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
- \(d((0,1,0,1,0,1,1), (1,1,0,0,0,0,1,0)) = 3\)
- 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 $2^{20} \approx 1,000,000$ 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
  – Negative, 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 iteration 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 affects occur
Psychological Effects

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

Email and Web Addresses

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