$

where  $\lambda_i := |\alpha_i|$ .  $\square$

# Proof of the other direction of (1)



# Proof of the other direction of (1)

**Assumptions:**

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:**

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not.

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.)

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ .



# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ .

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ . We must have  $v \leq |\alpha| \leq \alpha < \kappa$  and  $\lambda_i \leq |\alpha| < \kappa$  for all  $i < v$ .

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ . We must have  $v \leq |\alpha| \leq \alpha < \kappa$  and  $\lambda_i \leq |\alpha| < \kappa$  for all  $i < v$ . Thus,

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ . We must have  $v \leq |\alpha| \leq \alpha < \kappa$  and  $\lambda_i \leq |\alpha| < \kappa$  for all  $i < v$ . Thus,

$\kappa$   
 $\uparrow$

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ . We must have  $v \leq |\alpha| \leq \alpha < \kappa$  and  $\lambda_i \leq |\alpha| < \kappa$  for all  $i < v$ . Thus,

$$\begin{array}{c} \kappa \\ \uparrow \\ \text{red} \end{array} = \sum_{i < v} \lambda_i$$

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ . We must have  $v \leq |\alpha| \leq \alpha < \kappa$  and  $\lambda_i \leq |\alpha| < \kappa$  for all  $i < v$ . Thus,

$$\underset{\text{red } \uparrow}{\kappa} = \sum_{i < v} \lambda_i \leq |\alpha| \cdot v$$

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ . We must have  $v \leq |\alpha| \leq \alpha < \kappa$  and  $\lambda_i \leq |\alpha| < \kappa$  for all  $i < v$ . Thus,

$$\underset{\uparrow}{\kappa} = \sum_{i < v} \lambda_i \leq |\alpha| \cdot v \leq |\alpha|^2$$

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ . We must have  $v \leq |\alpha| \leq \alpha < \kappa$  and  $\lambda_i \leq |\alpha| < \kappa$  for all  $i < v$ . Thus,

$$\underset{\uparrow}{\kappa} = \sum_{i < v} \lambda_i \leq |\alpha| \cdot v \leq |\alpha|^2 = |\alpha|$$



# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ . We must have  $v \leq |\alpha| \leq \alpha < \kappa$  and  $\lambda_i \leq |\alpha| < \kappa$  for all  $i < v$ . Thus,

$$\underset{\uparrow}{\kappa} = \sum_{i < v} \lambda_i \leq |\alpha| \cdot v \leq |\alpha|^2 = |\alpha| \underset{\uparrow}{<} \underset{\uparrow}{\kappa},$$

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ . We must have  $v \leq |\alpha| \leq \alpha < \kappa$  and  $\lambda_i \leq |\alpha| < \kappa$  for all  $i < v$ . Thus,

$$\underset{\uparrow}{\kappa} = \sum_{i < v} \lambda_i \leq |\alpha| \cdot v \leq |\alpha|^2 = |\alpha| \underset{\uparrow}{<} \underset{\uparrow}{\kappa},$$

a contradiction.

# Proof of the other direction of (1)

**Assumptions:**  $v < \text{cf}(\kappa)$  ( $\leq \kappa$ ).

**Conclusion:** It is not possible to express  $\kappa$  as  $\kappa = \sum_{i < v} \lambda_i$ , each cardinal  $\lambda_i < \kappa$ .

Assume not. (I.e., it IS possible.) The set  $\{\lambda_i \mid i < v\} \cup \{v\}$  is a subset of  $\kappa$  that cannot be cofinal in  $\kappa$ . There must be an ordinal  $\alpha < \kappa$  such that  $v < \alpha$  and  $\lambda_i < \alpha$  for all  $i < v$ . We must have  $v \leq |\alpha| \leq \alpha < \kappa$  and  $\lambda_i \leq |\alpha| < \kappa$  for all  $i < v$ . Thus,

$$\underset{\uparrow}{\kappa} = \sum_{i < v} \lambda_i \leq |\alpha| \cdot v \leq |\alpha|^2 = |\alpha| \underset{\uparrow}{<} \underset{\uparrow}{\kappa},$$

a contradiction.  $\square$

# Proof of (2)(a)

# Proof of (2)(a)

**Assumption:**

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular.



## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal.

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal.  
Necessarily,  $\lambda_i \leq \aleph_{\alpha}$ .

