Defn: Sample Space

The sample space S is the set of possible outcomes.

Ex. Flip a coin

$$S = \{H, T\}.$$

Ex. Roll a 6-sided die:

$$S = \{1, 2, \ldots, 6\}$$

Ex. Roll two dice

$$S = \{(1,1), (1,2), (2,1), \ldots\}$$

Ex. Waiting for bus to arrive, wait time

$$S = [0, \infty)$$

Ex. Number of customers arriving at my restaurant

$$S = \{0, 1, 2, 3, \ldots\} = \mathbb{N}_0$$

Types of sample spaces:

1. finite $|S| < \infty$ (e.g. $\{H, T\}$)

2. infinite $|S| \geq \infty$
   - (i) countable (e.g. $\mathbb{N}_0$)
   - (ii) uncountable (e.g. $[0, \infty)$)

Defn: Outcome

We call elements of the sample space outcomes:

$$\underbrace{s}_{\text{outcome}} \in \underbrace{S}_{\text{sample space}}$$

Ex. $S = \{1, \ldots, 6\}$

then $1 \in S$ so 1 is a outcome.

Defn: Event

An event E is a subset of S:

$$E \subset S.$$

ECS.

<u>Ex.</u> $S = \{1, \dots, 6\}$ then

$$E = \{1, 2\} \subset S$$

is the event that I roll either a 1 or 2.

<u>Ex.</u> $S = \{(i,j) \mid 1 \le i \le 6,\ 1 \le j \le 6\}$

then

$$E = \{(2,1), (3,2)\} \subset S$$

$$F = \{(1,2), (2,3)\}$$

We say an event "happens" or "occurs" if the observed outcome of our experiment is in E

<u>Ex.</u> $S \subset S$ so S is an event.

the event that something happens.

<u>Ex.</u> $\emptyset \subset S$ so $\emptyset$ is an event.

nothing happens???

Ex. $\emptyset \subset S$ so $\emptyset$ is an event.

the event nothing happens???

Axiomatic Probability

Given: a sample space S

Want: for any event $E \subset S$ want to assign some measure of the probability of E occurring.

probability function

Mathematically:

For each $E \subset S$ we assign $\mathbb{P}(E)$

prob. of E

What are the rules for building $\mathbb{P}$?

1. mathematically consistent
2. encode some intuitions about probability

Defn: Probability Function

Given a sample space S and ...

Given a sample space S a prob. fn $\mathbb{P}$ is a function

$$\mathbb{P} : 2^S \to \mathbb{R}$$

that satisfies the <u>Kolmogorov Axioms</u> :

① <u>non-negativity</u>

$$\mathbb{P}(E) \geq 0 \quad \forall E \subset S$$

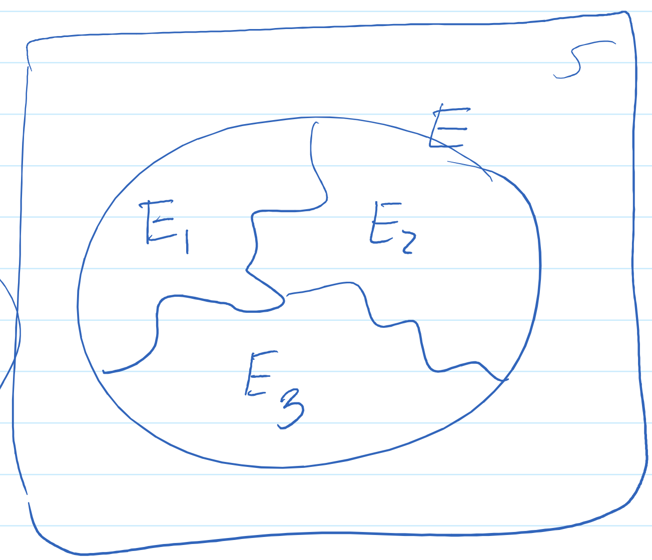
② <u>unit-measure</u>

$$\mathbb{P}(S) = 1$$

③ <u>Countable Additivity</u>

If $(E_i)_{i=1}^{\infty}$ is a partition of E.

