

Foundations for Type-Driven Probabilistic Modelling

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Laboratory for Foundations
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Computational golden era

logic-rich & type-rich computation

statistical computation

Computational golden era

logic-rich & type-rich computation

- ▶ Expressive type systems: Haskell, OCaml, Rust, Agda, Idris
- ▶ Mechanised mathematics: Agda, Rocq, Isabelle/HOL, Lean
- ▶ Verification: SMT-powered real-world systems

statistical computation

Generative modelling with efficient inference: Monte-Carlo simulation or gradient-based optimisation

This course

Typed interface to probability/statistics

Every concept has:

- ▶ a type
- ▶ associated operations
- ▶ properties in terms of these operations.



Two implementations/models

course page

discrete model



familiar maths
introductory

full model

supports discrete
and
continuous distributions
same language

Motivation: why foundations?

discrete probability

countably supported distributions
good type-structure
(this course)

measure theory

standard, established
poor type-structure

↳ well-behaved probability
s-finite distributions
over standard Borel spaces

continuous probability

Lebesgue measure over \mathbb{R}^n

↳ quasi-Borel spaces
new, experimental
rich type-structure
(this course)

Takeaway

Use types to abstract away from the model

Motivation: why types?

- ▶ **spotlights** meaningful operations

$$\int : (\text{Distribution} X) \times (\text{RandomVariable} X) \rightarrow [0, \infty]$$

- ▶ document **intent**:
probability (**Distribution** X) vs. density ($X \rightarrow [0, \infty]$) vs. random variable
- ▶ succinctness: omit and elaborate details
- ▶ especially **formal** types, allow using theory correctly without fully understanding it

Lecture plan

Lecture 1: discrete model (today)

- ▶ Motivation
- ▶ Language of probability and distribution
- ▶ Discrete model
- ▶ Simply-typed probability
- ▶ Dependently-typed probability



course page

Lecture 2: the full model

- ▶ Borel sets and measurable spaces
- ▶ Quasi-Borel spaces
- ▶ Type structure & standard Borel spaces
- ▶ Integration & random variables



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Language of probability & distribution

X type (=space) of **values/outcomes**

DX type of **distributions/measures** over X

$\text{PX} \subseteq \text{DX}$ sub-type of **probability distributions** over X

$\mathcal{B}_X \subseteq \mathcal{P}X$ type of **events**: subsets we wish to measure

\mathbb{W} type of **weights**: values in $[0, \infty]$

\int, \mathbb{E} Lebesgue integration and the expectation operation

Type judgements describe well-formed values/outcomes of a given type, e.g.:

$$\mu : \text{DX}, E : \mathcal{B}_X \vdash \text{Ce}_{\mu}[E] : \mathbb{W}$$

(measures weight $\text{Ce}_{\mu}[E]$ of event E according to distribution μ)

Propositions describe properties of well-formed values/outcomes of a given type, e.g.:

$$y_1, y_2 : Y \vdash y_1 \stackrel{Y}{=} y_2 : \text{Prop} \quad \mu : \text{PX}, E : \mathcal{B}_X \vdash \Pr_{\mu}[E] = \text{Ce}_{\mu}[E]$$

(probability of event according to probability distribution is its measure)

Axioms for events and distributions

Empty event

$$\emptyset : \mathcal{B}_{\textcolor{red}{X}}$$

Empty events weight zero

$$\mu : \textcolor{blue}{D} X \vdash \textcolor{teal}{Ce}_{\mu} [\emptyset] = 0$$

Axioms for events and distributions

Boolean Sub-algebra of Events

$$E : \mathcal{B}_X \vdash E^C : \mathcal{B}_X \quad E, F : \mathcal{B}_X \vdash E \cap F : \mathcal{B}_X \quad \text{so also: } E, F : \mathcal{B}_X \vdash X, E \cup F : \mathcal{B}_X$$

Disjoint additivity

$$w, v : \mathbb{W} \vdash w + v : \mathbb{W} \quad E, C : \mathcal{B}_X, \mu : \mathsf{DX} \vdash \underset{\mu}{\mathsf{Ce}}[E] = \underset{\mu}{\mathsf{Ce}}[E \cap C] + \underset{\mu}{\mathsf{Ce}}[E \cap C^C]$$

Axioms for events and distributions

Boolean Sub-algebra of Events

$$E : \mathcal{B}_X \vdash E^C : \mathcal{B}_X \quad E, F : \mathcal{B}_X \vdash E \cap F : \mathcal{B}_X \quad \text{so also: } E, F : \mathcal{B}_X \vdash X, E \cup F : \mathcal{B}_X$$

Disjoint additivity

$$w, v : \mathbb{W} \vdash w + v : \mathbb{W} \quad E, C : \mathcal{B}_X, \mu : \mathsf{DX} \vdash \underset{\mu}{\mathsf{Ce}}[E] = \underset{\mu}{\mathsf{Ce}}[E \cap C] + \underset{\mu}{\mathsf{Ce}}[E \cap C^C]$$

Exercise

Derive ‘axiomatically’ that:

- ▶ measurement is **monotone**:

$$\mu : \mathsf{DX}, E \subseteq F \vdash \underset{\mu}{\mathsf{Ce}}[E] \leq \underset{\mu}{\mathsf{Ce}}[F]$$

- ▶ the **inclusion-exclusion** principle:

$$\mu : \mathsf{DX}, E, F : \mathcal{B}_X \vdash \underset{\mu}{\mathsf{Ce}}[E \cup F] + \underset{\mu}{\mathsf{Ce}}[E \cap F] = \underset{\mu}{\mathsf{Ce}}[E] + \underset{\mu}{\mathsf{Ce}}[F]$$

Axioms for events and distributions

Consider posets:

$$\omega := (\mathbb{N}, \leq) \quad (\mathcal{B}_X, \subseteq) \quad (\mathbb{W}, \leq)$$

ω -chains in a poset $P = (\underline{P}, \leq)$:

$$P^\omega := \{ p_\cdot \in \underline{P}^{\mathbb{N}} \mid p_0 \leq p_1 \leq \dots \}$$

Chain-closure of events and weights

$$E_\cdot : (\mathcal{B}_X, \subseteq)^\omega \vdash \bigcup_n E_n : \mathcal{B}_X \quad w_\cdot : (\mathbb{W}, \leq)^\omega \vdash \sup_n w_n : \mathbb{W}$$

Scott-continuity of measurement

$$E_\cdot : (\mathcal{B}_X, \subseteq)^\omega, \mu : \text{DX} \vdash \text{Ce}_\mu [\bigcup_n E_n] = \sup_n \text{Ce}_\mu [E_n]$$

Axiom for probability

Probability distributions have total mass one

$$\text{PX} := \{\mu \in \text{DX} \mid \text{Ce}_\mu[X] = 1\} \quad \mu : \text{PX} \vdash \text{cast } \mu : \text{DX}$$

i.e., if we define:

$$\mathbb{I} := [0,1] \quad \mu : \text{PX}, E : \mathcal{B}_X \vdash \Pr_\mu[E] := \text{Ce}_{\text{cast } \mu}[E] : \mathbb{I}$$

then:

$$\mu : \text{PX} \vdash \Pr_\mu[X] = 1$$

Integration

Lebesgue integration w.r.t. a distribution

$$\mu : \mathsf{D}X, f : \mathbb{W}^X \vdash \int \mu(dx) f(x) : \mathbb{W}$$

(NB: We succinctly write \mathbb{W}^X for the type of functions $X \rightarrow \mathbb{W}$.)