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_{\alpha}$ . Hence

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_\alpha$ . Hence

$$\begin{array}{c} \aleph_{\alpha+1} \\ \uparrow \end{array}$$

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_\alpha$ . Hence

$$\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$$

↑

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal.  
Necessarily,  $\lambda_i \leq \aleph_\alpha$ . Hence

$$\underset{\uparrow}{\aleph_{\alpha+1}} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i \leq \aleph_\alpha \cdot \underset{\uparrow}{\text{cf}(\aleph_{\alpha+1})}$$

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_{\alpha}$ . Hence

$$\underset{\uparrow}{\aleph_{\alpha+1}} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i \leq \aleph_{\alpha} \cdot \underset{\uparrow}{\text{cf}(\aleph_{\alpha+1})} \leq \aleph_{\alpha+1}^2$$



## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_{\alpha}$ . Hence

$$\underset{\uparrow}{\aleph_{\alpha+1}} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i \leq \aleph_{\alpha} \cdot \underset{\uparrow}{\text{cf}(\aleph_{\alpha+1})} \leq \aleph_{\alpha+1}^2 = \underset{\uparrow}{\aleph_{\alpha+1}}.$$

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_\alpha$ . Hence

$$\underset{\uparrow}{\aleph_{\alpha+1}} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i \leq \aleph_\alpha \cdot \underset{\uparrow}{\text{cf}(\aleph_{\alpha+1})} \leq \aleph_{\alpha+1}^2 = \underset{\uparrow}{\aleph_{\alpha+1}}.$$

Hence  $\kappa$

# Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_\alpha$ . Hence

$$\underset{\uparrow}{\aleph_{\alpha+1}} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i \leq \aleph_\alpha \cdot \underset{\uparrow}{\text{cf}(\aleph_{\alpha+1})} \leq \aleph_{\alpha+1}^2 = \underset{\uparrow}{\aleph_{\alpha+1}}.$$

Hence  $\kappa = \aleph_{\alpha+1}$

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_\alpha$ . Hence

$$\underset{\uparrow}{\aleph_{\alpha+1}} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i \leq \aleph_\alpha \cdot \underset{\uparrow}{\text{cf}(\aleph_{\alpha+1})} \leq \aleph_{\alpha+1}^2 = \underset{\uparrow}{\aleph_{\alpha+1}}.$$

Hence  $\kappa = \aleph_{\alpha+1} = \aleph_\alpha \cdot \text{cf}(\aleph_{\alpha+1})$

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_\alpha$ . Hence

$$\underset{\uparrow}{\aleph_{\alpha+1}} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i \leq \aleph_\alpha \cdot \underset{\uparrow}{\text{cf}(\aleph_{\alpha+1})} \leq \aleph_{\alpha+1}^2 = \underset{\uparrow}{\aleph_{\alpha+1}}.$$

Hence  $\kappa = \aleph_{\alpha+1} = \aleph_\alpha \cdot \text{cf}(\aleph_{\alpha+1}) = \max(\aleph_\alpha, \text{cf}(\aleph_{\alpha+1}))$

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_\alpha$ . Hence

$$\underset{\uparrow}{\aleph_{\alpha+1}} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i \leq \aleph_\alpha \cdot \underset{\uparrow}{\text{cf}(\aleph_{\alpha+1})} \leq \aleph_{\alpha+1}^2 = \underset{\uparrow}{\aleph_{\alpha+1}}.$$

Hence  $\kappa = \aleph_{\alpha+1} = \aleph_\alpha \cdot \text{cf}(\aleph_{\alpha+1}) = \max(\aleph_\alpha, \text{cf}(\aleph_{\alpha+1})) = \text{cf}(\aleph_{\alpha+1})$ .

