1. Combinatorics

Suppose we have an infinite collection of sets \mathcal{F} . Take n many of those sets. They generate a boolean algebra. Count the number of atoms in it. There can be at most 2^n atoms, though depending on the collection there may be much less. For a given n, out of all choices of n sets, record the highest possible number of atoms generated. We define that to be a shatter function.

Definition 1.1.

 $\pi_{\mathcal{F}}(n) = \max \{ \# \text{ of atoms in boolean algebra generated by } S \mid S \subset \mathcal{F} \text{ and } |S| = n \}$

Example: Let \mathcal{F} consist of all discs in the plane.

$$\pi_{\mathcal{F}}(1) = 2$$
 $\pi_{\mathcal{F}}(2) = 4$ $\pi_{\mathcal{F}}(3) = 8$ $\pi_{\mathcal{F}}(4) = 14$

$$\pi_{\mathcal{F}}(n) = n^2 - n + 2$$

Example: Let \mathcal{F} consist of all half-planes in the plane.

$$\pi_{\mathcal{F}}(1) = 2$$
 $\pi_{\mathcal{F}}(2) = 4$ $\pi_{\mathcal{F}}(3) = 7$ $\pi_{\mathcal{F}}(4) = 11$

$$\pi_{\mathcal{F}}(n) = n^2/2 + n/2 + 1$$

Example 1.2. (1) Let \mathcal{F} be a set of lines on a plane. Then

$$\pi_{\mathcal{F}}(n) = n(n+1)/2 + 1$$

(2) Let \mathcal{F} be a set of disks on a plane. Then

$$\pi_{\mathcal{F}}(n) = n^2 - n + 2$$

(3) Let \mathcal{F} be a set of balls in \mathbb{R}^3 . Then

$$\pi_{\mathcal{F}}(n) = n(n^2 - 3n + 8)/3$$

(4) Let \mathcal{F} be a set of intervals on a line. Then

$$\pi_{\mathcal{F}}(n) = 2n$$

(5) Let \mathcal{F} be a set of half-planes. Then

$$\pi_{\mathcal{F}}(n) = n(n+1)/2 + 1$$

(6) Let \mathcal{F} be a collection of finite subsets of \mathbb{N} . Then

$$\pi_{\mathcal{F}}(n) = 2^n$$

(7) Let \mathcal{F} be a collection of polygons in a plane. Then

$$\pi_{\mathcal{F}}(n) = 2^n$$

Theorem 1.3 (Sauer-Shelah). Shatter function is either 2^n or bounded by a polynomial

Definition 1.4. Suppose growth of shatter function for \mathcal{F} is polynomial. Let r be the smallest real such that

$$\pi_{\mathcal{F}}(n) = O(n^r)$$

We define such r to be the vc-density of \mathcal{F} . If shatter function grows exponentially, we let vc-density to be infinite.

2. Model Theory

Consider a structure with a language

$$(\mathbb{R},0,1,+,\cdot,\leq)$$

We work with subsets of the underlying set definable by first-order formulas. Those are called definable sets.

$$\phi(x) = 5 \le x \le 7.7 \lor x \le 0$$

$$\psi(x) = \exists y \ y \cdot y = x$$

$$\gamma(x) = x \cdot x \cdot x \cdot x = 2$$

 $\phi(\mathbb{R})$ defines the set $[5,7.7] \cup (-\infty,0]$ in the structure above. $\psi(\mathbb{R})$ defines the set $[0,\infty)$ in the structure above.

- (1) in rationals (\mathbb{Q},\cdot) $\gamma(x)$ defines an empty subset
- (2) in reals (\mathbb{R},\cdot) $\gamma(x)$ defines a subset with two elements
- (3) in complex numbers (\mathbb{C},\cdot) $\gamma(x)$ defines a subset with four elements
- (4) in quaternions (\mathbb{H},\cdot) $\gamma(x)$ defines an infinite subset

$$\theta(x) = \forall y \exists z \ x \le z \le y$$

- (1) in (\mathbb{Q}, \leq) $\theta(x)$ defines an empty subset
- (2) in (\mathbb{N}, \leq) $\theta(x)$ defines an empty subset
- (3) in $(\mathbb{Q}^{\geq 0}, \leq)$ $\theta(x)$ defines the set $\{0\}$

Definition 2.1. for a formula $\phi(x_1 \dots x_n, y_1, \dots y_m)$ we can plug in elements of our structure as parameters in places of y variables. This gives us a collection of definable sets.

Example 2.2.

$$\phi(x_1, x_2, y_1, y_2, y_3) = (x_1 - y_1)^2 + (x_2 - y_2)^2 \le y_3^2$$

In structure $(\mathbb{R}, +, \cdot, \leq)$ given $a, b, r \in \mathbb{R}$ the formula $\phi(x_1, x_2, a, b, r)$ defines a disk in \mathbb{R}^2 with radius r with center (a, b).

Thus all discs in \mathbb{R}^2 are defined uniformly by ϕ .

What are the collection of sets we can consider when working with a model?

We can look at all definable subsets. That's not interesting, always has an infinite vc-density. Uniformly definable families offer more interesting behavior.

A model is said to be NIP if all uniformly definable families have finite vc-density.

For a given model M, let vc function of n to be the largest vc-density achieved by n-dimensional families of uniformly definable sets.

$$\operatorname{vc}^{M}(n) = \max \left\{ \operatorname{vc}(\phi) \mid \phi(\vec{x}, \vec{y}) \text{ with } |\vec{x}| = n \right\}$$

It is easy to show that $vc_M(n) \ge n$ for all models.

Open questions about vc functions. Is $vc_M(n) = n vc_M(1)$? If not, is there a linear relationship?

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