$\left(E = \bigcup_i E_i \; ; \; E_i E_j = \emptyset\right)$



then

$$\mathbb{P}(E) = \sum_{i=1}^{\infty} \mathbb{P}(E_i).$$

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① Axiom 3 is basically a distributive law for disjoint

$$\mathbb{P}\left(\bigcup_{i=1}^{\infty} E_i\right) = \sum_{i=1}^{\infty} \mathbb{P}(E_i)$$

$$P\left(\bigcup_{i=1}^{\infty} E_i\right) = \sum_{i=1}^{\infty} P(E_i).$$

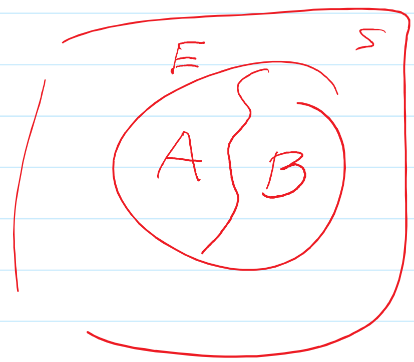
(2) It also holds for finite partitions.

$$P\left(\bigcup_{i=1}^{n} E_i\right) = \sum_{i=1}^{n} P(E_i)$$

in particular:

$E = A \cup B$ and $AB = \emptyset$

then $P(E) = P(A) + P(B)$.



Ex. Flip a coin

$$S = \{H, T\}$$

What is a possible valid P on S?

$$P(\{H\}) = 1/2 \qquad \underline{P(\overbrace{\{H, T\}}^{S}) = 1}$$

$$P(\{T\}) = 1/2 \qquad P(\emptyset) = 0$$

Is this a valid P?

✓ (1) $P(E) \geq 0$

① $P(E) \geq 0$

② $P(S) = 1$

③ $P\left(\bigcup_{i=1}^{\infty} E_i\right) = \sum_{i=1}^{\infty} P(E_i)$ for disjoint E_i

One example: $E = S$

$E_1 = \{H\}$, $E_2 = \{T\}$

then E_1 and E_2 partition E

$1 = P(S) = P(E) = P(E_1) + P(E_2) = \frac{1}{2} + \frac{1}{2}$

Ex. $S = \{H, T\}$

$P(S) = 1$

$P(\emptyset) = 0$

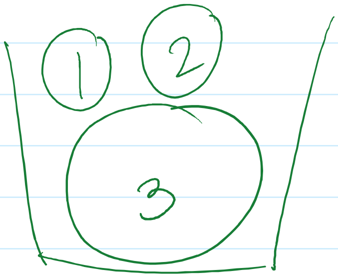
and

$P(\{T\}) = \alpha$

$P(\{H\}) = 1 - \alpha$

$0 \leq \alpha \leq 1$

Ex.



$S = \{1, 2, 3\}$

$P_1 = \frac{1}{4}$ $P_2 = \frac{1}{4}$ $P_3 = \frac{1}{2}$

(pos. and sum to 1)

$\mathbb{P}(\{2,3\}) = P_2 + P_3 = 3/4$

$\mathbb{P}(\{1,3\}) = P_1 + P_3 = 3/4$

Theorem: Discrete Sample Space Theorem

If $S = \{s_1, \dots, s_n\}$ so that $|S| = n$

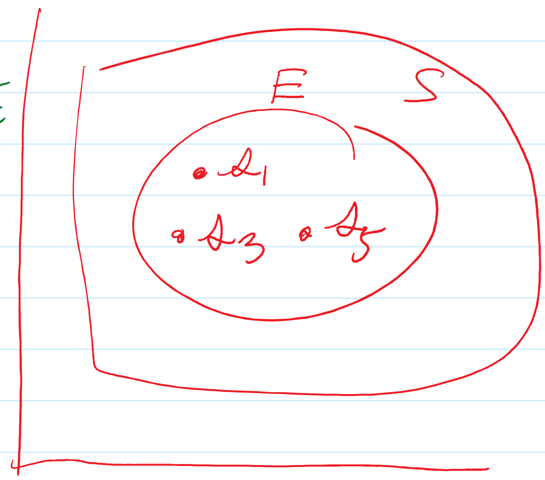
and we choose $p_1, p_2, \dots, p_n$ so that