## Proof of (2)(a)

**Assumption:**  $\kappa = \aleph_{\alpha+1}$  is an infinite successor cardinal.

**Conclusion:**  $\kappa$  is regular. ( $\text{cf}(\kappa) = \kappa$ .)

Assume that  $\aleph_{\alpha+1} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i$  where each  $\lambda_i < \aleph_{\alpha+1}$  is a cardinal. Necessarily,  $\lambda_i \leq \aleph_\alpha$ . Hence

$$\underset{\uparrow}{\aleph_{\alpha+1}} = \sum_{i < \text{cf}(\aleph_{\alpha+1})} \lambda_i \leq \aleph_\alpha \cdot \underset{\uparrow}{\text{cf}(\aleph_{\alpha+1})} \leq \aleph_{\alpha+1}^2 = \underset{\uparrow}{\aleph_{\alpha+1}}.$$

Hence  $\kappa = \aleph_{\alpha+1} = \aleph_\alpha \cdot \text{cf}(\aleph_{\alpha+1}) = \max(\aleph_\alpha, \text{cf}(\aleph_{\alpha+1})) = \text{cf}(\aleph_{\alpha+1})$ . □

# Proof of (2)(b)



# Proof of (2)(b)

**Assumption:**

# Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

# Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

**Conclusion:**

## Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

**Conclusion:**  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ .

## Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

**Conclusion:**  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ .  
(I.e.,  $\lambda_0 < \lambda_1 < \lambda_2 < \dots < \kappa$  and  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

## Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

**Conclusion:**  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ .  
(I.e.,  $\lambda_0 < \lambda_1 < \lambda_2 < \dots < \kappa$  and  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

Choose a sequence of ordinals  $(\alpha_i)_{i < \text{cf}(\kappa)} \nearrow \kappa$ .

## Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

**Conclusion:**  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ .  
(I.e.,  $\lambda_0 < \lambda_1 < \lambda_2 < \dots < \kappa$  and  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

Choose a sequence of ordinals  $(\alpha_i)_{i < \text{cf}(\kappa)} \nearrow \kappa$ . Since  $\kappa$  is a limit cardinal, there exists a strictly increasing sequence  $(\mu_i)_{i < \nu}$  of cardinals  $\mu_i < \kappa$  whose union is  $\kappa$ .

## Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

**Conclusion:**  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ .  
(I.e.,  $\lambda_0 < \lambda_1 < \lambda_2 < \dots < \kappa$  and  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

Choose a sequence of ordinals  $(\alpha_i)_{i < \text{cf}(\kappa)} \nearrow \kappa$ . Since  $\kappa$  is a limit cardinal, there exists a strictly increasing sequence  $(\mu_i)_{i < \nu}$  of cardinals  $\mu_i < \kappa$  whose union is  $\kappa$ . Recursively define a function  $F: \text{cf}(\kappa) \rightarrow M := \{\mu_i \mid i < \nu\}$  as follows:



## Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

**Conclusion:**  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ .  
(I.e.,  $\lambda_0 < \lambda_1 < \lambda_2 < \dots < \kappa$  and  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

Choose a sequence of ordinals  $(\alpha_i)_{i < \text{cf}(\kappa)} \nearrow \kappa$ . Since  $\kappa$  is a limit cardinal, there exists a strictly increasing sequence  $(\mu_i)_{i < \nu}$  of cardinals  $\mu_i < \kappa$  whose union is  $\kappa$ . Recursively define a function  $F: \text{cf}(\kappa) \rightarrow M := \{\mu_i \mid i < \nu\}$  as follows:

$$F(0) = \text{least element of } M \text{ above } \alpha_0,$$

## Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

**Conclusion:**  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ .  
(I.e.,  $\lambda_0 < \lambda_1 < \lambda_2 < \dots < \kappa$  and  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

Choose a sequence of ordinals  $(\alpha_i)_{i < \text{cf}(\kappa)} \nearrow \kappa$ . Since  $\kappa$  is a limit cardinal, there exists a strictly increasing sequence  $(\mu_i)_{i < \nu}$  of cardinals  $\mu_i < \kappa$  whose union is  $\kappa$ . Recursively define a function  $F: \text{cf}(\kappa) \rightarrow M := \{\mu_i \mid i < \nu\}$  as follows:

$$\begin{aligned} F(0) &= \text{least element of } M \text{ above } \alpha_0, \\ F(\beta) &= \text{least element of } M \text{ above } \alpha_\beta \text{ and } \text{im}(F|_\beta). \end{aligned}$$

## Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

**Conclusion:**  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ .  
(I.e.,  $\lambda_0 < \lambda_1 < \lambda_2 < \dots < \kappa$  and  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

Choose a sequence of ordinals  $(\alpha_i)_{i < \text{cf}(\kappa)} \nearrow \kappa$ . Since  $\kappa$  is a limit cardinal, there exists a strictly increasing sequence  $(\mu_i)_{i < \nu}$  of cardinals  $\mu_i < \kappa$  whose union is  $\kappa$ . Recursively define a function  $F: \text{cf}(\kappa) \rightarrow M := \{\mu_i \mid i < \nu\}$  as follows:

$$\begin{aligned} F(0) &= \text{least element of } M \text{ above } \alpha_0, \\ F(\beta) &= \text{least element of } M \text{ above } \alpha_\beta \text{ and } \text{im}(F|_\beta). \end{aligned}$$

The image of  $F$  is a strictly increasing, cofinal,  $(\leq \text{cf}(\kappa))$ -sequence of cardinals in  $\kappa$ .

