# Automated dating of ice cores

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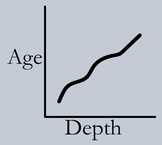
## Ice records past climate

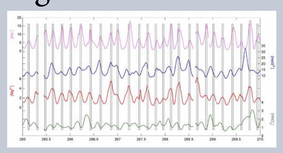
An ice core is a rich record of Earth's past climate. Ice cores contain more climate proxies that any other natural records.

## Layer Counting

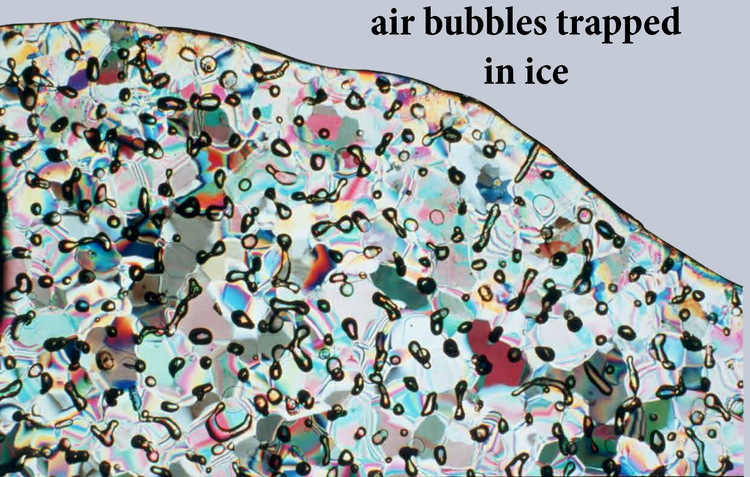
Once we have an ice core, we want to know: How old is the core at each depth?




Layer counting is one of the most accurate methods for dating. Glacial ice contains checmical impurities from atmospheric dust. Chemicals are deposited by snow with seasonally varying concentration:



We can date the core by counting down the number of layers from the top. This is traditionally done by hand, which is laborious and lacks uncertainty estimates.



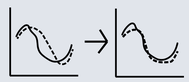
**air bubbles trapped in ice**

## Methods

We have developed a semi-hidden Markov model for layer counting.

### Training

We use dynamic time warping to produce aligned yearly signals.



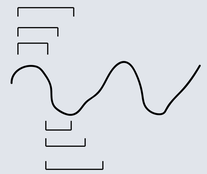
Now we estimate statistics on the signals:

$$\mathbf{y}_i = X \cdot \mathbf{a}_i + \epsilon_i$$
$$\mathbf{a}_i \sim N(\mathbf{0},\, \Phi)$$
$$\epsilon_i \sim N(\mathbf{0},\, \sigma^2 I)$$

where $y_i$ is the yearly signal, X contains component functions, and the $a_i$ are coefficients.

### Production

We move down the data series, looking for yearly signals. For each section, we calculate the probability that it represents a yearly signal.



We use the forward-backward algorithm to find the most likely year markings, and to obtain uncertainty estimates.

## Results

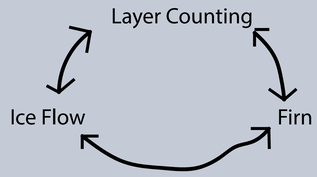
This model has been shown to perform as well as traditional layer-counting methods.

## Future Research

To obtain more precise chronologies, we must combine information from multiple sources.

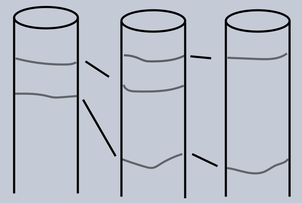
### Other Dating Methods

Ice flow models and firn models can both be used to date ice cores as well. The dating methods inform each other in complicated ways.




### Multiple Cores

Cores can be aligned using volcanic markers or other tie points. To do this well, we need excellent uncertainty estimates for each of our models.



## CSciBox

We are collaborating with Elizabeth Bradley and Laura Rassbach-deVesine in the creation of CSciBox, an AI system. CSciBox can assist in dating a single core, and will help us intelligently combine information from multiple cores and dating methods. More information at

http://www.cs.colorado.edu/~lizb/cscience.html

"State of the art of ice core annual layer dating. Rasmussen, Svensson, and Winstrup. PAGES magazine, April 2014.

"An Automated Method for Annual Layer Counting in Ice Cores." Mai Winstrup, PhD Thesis, University of Copenhagen, Nov. 2011.

Figures:

Ice core data: http://www.washington.edu/news/blog/ice-cores-tree-rings-show-how-huge-volcanic-eruptions-cooled-the-planet/

GISP2 ice core at 1837 meters depth with clearly visible annual layers: National Ice Core Laboratory

Bubbles in an Antarctic ice sample Illuminated with polarised light: CSIRO