# How Minds Work
# Sparse Distributed Memory

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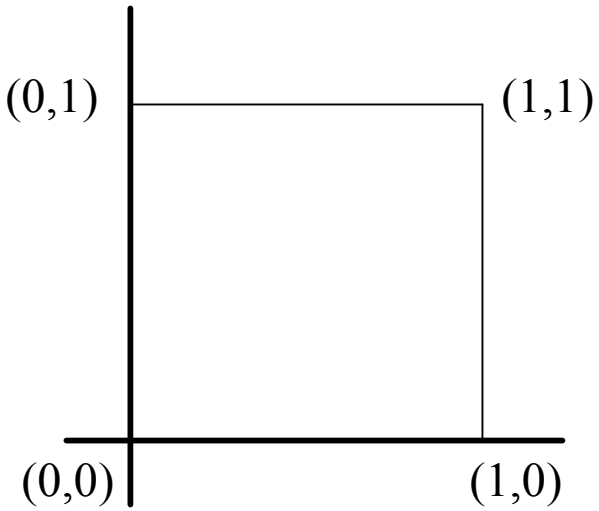
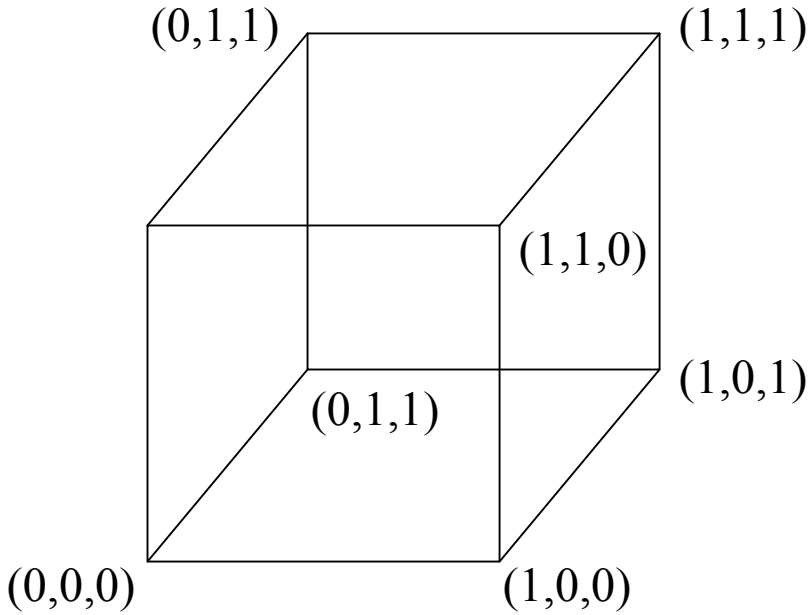
# Boolean Geometry

- The geometry of Boolean space
- Boolean space of dimension n— the set of all Boolean vectors of length n
- One dimensional Boolean space— {(0), (1)}
- Two dimensional Boolean space— {(0,0), (0,1), (1,0), (1,1)}

# Boolean Spaces

Two dimensional




Three dimensional

# Cardinality of Boolean Spaces

- $B_1$ has $2^1$=2 elements
- $B_2$ has $2^2$=4 elements
- $B_3$ has $2^3$=8 elements
- $B_4$ has $2^4$=16 elements
- …
- $B_n$ has $2^n$ elements

$B_{1000}$ has $2^{1000}$ elements

More than the number of atoms in the universe!

# Hamming Distance

- Number of dimensions in which two Boolean vectors differ
- d((0,1,0,1,0,1,1), (1,1,0,0,0,1,0)) = 3
- 99.9999% of $B_{1000}$ lies between 422 & 578 from a given vector.
- Almost all of a Boolean space is far from any given vector
- Every Boolean space is thinly populated

# Boolean Spheres

- Locus of points at some fixed distance, the radius, from its center
- $O(r,x) = \{ y \mid d(x,y) \leq r \}$
- For $r \leq n/2$ most of the points in $O(r,x)$ lie close to its boundary.

# SDM as Memory

- Random (vs sequential access)
  - Retrieve in equal time from any location
- Content addressable
  - Find complete contents from a part
- Associative
  - Find contents similar to a cue

# Addresses in SDM

- Addresses — Boolean vectors of length 1000
- Address space = $B_{1000}$
- Too enormous to ever implement
- Each dimension a feature, either on (1) or off (0)
- 1000 not many features

# Hard Locations in SDM

- Choose $2^{20}$ (~1,000,000) hard locations
- Uniformly distributed in address space
- $2^{20}$ hard locations out of $2^{1000}$ locations, ratio is $1/2^{980}$ — very sparse indeed
- median distance from random location to nearest hard location is 424
- Hard locations are certainly sparse

# Counters

- Each hard location has 1000 counters
- Each counter has range -40 to 40
- Takes about a gigabyte of memory
- Writing a 1 to a counter increments it; writing a 0 decrements it
- Write to a hard location– write each coordinate to the corresponding counter

# Access Sphere

- Access sphere at some location x — sphere of radius 451 centered at x
- Contains about 1000 hard locations
- To write to a location x — write to each hard location in its access sphere
- Distributed representation
- Hence Sparse Distributed Memory

# Reading from a Hard Location

- If the *i*th counter of the hard location is
  - Positive, put a 1 in the *i*th dimension
  - Negitive, put a 0 in the *i*th dimension
- This is majority rule at each dimension
- A Boolean vector of the right dimension results
- It may differ from any previously written

# Reading from any Location

- Find the access circle centered at the given location
- Read at each hard location in the circle
- Majority rule over these reading
- Iterate using the result as a new location
- Stop if the itteration stabilizes

# Retrieval

- Items read in (with themselves as address) can be reconstructed
- Iterated reading allows reconstruction from a partial or noisy cue
- Reconstructions may not be exact
- Interference affect occur

# Psychological Effects

- Knowing that one does or doesn’t know
- Tip of the tongue feeling

# Readings

- Kanerva, P. 1988. *Sparse Distributed Memory*. Cambridge MA: The MIT Press.
- Franklin, S. 1995. *Artificial Minds*. Cambridge MA: MIT Press

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