## Proof of (2)(b)

**Assumption:**  $\kappa = \aleph_\lambda$  is an infinite limit cardinal.

**Conclusion:**  $\text{cf}(\kappa)$  is the least cardinal  $\chi$  for which there is a strictly increasing  $\chi$ -sequence of cardinals,  $(\lambda_i)_{i < \chi} \nearrow \kappa$ .  
(I.e.,  $\lambda_0 < \lambda_1 < \lambda_2 < \dots < \kappa$  and  $\kappa = \bigcup_{i < \chi} \lambda_i$ .)

Choose a sequence of ordinals  $(\alpha_i)_{i < \text{cf}(\kappa)} \nearrow \kappa$ . Since  $\kappa$  is a limit cardinal, there exists a strictly increasing sequence  $(\mu_i)_{i < \nu}$  of cardinals  $\mu_i < \kappa$  whose union is  $\kappa$ . Recursively define a function  $F: \text{cf}(\kappa) \rightarrow M := \{\mu_i \mid i < \nu\}$  as follows:

$$\begin{aligned} F(0) &= \text{least element of } M \text{ above } \alpha_0, \\ F(\beta) &= \text{least element of } M \text{ above } \alpha_\beta \text{ and } \text{im}(F|_\beta). \end{aligned}$$

The image of  $F$  is a strictly increasing, cofinal,  $(\leq \text{cf}(\kappa))$ -sequence of cardinals in  $\kappa$ .  $\square$ .

# Constructing cardinals of a given cofinality

# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

First we claim that the union of any strictly increasing sequence  $(\lambda)_{i < \alpha}$  of cardinals is a cardinal.



# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

First we claim that the union of any strictly increasing sequence  $(\lambda)_{i < \alpha}$  of cardinals is a cardinal. This is clear if  $\alpha$  is a successor ordinal, since then the union is the last cardinal in the sequence.

# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

First we claim that the union of any strictly increasing sequence  $(\lambda)_{i < \alpha}$  of cardinals is a cardinal. This is clear if  $\alpha$  is a successor ordinal, since then the union is the last cardinal in the sequence. If  $\alpha$  is a limit ordinal, then for any  $i < \alpha$  we have  $\lambda_i \subseteq \bigcup_{i < \alpha} \lambda_i = \kappa$ , so  $\lambda_i \subseteq |\kappa|$  for all  $i$ .

# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

First we claim that the union of any strictly increasing sequence  $(\lambda)_{i < \alpha}$  of cardinals is a cardinal. This is clear if  $\alpha$  is a successor ordinal, since then the union is the last cardinal in the sequence. If  $\alpha$  is a limit ordinal, then for any  $i < \alpha$  we have  $\lambda_i \subseteq \bigcup_{i < \alpha} \lambda_i = \kappa$ , so  $\lambda_i \subseteq |\kappa|$  for all  $i$ . This implies that

# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

First we claim that the union of any strictly increasing sequence  $(\lambda)_{i < \alpha}$  of cardinals is a cardinal. This is clear if  $\alpha$  is a successor ordinal, since then the union is the last cardinal in the sequence. If  $\alpha$  is a limit ordinal, then for any  $i < \alpha$  we have  $\lambda_i \subseteq \bigcup_{i < \alpha} \lambda_i = \kappa$ , so  $\lambda_i \subseteq |\kappa|$  for all  $i$ . This implies that

$$\kappa = \bigcup_{i < \chi} \lambda_i \subseteq |\kappa| \subseteq \kappa,$$

# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

First we claim that the union of any strictly increasing sequence  $(\lambda)_{i < \alpha}$  of cardinals is a cardinal. This is clear if  $\alpha$  is a successor ordinal, since then the union is the last cardinal in the sequence. If  $\alpha$  is a limit ordinal, then for any  $i < \alpha$  we have  $\lambda_i \subseteq \bigcup_{i < \alpha} \lambda_i = \kappa$ , so  $\lambda_i \subseteq |\kappa|$  for all  $i$ . This implies that

$$\kappa = \bigcup_{i < \chi} \lambda_i \subseteq |\kappa| \subseteq \kappa,$$

so  $\kappa = |\kappa|$  is a cardinal.

# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

First we claim that the union of any strictly increasing sequence  $(\lambda)_{i < \alpha}$  of cardinals is a cardinal. This is clear if  $\alpha$  is a successor ordinal, since then the union is the last cardinal in the sequence. If  $\alpha$  is a limit ordinal, then for any  $i < \alpha$  we have  $\lambda_i \subseteq \bigcup_{i < \alpha} \lambda_i = \kappa$ , so  $\lambda_i \subseteq |\kappa|$  for all  $i$ . This implies that

$$\kappa = \bigcup_{i < \chi} \lambda_i \subseteq |\kappa| \subseteq \kappa,$$

so  $\kappa = |\kappa|$  is a cardinal.

Since  $\kappa$  is the union of a  $\chi$ -sequence of cardinals,  $\text{cf}(\kappa) \leq \chi$ .

# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

First we claim that the union of any strictly increasing sequence  $(\lambda)_{i < \alpha}$  of cardinals is a cardinal. This is clear if  $\alpha$  is a successor ordinal, since then the union is the last cardinal in the sequence. If  $\alpha$  is a limit ordinal, then for any  $i < \alpha$  we have  $\lambda_i \subseteq \bigcup_{i < \alpha} \lambda_i = \kappa$ , so  $\lambda_i \subseteq |\kappa|$  for all  $i$ . This implies that

$$\kappa = \bigcup_{i < \chi} \lambda_i \subseteq |\kappa| \subseteq \kappa,$$

so  $\kappa = |\kappa|$  is a cardinal.

Since  $\kappa$  is the union of a  $\chi$ -sequence of cardinals,  $\text{cf}(\kappa) \leq \chi$ . We cannot have  $\text{cf}(\kappa) < \chi$  or (by copying the proof on the previous slide) we could find a  $\text{cf}(\kappa)$ -subsequence  $(\lambda_{i_j})_{j < \chi'}$  such that  $\kappa = \bigcup_{j < \chi'} \lambda_{i_j}$ .

# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

First we claim that the union of any strictly increasing sequence  $(\lambda)_{i < \alpha}$  of cardinals is a cardinal. This is clear if  $\alpha$  is a successor ordinal, since then the union is the last cardinal in the sequence. If  $\alpha$  is a limit ordinal, then for any  $i < \alpha$  we have  $\lambda_i \subseteq \bigcup_{i < \alpha} \lambda_i = \kappa$ , so  $\lambda_i \subseteq |\kappa|$  for all  $i$ . This implies that

$$\kappa = \bigcup_{i < \chi} \lambda_i \subseteq |\kappa| \subseteq \kappa,$$

so  $\kappa = |\kappa|$  is a cardinal.

Since  $\kappa$  is the union of a  $\chi$ -sequence of cardinals,  $\text{cf}(\kappa) \leq \chi$ . We cannot have  $\text{cf}(\kappa) < \chi$  or (by copying the proof on the previous slide) we could find a  $\text{cf}(\kappa)$ -subsequence  $(\lambda_{i_j})_{j < \chi'}$  such that  $\kappa = \bigcup_{j < \chi'} \lambda_{i_j}$ . Now  $(i_j)_{j < \chi'}$  is a cofinal,  $\text{cf}(\kappa)$ -subsequence of  $\chi$ , contradicting the regularity of  $\chi$ .



# Constructing cardinals of a given cofinality

## Theorem

*Let  $\chi$  be an infinite, regular cardinal. If  $\lambda_0 < \lambda_1 < \dots$  is a strictly increasing  $\chi$ -sequence of cardinals, then  $\kappa := \bigcup_{i < \chi} \lambda_i$  is a cardinal of cofinality  $\chi$ .*

First we claim that the union of any strictly increasing sequence  $(\lambda)_{i < \alpha}$  of cardinals is a cardinal. This is clear if  $\alpha$  is a successor ordinal, since then the union is the last cardinal in the sequence. If  $\alpha$  is a limit ordinal, then for any  $i < \alpha$  we have  $\lambda_i \subseteq \bigcup_{i < \alpha} \lambda_i = \kappa$ , so  $\lambda_i \subseteq |\kappa|$  for all  $i$ . This implies that

$$\kappa = \bigcup_{i < \chi} \lambda_i \subseteq |\kappa| \subseteq \kappa,$$

so  $\kappa = |\kappa|$  is a cardinal.