Expectation w.r.t. a probability distribution

$$\mu : \mathsf{P}X, f : \mathbb{W}^X \vdash \mathbb{E}_{x \sim \mu} [f(x)] := \int (\mathsf{cast} \mu)(dx) f(x) : \mathbb{W}$$

We'll use variations on this notation, e.g.:

$$\int d\mu f, \int f d\mu, \int f(x) \mu(dx), \mathbb{E}_\mu [f]$$

Summary

Have: Language and (some) axioms

Want: Model

Today: **discrete** model

Next week: **full** model

Lecture plan

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Discrete model

X : types denote **sets**

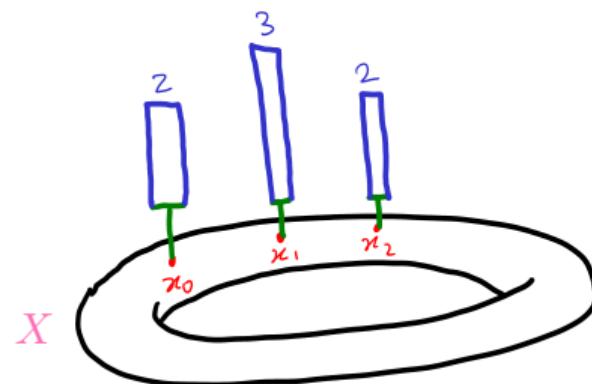
$\mathbf{D}X$: set of **histograms**:

Discrete model

X : types denote **sets**

$\mathbb{D}X$: set of **histograms**:

$\mathbb{D}X := \{\mu : X \rightarrow \mathbb{W} \mid \mu \text{ is } \mathbf{countably \ supported} \text{ (next slide)}\}$



$$\mu x_0 = 2 \quad \mu x_1 = 3 \quad \mu x_2 = 2$$

Countably supported distributions

Support

A subset S **supports** a weight function $\mu : X \rightarrow \mathbb{W}$ when μ is 0 outside S :

$$\mu : \mathbb{W}^X, S : \mathcal{P}X \vdash S \text{ supports } \mu := (\forall x : X. (\mu x > 0) \implies x \in S) : \text{Prop}$$

The subsets supporting a weight function μ are closed under intersections.

\implies There is a smallest supporting subset, called the **support** of μ :

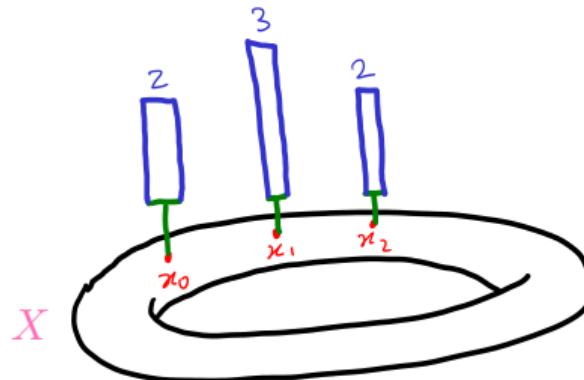
$$\mu : \mathbb{W}^X \vdash \text{supp } \mu := \{x \in X | \mu x > 0\}$$

Discrete model

X : types denote **sets**

\mathbf{DX} : set of **histograms**:

$$\begin{aligned}\mathbf{DX} &:= \{\mu : X \rightarrow \mathbb{W} \mid \mu \text{ is } \mathbf{countably\ supported}\} \\ &:= \{\mu : X \rightarrow \mathbb{W} \mid \exists S \in \mathcal{P}X. S \text{ is countable}\} \\ &:= \{\mu : X \rightarrow \mathbb{W} \mid \text{supp } \mu \text{ is countable}\}\end{aligned}$$



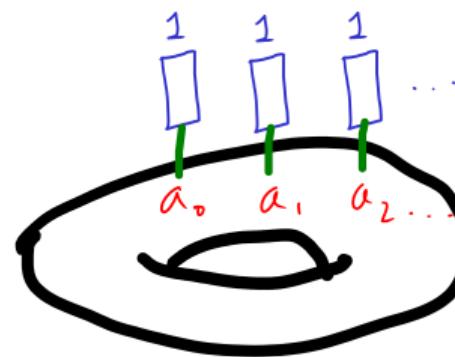
$$\mu x_0 = 2 \quad \mu x_1 = 3 \quad \mu x_2 = 2$$

Example distributions

Counting distribution

Counts the outcomes in a countable subset:

$$S : \mathcal{P}_{\text{fin}}(X) \vdash \#_S := \left(\lambda x. \begin{cases} x \in S & 1 \\ x \notin S & 0 \end{cases} \right) : \mathbf{D}X$$

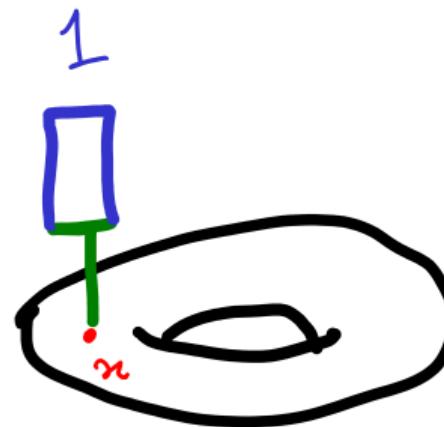


Example distributions

Dirac

A point mass:

$$x : X \vdash \delta_x := \left(\lambda x'. \begin{cases} x' = x & 1 \\ x' \neq x & 0 \end{cases} \right) : \mathbf{D}X$$



(NB: $x : X \vdash \delta_x = \#_{\{x\}}.$)

Example distributions

Zero

No mass anywhere:

$$\vdash \mathbf{0} := \underline{0} := (\lambda x.0) : \mathbf{D}X$$

(NB: $\vdash \mathbf{0} = \#_\emptyset.$)

Discrete model

X : types denote **sets**

$\text{D}X$: set of **histograms**:

$$\text{D}X := \{\mu : X \rightarrow \mathbb{W} \mid \mu \text{ is } \text{countably supported}\}$$

\mathcal{B}_X : **every subset** can be measured:

$$\mathcal{B}_X := \mathcal{P}X$$

Measurement: weighted sum of all (supported) outcomes:

$$\begin{aligned}\mu : \text{D}X, E : \mathcal{B}_X \vdash \text{Ce}_{\mu}[E] &:= \sum_{x \in E} \mu x \\ &:= \sum_{x \in E \cap \text{supp } \mu} \mu x\end{aligned}$$

NB: $\mu : \text{D}X, E : \mathcal{B}_X, S : \mathcal{P}_{\text{ctbl}}X, S \text{ supports } \mu \vdash \text{Ce}_{\mu}[E] = \sum_{x \in E \cap S} \mu x.$

Example measurements

(NB: $\mu : \text{DX}, E : \mathcal{B}_X, S : \mathcal{P}_{\text{ctbl}} X, S$ supports $\mu \vdash \text{Ce}_\mu [E] = \sum_{x \in E \cap S} \mu x.$)

Counting distribution

counts supported outcomes

$$S : \mathcal{P}_{\text{fin}}(X), E : \mathcal{B}_X \vdash \text{Ce}_{\#_S}[E] = |E \cap S| := \begin{cases} E \text{ has } n \in \mathbb{N} \text{ elements:} & n \\ E \text{ is infinite:} & \infty \end{cases}$$

Example measurements

(NB: $\mu : \text{DX}, E : \mathcal{B}_X, S : \mathcal{P}_{\text{ctbl}} X, S$ supports $\mu \vdash \text{Ce}_\mu [E] = \sum_{x \in E \cap S} \mu x.$)