$$\text{(1) } p_i \geq 0 \quad \text{and} \quad \text{(2) } \sum_{i=1}^{n} p_i = 1$$

and we define a $\mathbb{P}$ so that for $E \subset S$

$$\mathbb{P}(E) = \text{sum } p_i \text{ with corresponding } s_i \in E$$

$$= \sum_{i;\, s_i \in E} p_i$$



$P(E) = p_1 + p_3 + p_5$

Then $\mathbb{P}$ is a valid prob. fn.

Pf. Need to check sats. Komogorov Axioms

(1) $P(E) \geq 0 \quad \forall E \subset S$

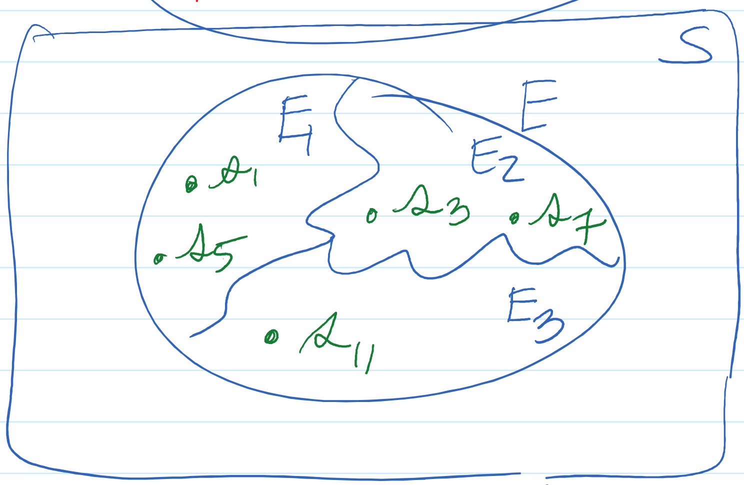
$$P(E) = \sum_{\text{some } i\text{s}} p_i \geq 0 \qquad p_i \geq 0$$

(2) $P(S) = 1$

(2) $P(S) = 1$

$$P(S) = \sum_{i : s_i \in S} p_i = \sum_{i=1}^{n} p_i = \underline{1}$$

(3) E_i partition E then $\sum_{i=1}^{\infty} P(E_i) = \underline{P(E)}$



$$P(E) = (p_1 + p_5) + (p_3 + p_7) + (p_{11})$$
$$= P(E_1) + P(E_2) + P(E_3).$$

$\boxed{\text{Theorem: } P(\emptyset) = 0.}$

<u>pf.</u>

$S = S \cup \emptyset \cup \emptyset \cup \emptyset \cup \emptyset \cup \dots$

then by Axiom 3

$$\underbrace{P(S)}_{1} = P(S) + P(\emptyset) + P(\emptyset) + P(\emptyset) + \dots$$
$$= \underbrace{P(S)}_{1} + \sum_{i=1}^{\infty} P(\emptyset)$$

I can add any number of $\emptyset$ to a partition and it remains a partition

So $\sum_{i=1}^{\infty} P(\emptyset) = 0 \Rightarrow$ This only works if

So $\sum_{i=1}^{\infty} P(\emptyset) = 0$. $\Rightarrow$ This only works if

$$P(\emptyset) = 0.$$

Third Axiom: $P\left(\bigcup_{i=1}^{\infty} E_i\right) = \sum_{i=1}^{\infty} P(E_i)$ if E_i disjoint

Finite Additivity: $P\left(\bigcup_{i=1}^{n} E_i\right) = \sum_{i=1}^{n} P(E_i)$ if E_i disjoint

Pf $E = A \cup B$, $AB = \emptyset$.

Notice $E = A \cup B \cup \emptyset \cup \emptyset \cup \emptyset \cup \dots$

add countable number of $\emptyset$

Apply Axiom 3

$$\boxed{P(E) = P(A) + P(B) +} 0 + 0 + 0 + 0 + \dots$$

For ≥ 2 sets use induction.