Since  $\kappa$  is the union of a  $\chi$ -sequence of cardinals,  $\text{cf}(\kappa) \leq \chi$ . We cannot have  $\text{cf}(\kappa) < \chi$  or (by copying the proof on the previous slide) we could find a  $\text{cf}(\kappa)$ -subsequence  $(\lambda_{i_j})_{j < \chi'}$  such that  $\kappa = \bigcup_{j < \chi'} \lambda_{i_j}$ . Now  $(i_j)_{j < \chi'}$  is a cofinal,  $\text{cf}(\kappa)$ -subsequence of  $\chi$ , contradicting the regularity of  $\chi$ .  $\square$

# Constructing $\lambda$ -unreachable cardinals

# Constructing $\lambda$ -unreachable cardinals

## Theorem

*Let  $\lambda$  be an infinite cardinal. Given any cardinal  $\mu$  there is a least  $\lambda$ -unreachable cardinal  $\kappa$  strictly above  $\mu$ , and it is the union of (the even terms of) the sequence*

$$\mu \leq \mu^\lambda < (\mu^\lambda)^+ \leq \left( (\mu^\lambda)^+ \right)^\lambda < \left( \left( (\mu^\lambda)^+ \right)^\lambda \right)^+ \leq \dots$$

# Constructing $\lambda$ -unreachable cardinals

## Theorem

*Let  $\lambda$  be an infinite cardinal. Given any cardinal  $\mu$  there is a least  $\lambda$ -unreachable cardinal  $\kappa$  strictly above  $\mu$ , and it is the union of (the even terms of) the sequence*

$$\mu \leq \mu^\lambda < (\mu^\lambda)^+ \leq \left( (\mu^\lambda)^+ \right)^\lambda < \left( \left( (\mu^\lambda)^+ \right)^\lambda \right)^+ \leq \dots$$

# Constructing $\lambda$ -unreachable cardinals

## Theorem

*Let  $\lambda$  be an infinite cardinal. Given any cardinal  $\mu$  there is a least  $\lambda$ -unreachable cardinal  $\kappa$  strictly above  $\mu$ , and it is the union of (the even terms of) the sequence*

$$\mu \leq \mu^\lambda < (\mu^\lambda)^+ \leq \left( (\mu^\lambda)^+ \right)^\lambda < \left( \left( (\mu^\lambda)^+ \right)^\lambda \right)^+ \leq \dots$$

[Idea:]

# Constructing $\lambda$ -unreachable cardinals

## Theorem

*Let  $\lambda$  be an infinite cardinal. Given any cardinal  $\mu$  there is a least  $\lambda$ -unreachable cardinal  $\kappa$  strictly above  $\mu$ , and it is the union of (the even terms of) the sequence*

$$\mu \leq \mu^\lambda < (\mu^\lambda)^+ \leq \left( (\mu^\lambda)^+ \right)^\lambda < \left( \left( (\mu^\lambda)^+ \right)^\lambda \right)^+ \leq \dots$$

[Idea:] The union of a strictly increasing chain of cardinals is a limit cardinal.

# Constructing $\lambda$ -unreachable cardinals

## Theorem

*Let  $\lambda$  be an infinite cardinal. Given any cardinal  $\mu$  there is a least  $\lambda$ -unreachable cardinal  $\kappa$  strictly above  $\mu$ , and it is the union of (the even terms of) the sequence*

$$\mu \leq \mu^\lambda < (\mu^\lambda)^+ \leq \left( (\mu^\lambda)^+ \right)^\lambda < \left( \left( (\mu^\lambda)^+ \right)^\lambda \right)^+ \leq \dots$$

[Idea:] The union of a strictly increasing chain of cardinals is a limit cardinal.  
If  $\nu < \kappa$ ,