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Dirac

detects given outcome:

$$x : X, E : \mathcal{B}_X \vdash \text{Ce}_{\delta_x}[E] = \begin{cases} x \in E : & 1 \\ x \notin E : & 0 \end{cases}$$

Example measurements

(NB: $\mu : \text{DX}, E : \mathcal{B}_X, S : \mathcal{P}_{\text{ctbl}} X, S$ supports $\mu \vdash \text{Ce}_\mu [E] = \sum_{x \in E \cap S} \mu x.$)

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Dirac

detects given outcome:

$$x : X, E : \mathcal{B}_X \vdash \text{Ce}_{\delta_x}[E] = \begin{cases} x \in E : & 1 \\ x \notin E : & 0 \end{cases}$$

Zero

measures every event as zero:

$$E : \mathcal{B}_X \vdash \text{Ce}_0[E] = 0$$

The discrete model validates the axioms

Exercise

$$\mu : \mathbf{D} \quad \vdash_{\mu} \text{Ce}[\emptyset] = 0$$

$$E, C : \mathcal{B}_X, \mu : \mathbf{D} \quad \vdash_{\mu} \text{Ce}[E] = \text{Ce}_{\mu}[E \cap C] + \text{Ce}_{\mu}[E \cap C^c]$$

$$E_+ : (\mathcal{B}_X, \subseteq)^\omega, \mu : \mathbf{D}x \vdash_{\mu} \text{Ce}\left[\bigcup_n E_n\right] = \sup_n \text{Ce}_{\mu}[E_n]$$

Parameterised distributions

Kernel

$k : X \rightsquigarrow Y$ from X to Y : function $k : X \rightarrow \mathbf{D}Y$.

Kernels are open/parameterised distributions.

Examples

Dirac and the counting distribution form kernels:

$$\delta_- : X \rightsquigarrow \mathbf{D}X \quad \#_- : \mathcal{P}_{\text{fin}}(X) \rightsquigarrow \mathbf{D}X$$

NB: This definition is **internal**: when we consider the full model, we will define kernels as those functions internal to the model rather than the set-theoretic functions.

Action of kernels on distributions

Kock integral

$$\mu : \mathbf{D}X, k : (\mathbf{D}Y)^X \vdash \oint d\mu k : \mathbf{D}Y$$

This **distribution-valued** integral is implicit in many probability texts. It corresponds to integrating against an arbitrary weight function or random variable.

Discrete model interpretation

$$\begin{aligned}\oint d\mu k &:= \lambda y. \sum_{x \in X} \mu x \cdot k(x; y) \\ &:= \lambda y. \sum_{x \in \text{supp } \mu} \mu x \cdot k(x; y)\end{aligned}$$

NB1: we write $k(x; y) := k(x)(y)$ for the uncurried function.

NB2: $\mu : \mathbf{D}X, k : (\mathbf{D}Y)^X, S : \mathcal{P}_{\text{ctbl}} X, S \text{ supports } \mu \vdash \oint d\mu k = \lambda y. \sum_{x \in S} \mu x \cdot k(x; y)$

Example

Weak Disintegration Problem (non-standard terminology)

Input: distributions $\mu : D\Theta$, $\nu : DX$

Output: kernel $k : \Theta \rightsquigarrow DX$ such that: $\nu = \oint d\mu k$.

Such a **weak disintegration** of ν w.r.t. μ provides an ‘explanation’ of an observed distribution $\nu \in DX$ in terms of a given distribution on parameters $\mu \in D\Theta$. I use the term ‘explanation’ because it explains how the parameters transform into observations.

Example

Weak Disintegration Problem (non-standard terminology)

Input: distributions $\mu : D\Theta$, $\nu : DX$

Output: kernel $k : \Theta \rightsquigarrow DX$ such that: $\nu = \oint d\mu k$.

Example disintegration

For $n \in \mathbb{N}$, write $\text{Fin } n := \{0, \dots, n - 1\}$. For countable X , write $\# := \#_X : DX$.

Here is a disintegration of $\# \in D((\text{Fin } 2)^{\text{Fin}(n+1)})$ w.r.t. $\# \in D(\text{Fin } 2)$:

$$k(x; f) := \begin{cases} fn = x : & 1 \\ \text{otherwise:} & 0 \end{cases} \quad \text{Indeed: } \left(\oint d\# k \right) f = \sum_{b \in \text{Fin } 2} \overbrace{\# b}^1 \cdot k(b; f) = k(0; f) + k(1; f)$$

$f : \text{Fin}(n+1) \rightarrow \text{Fin } 2$ function

so can take only one value: 0 or 1

$$\downarrow \\ = 1 = \# f$$

Sub-type of probability distributions

Sub-types

Given type X and $x : X \vdash \varphi : \text{Prop}$, take the **sub-type** and the **coercion** as follows:

$$\{x : X | \varphi\} \subseteq X \quad y : \{x : X | \varphi\} \vdash \text{cast } y := y : X$$

we **lift** values in X that satisfy φ to the sub-type:

$$\frac{\Gamma \vdash M : X \quad \Gamma \vdash \varphi [x \mapsto M]}{\Gamma \vdash \text{lift } M : \{x : X | \varphi\}} \quad \frac{\Gamma \vdash M : X \quad \Gamma \vdash \{\varphi\} x \mapsto M}{\Gamma \vdash \text{cast}(\text{lift } M) = M}$$

The axiom implies that $\text{lift } M$ lifts M along cast . Moreover:

$$y : \{x \in X | \varphi\} \vdash \text{lift}(\text{cast } y) = y \quad y : \{x \in X | \varphi\} \vdash \varphi [x \mapsto \text{cast } y]$$

i.e., the lifting is unique and elements in the sub-type satisfy φ .

Sub-type of probability distributions

Magnitude and probability distributions

$$\mu : \mathsf{D}X \vdash \|\mu\| := \mathsf{Ce}_{\mu}[X] : \mathbb{W} \quad \mathsf{P}X := \{\mu \in \mathsf{D}X \mid \|\mu\| = 1\} \quad \mathbb{I} := [0,1] := \{w \in \mathbb{W} \mid w \leq 1\}$$

Event probability

$$\mu : \mathsf{P}X, E : \mathcal{B}_X \vdash \Pr_{\mu}[E] := \mathsf{lift} \left(\mathsf{Ce}_{\mathsf{cast} \mu}[E] \right) : \mathbb{I}$$

Stochastic kernel

$k : X \rightsquigarrow Y$ from X to Y : function $X \rightarrow \mathsf{P}Y$.

NB: in the **discrete model** these distinctions and rules amount to pure pedantry. This pedantry will pay off in the **full model**.

Lifting Dirac and Kock

Lemma

Dirac kernels $\delta_- : X \rightarrow DX$ lift along `cast`:

$$x : X \vdash \|\delta_x\| = \underset{\delta_x}{\text{Ce}}[X] = 1 \quad \text{so we can overload:}$$

$$\begin{array}{ccc} \delta_- & \nearrow & PX \\ X & =: & \downarrow \text{cast} \\ \delta_- & \searrow & DX \end{array}$$

Kock integrals of stochastic kernels by probability distributions lift along `cast`:

$$\mu : PX, k : (PY)^X \vdash \underset{\oint(\text{cast } \mu)(dx) \text{ cast}(k x)}{\text{Ce}}[Y] = 1$$

$$\begin{array}{ccc} (PX) \times (PY)^X & \dashrightarrow^{\oint} & PY \\ \text{cast} \times (\text{cast} \circ) \downarrow & =: & \downarrow \text{cast} \\ (DX) \times (DY)^X & \xrightarrow{\oint} & DY \end{array}$$

so we can overload:

Proposition

The triple (D, δ_-, \oint) forms a monad over **Set**:

$$x : X, k : (DY)^X$$

$$\vdash \oint d\delta_x k = k x$$

$$\mu : DX$$

$$\vdash \oint \mu(dx) \delta_x = \mu$$

$$\mu : DX, k : (DY)^X, \ell : (DZ)^Y$$

$$\vdash \oint (\oint \mu(dx) k x) (dy) \ell y = \oint \mu(dx) \oint k(x; dy) \ell y$$

Corollary

The triple (P, δ_-, \oint) forms a monad over **Set**.

Weighted average

Lebesgue integral

Integration is the raison d'être for distributions:

$$\mu : \mathbf{D}X, f : \mathbb{W}^X \vdash \int d\mu f : \mathbb{W}$$

In the **discrete model**:

$$\int d\mu f := \sum_{x \in X} (\mu x) \cdot (f x) := \sum_{x \in \text{supp } \mu} (\mu x) \cdot (f x)$$

As usual, replace $\text{supp } \mu$ by any countable supporting set:

$$\mu : \mathbf{D}X, f : \mathbb{W}^X, S : \mathcal{P}X, S \text{ supports } \mu \vdash \int d\mu f = \sum_{x \in S} (\mu x) \cdot (f x)$$

Weighted average

Expectation

To emphasise that some μ is a probability distribution, we will use the notation:

$$\mu : \mathsf{P}X, f : \mathbb{W}^X \vdash \mathbb{E}_\mu [f] := \int d(\mathsf{cast} \mu) f : \mathbb{W}$$

When calculating, however, we will usually use \int and implicitly cast any probability distribution to its corresponding distribution.

Booleans

Boolean type

The simplest kind of distinguishing outcomes:

$$\mathbb{B} := \{\text{True}, \text{False}\} \quad \frac{\Gamma \vdash M : \mathbb{B} \quad \Gamma \vdash N_1 : X \quad \Gamma \vdash N_2 : X}{\Gamma \vdash \text{if } M \text{ then } N_1 \text{ else } N_2 : X}$$

Iverson bracket

Lets us replace Boolean propositions with arithmetic expressions:

$$b : \mathbb{B} \vdash [b] := (\text{if } b \text{ then } 1 \text{ else } 0) : \mathbb{W}$$

For example:

$$b : \mathbb{B}, w, v : \mathbb{W} \vdash \text{if } b \text{ then } w \text{ else } v = [b] \cdot w + (1 - [b]) \cdot v$$

Simplest probabilistic model

Bernoulli kernel

Single trial succeeding with the given probability:

$$\mathbf{B} : \mathbb{I} \rightsquigarrow \mathbb{B} \quad \mathbf{B}p := \lambda b. \begin{cases} b = \mathbf{True} : & p \\ b = \mathbf{False} : & 1 - p \end{cases}$$

For example, for a payoff of 10 units if the trial succeeds then the expected payoff is:

$$\mathbb{E}_{b \sim \mathbf{B} \frac{1}{4}} [[b] \cdot 10] = \frac{1}{4} \cdot 10 + (1 - \frac{1}{4}) \cdot 0 = \frac{10}{4} + 0 = \frac{5}{2}$$

Events as functions

Proposition

Membership testing induces an isomorphism between events and Boolean propositions:

$$(\in) : \mathcal{B}_X \xrightarrow{\cong} \mathbb{B}^X$$

Its inverse sends each Boolean property to the set of outcomes satisfying it:

$$\frac{x : X \vdash M : \mathbb{B}}{\{x \in X | M\} : \mathcal{B}_X} \quad \{x \in X | \varphi x\} := \{x \in X | \varphi x = \text{True}\}$$

Characteristic function

represents an event as weight functions: $E : \mathcal{B}_X \vdash [- \in E] : \mathbb{W}^X$

By the above proposition, every (internal) $\{0, 1\}$ -valued weight function is the characteristic function of some event, namely, the inverse image of 1.

Measurement through integration

Lemma

We can replace event measurement by integration of characteristic functions:

$$\mu : \mathbf{D}X, E : \mathcal{B}_X \vdash \mathbf{Ce}_{\mu}[E] = \int \mu(dx) [x \in E]$$

We can deduce properties for $\mathbf{Ce}[-]$ and $\mathbf{Pr}[-]$ from those of the Lebesgue integral.

Notation:

$$\frac{\Gamma \vdash \mu : \mathbf{D}X \quad \Gamma, x : X \vdash M : \mathbb{B}}{\Gamma \vdash \mathbf{Ce}_{x \sim \mu}[M] := \mathbf{Ce}_{\mu}[\{x \in X | M\}] : \mathbb{W}}$$

and similarly for $\mathbf{Pr}_{x \sim \mu}[M]$.

Language of probability & distribution (recap)

X type of **values/outcomes**

DX type of **distributions/measures** over X

$\text{PX} \subseteq \text{DX}$ sub-type of **probability distributions** over X

$\mathcal{B}_X \subseteq \mathcal{P}X$ type of **events**: subsets we wish to measure

\mathbb{W} type of **weights**: values in $[0, \infty]$

\int, \mathbb{E} Lebesgue integration and the expectation operation

Type judgements describe well-formed values/outcomes of a given type, e.g.:

$$\mu : \text{DX}, E : \mathcal{B}_X \vdash \text{Ce}_{\mu}[E] : \mathbb{W}$$

(measures weight $\text{Ce}_{\mu}[E]$ of event E according to distribution μ)

Propositions describe properties of well-formed values/outcomes of a given type, e.g.:

$$y_1, y_2 : Y \vdash y_1 \stackrel{Y}{=} y_2 : \text{Prop} \quad \mu : \text{PX}, E : \mathcal{B}_X \vdash \Pr_{\mu}[E] = \text{Ce}_{\mu}[E]$$

(probability of event according to probability distribution is its measure)

Lecture plan

Lecture 1: discrete model (today)

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Simply-typed foundations for probabilistic modelling

Compositional building blocks for modelling

- ▶ Affine combinations of distributions
- ▶ Product measures (\otimes) : $\mathbf{D}X \times \mathbf{D}Y \rightarrow \mathbf{D}(X \times Y)$
- ▶ Random elements and their laws (push-forward measure):
 $(\lambda(\mu, \alpha) . \mu_\alpha) : \mathbf{D}\Omega \times X^\Omega \rightarrow \mathbf{D}X$

NB:

- ▶ Dirac kernel $\delta_- : X \rightarrow \mathbf{D}X$
- ▶ Kock integration
 $\oint : \mathbf{D}X \times (\mathbf{D}Y)^{\mathbf{D}X} \rightarrow \mathbf{D}Y$

Standard vocabulary

- ▶ Joint and marginal distributions
- ▶ Independence
- ▶ Distribution/probability preservation and invariance
- ▶ Density and absolute continuity
- ▶ Almost certain/sure properties

Simply-typed foundations for probabilistic modelling

Compositional building blocks for modelling

- ▶ Affine combinations of distributions
- ▶ Product measures (\otimes) : $\mathbf{D}X \times \mathbf{D}Y \rightarrow \mathbf{D}(X \times Y)$
- ▶ Random elements and their laws (push-forward measure):
 $(\lambda(\mu, \alpha) . \mu_\alpha) : \mathbf{D}\Omega \times X^\Omega \rightarrow \mathbf{D}X$