# Constructing $\lambda$ -unreachable cardinals

## Theorem

*Let  $\lambda$  be an infinite cardinal. Given any cardinal  $\mu$  there is a least  $\lambda$ -unreachable cardinal  $\kappa$  strictly above  $\mu$ , and it is the union of (the even terms of) the sequence*

$$\mu \leq \mu^\lambda < (\mu^\lambda)^+ \leq \left( (\mu^\lambda)^+ \right)^\lambda < \left( \left( (\mu^\lambda)^+ \right)^\lambda \right)^+ \leq \dots .$$

[Idea:] The union of a strictly increasing chain of cardinals is a limit cardinal. If  $\nu < \kappa$ , then  $\nu < \mu^{\{\lambda, +\}^k}$  for some  $k$ ,



# Constructing $\lambda$ -unreachable cardinals

## Theorem

*Let  $\lambda$  be an infinite cardinal. Given any cardinal  $\mu$  there is a least  $\lambda$ -unreachable cardinal  $\kappa$  strictly above  $\mu$ , and it is the union of (the even terms of) the sequence*

$$\mu \leq \mu^\lambda < (\mu^\lambda)^+ \leq \left( (\mu^\lambda)^+ \right)^\lambda < \left( \left( (\mu^\lambda)^+ \right)^\lambda \right)^+ \leq \dots .$$

[Idea:] The union of a strictly increasing chain of cardinals is a limit cardinal. If  $\nu < \kappa$ , then  $\nu < \mu^{\{\lambda, +\}^k}$  for some  $k$ , so  $\nu^\lambda < \mu^{\{\lambda, +\}^{k+1}} < \kappa$ .

# Constructing $\lambda$ -unreachable cardinals

## Theorem

*Let  $\lambda$  be an infinite cardinal. Given any cardinal  $\mu$  there is a least  $\lambda$ -unreachable cardinal  $\kappa$  strictly above  $\mu$ , and it is the union of (the even terms of) the sequence*

$$\mu \leq \mu^\lambda < (\mu^\lambda)^+ \leq \left( (\mu^\lambda)^+ \right)^\lambda < \left( \left( (\mu^\lambda)^+ \right)^\lambda \right)^+ \leq \dots .$$

[Idea:] The union of a strictly increasing chain of cardinals is a limit cardinal. If  $\nu < \kappa$ , then  $\nu < \mu^{\{\lambda, +\}^k}$  for some  $k$ , so  $\nu^\lambda < \mu^{\{\lambda, +\}^{k+1}} < \kappa$ .  $\square$

# Constructing $\lambda$ -unreachable cardinals

## Theorem

*Let  $\lambda$  be an infinite cardinal. Given any cardinal  $\mu$  there is a least  $\lambda$ -unreachable cardinal  $\kappa$  strictly above  $\mu$ , and it is the union of (the even terms of) the sequence*

$$\mu \leq \mu^\lambda < (\mu^\lambda)^+ \leq \left( (\mu^\lambda)^+ \right)^\lambda < \left( \left( (\mu^\lambda)^+ \right)^\lambda \right)^+ \leq \dots .$$

[Idea:] The union of a strictly increasing chain of cardinals is a limit cardinal. If  $\nu < \kappa$ , then  $\nu < \mu^{\{\lambda, +\}^k}$  for some  $k$ , so  $\nu^\lambda < \mu^{\{\lambda, +\}^{k+1}} < \kappa$ .  $\square$

**Exercise.**

# Constructing $\lambda$ -unreachable cardinals

## Theorem

*Let  $\lambda$  be an infinite cardinal. Given any cardinal  $\mu$  there is a least  $\lambda$ -unreachable cardinal  $\kappa$  strictly above  $\mu$ , and it is the union of (the even terms of) the sequence*

$$\mu \leq \mu^\lambda < (\mu^\lambda)^+ \leq \left( (\mu^\lambda)^+ \right)^\lambda < \left( \left( (\mu^\lambda)^+ \right)^\lambda \right)^+ \leq \dots .$$

[Idea:] The union of a strictly increasing chain of cardinals is a limit cardinal. If  $\nu < \kappa$ , then  $\nu < \mu^{\{\lambda, +\}^k}$  for some  $k$ , so  $\nu^\lambda < \mu^{\{\lambda, +\}^{k+1}} < \kappa$ .  $\square$

**Exercise.** Given  $\kappa < \lambda$ , show how to find a  $\lambda$ -unreachable cardinal of cofinality  $\kappa^+$ .