NB:

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Affine combinations of distributions: scaling

Scaling distributions

$$w : \mathbb{W}, \mu : \mathbf{D}X \vdash w \cdot \mu : \mathbf{D}X$$

In the discrete model:

$$w \cdot \mu := \lambda x. w \cdot \mu x \quad \text{supp}(w \cdot \mu) \subseteq \text{supp } \mu$$

The function $(\cdot) : \mathbb{W} \times \mathbf{D}X \rightarrow \mathbf{D}X$ is a **monoid action** for the monoid $(\mathbb{W}, (\cdot), 1)$:

$$\mu : \mathbf{D}X \vdash 1 \cdot \mu = \mu \quad w, v : \mathbb{W}, \mu : \mathbf{D}X \vdash w \cdot (v \cdot \mu) = (w \cdot v) \cdot \mu$$

Integration and measurement are homogeneous w.r.t. scaling:

$$w : \mathbb{W}, \mu : \mathbf{D}X, k : (\mathbf{D}Y)^X \vdash \oint d(w \cdot \mu)k = w \cdot \oint d\mu k$$

$$w : \mathbb{W}, \mu : \mathbf{D}X, f : \mathbb{W}^X \vdash \int d(w \cdot \mu)f = w \cdot \int d\mu f$$

$$w : \mathbb{W}, \mu : \mathbf{D}X, E : \mathcal{B}_X \vdash \underset{w \cdot \mu}{\text{Ce}}[f] = w \cdot \underset{\mu}{\text{Ce}}[f]$$

Affine combinations of distributions: scaling

Normalisation

$$\mu : \text{DX}, \|\mu\| \neq 0, \infty \vdash \frac{\mu}{\|\mu\|} := \text{lift} \left(\frac{1}{\|\mu\|} \cdot \mu \right) : \text{PX}$$

measurement is homogeneous

$$\text{Indeed: } \left\| \frac{\mu}{\|\mu\|} \right\| = \left\| \frac{1}{\|\mu\|} \cdot \mu \right\| = \frac{1}{\|\mu\|} \cdot \|\mu\| = 1$$

Discrete uniform / categorical distribution

Random unbiased choice between finitely many options/categories:

$$S : \mathcal{P}_{\text{fin}}(X), S \neq \emptyset \vdash \mathbf{U}_S := \frac{\text{lift}\#_S}{\|\text{lift}\#_S\|} : \text{PX}$$

In the discrete model:

$$\mathbf{U}_S = \lambda x. \begin{cases} x \in S : & \frac{1}{|S|} \\ x \notin S : & 0 \end{cases}$$

so: $x : X \vdash \mathbf{U}_{\{x\}} = \delta_x$.

Weights as distributions

Unit type

$$\textcolor{blue}{\mathbb{1}} := \{()\}$$

Proposition

The following two functions are mutually inverse:

$$\begin{array}{ccc} & \parallel - \parallel & \\ \textcolor{blue}{D}\textcolor{blue}{\mathbb{1}} & \xrightarrow{\hspace{2cm}} & \textcolor{blue}{\mathbb{W}} \\ & \xleftarrow{\hspace{2cm}} & \\ & (\cdot \delta_0) & \end{array}$$

Proof

Calculate: $\mu : \textcolor{blue}{D}\textcolor{blue}{\mathbb{1}} \vdash \mu \mapsto \mu() \mapsto \lambda().\mu() = \mu$ and $w : \textcolor{blue}{\mathbb{W}} \vdash w \mapsto \lambda().w \mapsto w$. ■

Internalising Lebesgue integration

Proposition

We can recover Lebesgue integration from Kock integration:

$$\begin{array}{ccc} DX \times \mathbb{W}^X & \xrightarrow{\text{id} \times (\cong \circ)} & DX \times (D\mathbb{1})^X \\ \downarrow \int & = & \downarrow \oint \\ \mathbb{W} & \xleftarrow{\cong} & D\mathbb{1} \end{array}$$

Since measurement also reduced to Lebesgue integration, it usually suffices to prove properties of Kock integration and derive them for Lebesgue integration and for measurement.

Affine combinations of distributions: addition

Summation

$$\mu_- : (\mathbf{D}X)^I, I \text{ countable} \vdash \sum_{i \in I} \mu_i : \mathbf{D}X$$

In the discrete model:

$$\sum_{i \in I} \mu_i := \lambda x. \sum_{i \in I} \mu_i x \quad \text{supp } \sum_{i \in I} \mu_i = \bigcup_{i \in I} \text{supp } \mu_i$$

Affine and convex combinations

An **affine** combination is a countable sequence of weights $w_- : \mathbb{W}^I$.

It is **convex** when $\sum_{i \in I} w_i = 1$.

Bernoulli revisited

We can express the Bernoulli distribution as follows:

$$p : \mathbb{I} \vdash \mathbf{B}p = \text{lift}(p \cdot \delta_{\mathbf{True}} + (1 - p) \cdot \delta_{\mathbf{False}}) : \mathbf{PB}$$

Affinity of integration and convexity of expectation

Theorem (Multi-linearity)

The Kock and Lebesgue integrals and measurement are affine in each argument:

$$\mu_- : (\mathbf{D}X)^I, w_- : \mathbb{W}^I, k : X \rightsquigarrow Y \vdash \oint d(\sum_{i \in I} w_i \cdot \mu_i)k = \sum_{i \in I} w_i \cdot \oint d\mu_i k$$

$$\mu : \mathbf{D}X, w_- : \mathbb{W}^I, k_- : (X \rightsquigarrow B)^I \vdash \oint d\mu(\sum_{i \in I} w_i \cdot k_i) = \sum_{i \in I} w_i \cdot \oint d\mu k_i$$

$$\mu_- : (\mathbf{D}X)^I, w_- : \mathbb{W}^I, \varphi : \mathbb{W}^X \vdash \int d(\sum_{i \in I} w_i \cdot \mu_i)\varphi = \sum_{i \in I} w_i \cdot \int d\mu_i \varphi$$

$$\mu : \mathbf{D}X, w_- : \mathbb{W}^I, \varphi_- : (\mathbb{W}^X)^I \vdash \int d\mu(\sum_{i \in I} w_i \cdot \varphi_i) = \sum_{i \in I} w_i \cdot \int d\mu \varphi_i$$

$$\mu_- : (\mathbf{D}X)^I, w_- : \mathbb{W}^I, E : \mathcal{B}_X \vdash \sum_{i \in I} \text{Ce}_{w_i \cdot \mu_i}[E] = \sum_{i \in I} w_i \cdot \text{Ce}_{\mu_i}[E]$$

Weight arithmetic

This theorem, a working horse in probability, has several important consequences:

Proposition

The isomorphism $\mathbf{D}\mathbb{1} \cong \mathbb{W}$ is a σ -semiring isomorphism:

$$(\mathbf{D}\mathbb{1}, \sum, (\cdot)) \cong (\mathbb{W}, \sum, (\cdot))$$

and $(\cdot) : \mathbb{W} \times \mathbf{D}\mathcal{X} \rightarrow \mathbf{D}\mathcal{X}$ makes each $\mathbf{D}\mathcal{X}$ into a \mathbb{W} -module:

$$\left(\sum_{i \in I} w_i \right) \cdot \mu = \sum_{i \in I} (w_i \cdot \mu) \quad w \cdot \sum_{i \in I} \mu_i = \sum_{i \in I} w \cdot \mu_i$$

Lemma

Convex combination lifts to probability distributions:

$$w_- : \mathbb{W}^I, \mu_- : (\mathbf{P}X)^I, I \text{ countable}, \sum_{i \in I} w_i = 1 \vdash$$

$$\sum_{i \in I} w_i \cdot \mu_i \coloneqq \text{lift} \sum_{i \in I} w_i \cdot (\text{cast } \mu_i) : \mathbf{P}X$$

Proof

Calculate: $\left\| \sum_{i \in I} w_i \cdot (\text{cast } \mu_i) \right\| = \sum_{i \in I} w_i \cdot \|\text{cast } \mu_i\| = \sum_{i \in I} w_i \cdot 1 = 1$

■

Corollary (Multi-convexity)

Stochastic Kock integration, expectation and measurement are convex:

$$\mu_- : (\mathbf{D}X)^I, w_- : \mathbb{W}^I, k : X \rightsquigarrow Y, \sum_{i \in I} w_i = 1 \vdash \oint d(\sum_{i \in I} w_i \cdot \mu_i)k = \sum_{i \in I} w_i \cdot \oint d\mu_i k$$

$$\mu : \mathbf{D}X, w_- : \mathbb{W}^I, k_- : (X \rightsquigarrow B)^I, \sum_{i \in I} w_i = 1 \vdash \oint d\mu(\sum_{i \in I} w_i \cdot k_i) = \sum_{i \in I} w_i \cdot \oint d\mu k_i$$

$$\mu_- : (\mathbf{D}X)^I, w_- : \mathbb{W}^I, \varphi : \mathbb{W}^X, \sum_{i \in I} w_i = 1 \vdash \mathbb{E}_{\sum_{i \in I} w_i \cdot \mu_i} [\varphi] = \sum_{i \in I} w_i \cdot \mathbb{E}_{\mu_i} [\varphi]$$

$$\mu : \mathbf{D}X, w_- : \mathbb{W}^I, \varphi_- : (\mathbb{W}^X)^I, \sum_{i \in I} w_i = 1 \vdash \mathbb{E}_\mu \left[\sum_{i \in I} w_i \cdot \varphi_i \right] = \sum_{i \in I} w_i \cdot \mathbb{E}_\mu [\varphi_i]$$

$$\mu_- : (\mathbf{D}X)^I, w_- : \mathbb{W}^I, E : \mathcal{B}_X, \sum_{i \in I} w_i = 1 \vdash \Pr_{\sum_{i \in I} w_i \cdot \mu_i} [E] = \sum_{i \in I} w_i \cdot \Pr_{\mu_i} [E]$$

Products

Product distribution

$$\mu : \mathsf{D}X, \nu : \mathsf{D}Y \vdash \mu \otimes \nu := \oint \mu(dx) \oint \nu(dy) \delta_{(x,y)} : \mathsf{D}(X \times Y)$$

In the discrete model:

$$\mu \otimes \nu = \lambda(x, y) \cdot (\mu x) \cdot (\nu y) \quad \text{supp } (\mu \otimes \nu) = (\text{supp } \mu) \times (\text{supp } \nu)$$

Example: counting distribution on product space

$$S : \mathcal{P}_{\text{fin}}(X), T : \mathcal{P}_{\text{fin}}(Y) \vdash \#_{S \times T} \stackrel{\mathsf{D}(X \times Y)}{=} \#_S \otimes \#_T$$

Indeed: $\text{supp } (\#_S \otimes \#_T) = S \times T = \text{supp } \#_{S \times T}$ and for $(x, y) \in S \times T$:

$$(\#_S \otimes \#_T)(x, y) = 1 \cdot 1 = 1 = \#_{S \times T}(x, y)$$

Products

Notation:

$$\frac{\Gamma \vdash M : \mathbf{D}(X \times Y) \quad \Gamma, x : X, y : Y \vdash K : \mathbf{D}Z}{\Gamma \vdash \iint M(dx, dy)K := \oint dK(\lambda(x, y).K) : \mathbf{D}Z}$$

Theorem (Fubini-Tonelli)

We can integrate products in any order:

$$\mu : \mathbf{D}X, \nu : \mathbf{D}Y, k : (\mathbf{D}Z)^{X \times Y} \vdash$$

$$\oint \mu(dx) \oint \nu(dy) k(x, y) = \iint (\mu \otimes \nu)(dx, dy) k(x, y) = \oint \mu(dx) \oint \nu(dy) k(x, y)$$

$$\mu : \mathbf{D}X, \nu : \mathbf{D}Y, \varphi : \mathbb{W}^{X \times Y} \vdash$$

$$\int \mu(dx) \int \nu(dy) \varphi(x, y) = \iint (\mu \otimes \nu)(dx, dy) \varphi(x, y) = \int \mu(dx) \int \nu(dy) \varphi(x, y)$$

Applying Fubini-Tonelli

Theorem (Rule of Product)

We can factor out products:

$$\begin{array}{ll} \mu : \mathsf{D}X, f : \mathbb{W}^X, \nu : \mathsf{D}Y, g : \mathbb{W}^Y \vdash & \iint (\mu \otimes \nu)(dx, dy) fx \cdot gy = \left(\int d\mu f \right) \cdot \left(\int d\nu g \right) \\ \mu : \mathsf{D}X, E : \mathcal{B}_X, \nu : \mathsf{D}Y, F : \mathcal{B}_Y \vdash & \underset{\mu \otimes \nu}{\mathsf{Ce}} [E \times F] = \underset{\mu}{\mathsf{Ce}} [E] \cdot \underset{\nu}{\mathsf{Ce}} [F] \end{array}$$

Theorem

The product lifts to probability distributions:

$$\mu : \mathsf{P}X, \nu : \mathsf{P}Y \vdash (\mu \otimes \nu) := \mathsf{lift}(\mathsf{cast} \mu \otimes \mathsf{cast} \nu) : \mathsf{P}(X \times Y)$$

Products

Binomial distribution

the number of successful outcomes of n independent Bernoulli trials:

$$\mathbf{B}_n : \mathbb{I} \rightsquigarrow \mathsf{P}(\mathbf{Fin}(1+n)) \quad \mathbf{B}_0 p := \delta_0 : \mathsf{P}(\mathbf{Fin} 1)$$

$$\mathbf{B}_{1+n} p := \iint (\mathbf{B}_n p \otimes \mathbf{B} p)(dc, db) (\text{if } b \text{ then } \delta_{1+c} \text{ else } \delta_c) : \mathsf{P}(\mathbf{Fin}(2+n))$$

We can prove by induction on n , using Fubini-Tonelli and the Iverson bracket that:

$$p : \mathbb{I}, k : \mathbf{Fin}(1+n) \vdash \Pr_{c \sim \mathbf{B}_n p} [c = k] = \binom{n}{k}$$

Push-forward distributions

Random element

in X any (internal) function:

$$\mu : D\Omega \vdash \alpha : \Omega \rightarrow X$$

Law

of a random element is the distribution:

$$\mu : D\Omega, \alpha : X^\Omega \vdash \mu_\alpha := \int \mu(d\omega) \delta_{\alpha\omega} : DX$$

Example

Represent outcomes of die roll by $D6 := \{1, 2, \dots, 6\}$, and two rolls by $D6 \times D6$.

The sum of the rolls is a random element:

$$(+ : D6 \times D6 \rightarrow \mathbb{N})$$

The law of the distribution $\# \otimes \#$ counts the number of configurations in which the two rolls sum to a given number, e.g.: $(\# \otimes \#)(+) : 1 \mapsto 0, 2 \mapsto 1$.

Push-forward distributions

Theorem (Law of the Unconscious Statistician)

Formulae for reparameterising integration and measurement:

$$\mu : \Omega, \alpha : X^\Omega, k : X \rightsquigarrow Y \vdash \oint d\mu_\alpha k = \oint d\mu(k \circ \alpha)$$

$$\mu : \Omega, \alpha : X^\Omega, f : \mathbb{W}^X \vdash \int d\mu_\alpha f = \int d\mu(f \circ \alpha)$$

$$\mu : \Omega, \alpha : X^\Omega, E : \mathcal{B}_X \vdash \underset{\mu_\alpha}{\text{Ce}}[E] = \underset{\mu}{\text{Ce}}[\alpha^{-1}[E]] = \underset{\omega \sim \mu}{\text{Ce}}[\alpha \omega \in E]$$

Simply-typed foundations for probabilistic modelling

Compositional building blocks for modelling

- ▶ Affine combinations of distributions
- ▶ Product measures (\otimes) : $\mathbf{D}X \times \mathbf{D}Y \rightarrow \mathbf{D}(X \times Y)$
- ▶ Random elements and their laws (push-forward measure):
 $(\lambda(\mu, \alpha) . \mu_\alpha) : \mathbf{D}\Omega \times X^\Omega \rightarrow \mathbf{D}X$

NB:

- ▶ Dirac kernel $\delta_- : X \rightarrow \mathbf{D}X$
- ▶ Kock integration
 $\oint : \mathbf{D}X \times (\mathbf{D}Y)^{\mathbf{D}X} \rightarrow \mathbf{D}Y$

Standard vocabulary

- ▶ Joint and marginal distributions
- ▶ Independence
- ▶ Distribution/probability preservation and invariance
- ▶ Density and absolute continuity
- ▶ Almost certain/sure properties

Standard vocabulary: concepts concerning products

Let $\pi_i : \prod_{i \in I} X_i \rightarrow X_i$ be the i -th projection.

Joint distribution: $\mu : D(X \times Y)$, $\mu : D(\prod_{i \in I} X_i)$

Marginal distribution: the law of a projection:

$$\mu : D\left(\prod_{i \in I} X_i\right) \vdash \mu_{\pi_i} : D X_i$$

Sometimes refers to any law of a r.e..

Marginalisation: the action of calculating a marginal distribution by integrating all other components.

Exercise

$$\mu : P X, \nu : D X \vdash (\mu \otimes \nu)_{\pi_2} = \nu$$

Independence

Pairing random elements

$$\alpha : X^\Omega, \beta : Y^\Omega \vdash \lambda \omega. (\alpha \omega, \beta \omega) : (X \times Y)^\Omega$$

Independent random elements

The joint law is the product of the marginals:

$$\mu : \mathsf{D}\Omega, \alpha : X^\Omega, \beta : Y^\Omega \vdash \alpha \perp_{\mu} \beta := \left(\mu_{(\alpha, \beta)} \stackrel{\mathsf{D}(X \times Y)}{=} \mu_\alpha \otimes \mu_\beta \right)$$

More generally, for finite I :

$$\mu : \mathsf{D}\Omega, \alpha_i : (X^\Omega)^I \vdash \perp_{\mu} \alpha_i := \left(\mu_{(\alpha_i)_i} \stackrel{\mathsf{D}(\prod_i X_i)}{=} \bigotimes_{i \in I} \mu_{\alpha_i} \right)$$

Independence

Example [Durett]

Model 3 independent coin tosses:

$$\text{Toss} := \{\text{Head}, \text{Tail}\} \quad \Omega := \text{Toss}^3 \quad \mu := \mathbf{U}_{\text{Toss}} \otimes \mathbf{U}_{\text{Toss}} \otimes \mathbf{U}_{\text{Toss}} : P\Omega$$

The outcome of the i^{th} coin toss is the random element $\pi_i : \Omega \rightarrow \text{Toss}$.

Consider the Boolean proposition in which the i^{th} and j^{th} tosses ($i \neq j$) agree:

$$\text{Same}_{ij} := \lambda \omega. \pi_i \omega = \pi_j \omega : \Omega \rightarrow \mathbb{B}$$

Calculate:

	\downarrow LOTUS	\downarrow marginalisation
	$\Pr_{\mu} [\text{Same}_{12}] = \Pr_{(x,y) \sim \mu_{(\pi_1, \pi_2)}} [x = y]$	$= \Pr_{(x,y) \sim \mathbf{U} \otimes \mathbf{U}} [x = y]$
	$= \frac{1}{2} \cdot \Pr_{y \sim \mathbf{U}} [\text{Head} = y] + \frac{1}{2} \cdot \Pr_{y \sim \mathbf{U}} [\text{Tail} = y]$	$= \int \mathbf{U}(dx) \Pr_{y \sim \mathbf{U}} [x = y]$

$\Pr_{\mu} [\text{Same}_{12}] = \frac{1}{2} \cdot \Pr_{y \sim \mathbf{U}} [\text{Head} = y] + \frac{1}{2} \cdot \Pr_{y \sim \mathbf{U}} [\text{Tail} = y] = \frac{1}{4} + \frac{1}{4} = \frac{1}{2}$

Independence

Example [Durett]

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Consider the Boolean proposition in which the i^{th} and j^{th} tosses ($i \neq j$) agree:

$$\text{Same}_{ij} := \lambda \omega. \pi_i \omega = \pi_j \omega : \Omega \rightarrow \mathbb{B}$$

Therefore $\mu_{\text{Same}_{12}} = \mathbf{U}_{\mathbb{B}}$ and similarly $\mu_{\text{Same}_{ij}} = \mathbf{U}_{\mathbb{B}}$ for $i \neq j$.

Independence

π_1 , Same_{12} , and Same_{13} determine π_2, π_3 , so:

$$\Pr_{\omega \sim \mu} [\text{Same}_{12}\omega = \text{True}, \text{Same}_{13}\omega = \text{True}]$$

Fubini-Tonelli

$$\begin{aligned} & \downarrow \\ &= \int \mathbf{U}_{\text{Toss}}(db_1) \Pr_{(b_2, b_3) \sim (\mathbf{U} \otimes \mathbf{U})} [\text{Same}_{12}(b_1, b_2, b_3) = \text{True}, \text{Same}_{13}(b_1, b_2, b_3) = \text{True}] \\ &= \frac{1}{2} \Pr_{(b_2, b_3) \sim (\mathbf{U} \otimes \mathbf{U})} [\text{Same}_{12}(\text{Head}, b_2, b_3) = \text{True}, \text{Same}_{13}(\text{Head}, b_2, b_3) = \text{True}] \\ &\quad + \frac{1}{2} \Pr_{(b_2, b_3) \sim (\mathbf{U} \otimes \mathbf{U})} [\text{Same}_{12}(\text{Tail}, b_2, b_3) = \text{True}, \text{Same}_{13}(\text{Tail}, b_2, b_3) = \text{True}] \\ &= \frac{1}{2} \cdot \frac{1}{2} \cdot \frac{1}{2} + \frac{1}{2} \cdot \frac{1}{2} \cdot \frac{1}{2} = \frac{1}{4} \end{aligned}$$

and similarly we get $\frac{1}{4}$ in all other cases.

Independence

Example [Durett]

Model 3 independent coin tosses:

$$\text{Toss} := \{\text{Head}, \text{Tail}\} \quad \Omega := \text{Toss}^3 \quad \mu := \mathbf{U}_{\text{Toss}} \otimes \mathbf{U}_{\text{Toss}} \otimes \mathbf{U}_{\text{Toss}} : P\Omega$$

The outcome of the i^{th} coin toss is the random element $\pi_i : \Omega \rightarrow \text{Toss}$.

Consider the Boolean proposition in which the i^{th} and j^{th} tosses ($i \neq j$) agree:

$$\text{Same}_{ij} := \lambda \omega. \pi_i \omega = \pi_j \omega : \Omega \rightarrow \mathbb{B}$$

Therefore $\mu_{\text{Same}_{12}} = \mathbf{U}_{\mathbb{B}}$ and similarly $\mu_{\text{Same}_{ij}} = \mathbf{U}_{\mathbb{B}}$ for $i \neq j$. So:

$$\mu_{(\text{Same}_{12}, \text{Same}_{13})} = \mathbf{U}_{\mathbb{B} \times \mathbb{B}} = \mathbf{U}_{\mathbb{B}} \otimes \mathbf{U}_{\mathbb{B}} = \mu_{\text{Same}_{12}} \otimes \mu_{\text{Same}_{13}}$$

So $\text{Same}_{12} \perp \text{Same}_{13}$ even though their values depend on the outcome of the first toss.
 μ

Distribution preservation

Distribution space (Ω, μ)

A type Ω equipped with a distribution $\mu : D\Omega$. Define **probability space** analogously.

Distribution preserving function

$f : (\Omega_1, \mu_1) \rightarrow (\Omega_2, \mu_2)$ is a function whose is the co domain distribution:

$$f : \Omega_1 \rightarrow \Omega_2 \quad (\mu_1)_f = \mu_2$$

$\mu : DX$ is **invariant** under $f : X \rightarrow X$ when $f : (X, \mu) \rightarrow (X, \mu)$ is dist. preserving.

Example

Consider the swapping function: $\text{swap} := (\lambda(x, y). (y, x)) : X \times Y \rightarrow Y \times X$. Then, for each $\mu : DX$, $\nu : DY$, swapping is distribution preserving function:

$$\text{swap} : (X \times Y, \mu \otimes \nu) \rightarrow (Y \times X, \nu \otimes \mu)$$

swap is invariant in the case $X = Y$ and $\mu = \nu$.

Density and scaling

Density

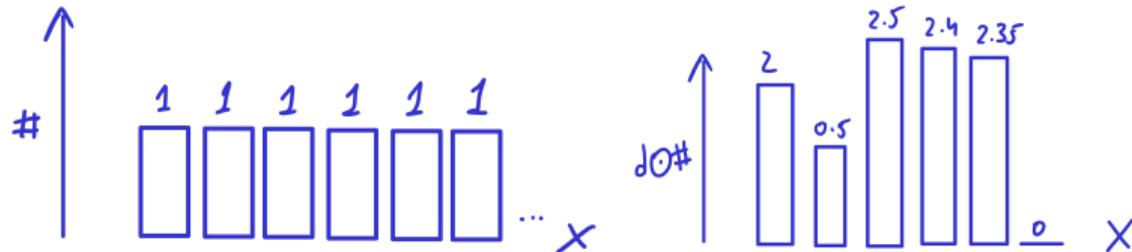
over X is any weight function $f : X \rightarrow \mathbb{W}$.

Density scaling

We can scale a distribution by a density:

$$f : \mathbb{W}^X, \mu : \mathbf{D}X \vdash f \odot \mu := \int \mu(dx)(f, x) \cdot \delta_x : \mathbf{D}X$$

Scaling does not lift to probability distributions: $\|f \odot \mu\| \neq 1$ even if $\|\mu\| = 1$.



Density and scaling

Density

over X is any weight function $f : X \rightarrow \mathbb{W}$.

Density scaling

We can scale a distribution by a density:

$$f : \mathbb{W}^X, \mu : \mathsf{D}X \vdash f \odot \mu := \oint \mu(dx)(f, x) \cdot \delta_x : \mathsf{D}X$$

Scaling does not lift to probability distributions: $\|f \odot \mu\| \neq 1$ even if $\|\mu\| = 1$.

Warning!

The types of distributions and densities over X in the **discrete** model are close, but still **different**. They coincide on **countable** types, so people often confuse them. Types help us keep them separate.

Density and absolute continuity

Having density

This concept has several names in the literature:

$$\mu, \nu : \mathbf{D}X, f : \mathbb{W}^X \vdash \left(f = \frac{d\mu}{d\nu} \right) := (\mu = f \odot \nu) : \mathbf{Prop}$$

- ▶ f is the **density** of μ w.r.t. ν
- ▶ f is a **Radon-Nikodym derivative** of μ w.r.t. ν .

Absolute continuity

μ is **absolutely continuous** w.r.t. ν when μ has a density w.r.t. ν :

$$\mu, \nu : \mathbf{D}X \vdash (\mu \ll \nu) := \exists f : \mathbb{W}^X. f = \frac{d\mu}{d\nu} : \mathbf{Prop}$$

Density and absolute continuity

Example

The **uniform distribution** is absolutely continuous w.r.t. the **counting measure** over the same support. Indeed, it has these two densities:

$$S : \mathcal{P}_{\text{fin}}(X) \vdash \left(\lambda x. \frac{1}{|S|} \right), \left(\lambda x. \begin{cases} x \in S : & \frac{1}{|S|} \\ x \notin S : & 0 \end{cases} \right) = \frac{d\mathbf{U}_S}{d\#_S}$$

These two densities are different, but they agree on the support, motivating the following concept.

Almost certain/sure properties

Almost certain event

is one we can assert without changing the distribution:

$$\frac{\Gamma \vdash \mu : \mathbf{D}X \quad \Gamma, x : X \vdash M : \mathbb{B}}{\Gamma \vdash \mu(\mathrm{d}x) \text{ almost certainly } M := [M] \odot \mu = \mu : \mathbf{Prop}}$$

For probabilities we define:

$$\frac{\Gamma \vdash \mu : \mathbf{P}X \quad \Gamma, x : X \vdash M : \mathbb{B}}{\Gamma \vdash \mu(\mathrm{d}x) \text{ almost surely } M := (\mathbf{cast}\ \mu)(\mathrm{d}x) \text{ almost certainly } M : \mathbf{Prop}}$$

Existence and almost-sure uniqueness of densities

Theorem (Radon-Nikodym)

For **probability** distributions, we characterise absolute continuity as follows:

$$\mu, \nu : \mathbf{P} X \vdash (\mu \ll \nu) \iff \forall E : \mathcal{B}_X. \Pr_{\nu}[E] = 0 \implies \Pr_{\mu}[E] = 0$$

In that case, if $f, g = \frac{d\mu}{d\nu}$ then $\nu(dx)$ almost surely $f x = g x$.

In the **discrete model**, this characterisation amounts to $\text{supp } \mu \subseteq \text{supp } \nu$.

Example

For all countable X , we have:

$$\forall \mu : \mathbf{D} X. \mu \ll \#_X$$

Indeed, apply the Radon-Nikodym theorem, since $\text{supp } \# = X$.

Constructively, direct calculation shows: $(\lambda x. \mu x) = \frac{d\mu}{d\#}$.

Simply-typed foundations for probabilistic modelling

Compositional building blocks for modelling

- ▶ Affine combinations of distributions
- ▶ Product measures (\otimes) : $\mathbf{D}X \times \mathbf{D}Y \rightarrow \mathbf{D}(X \times Y)$
- ▶ Random elements and their laws (push-forward measure):
 $(\lambda(\mu, \alpha) . \mu_\alpha) : \mathbf{D}\Omega \times X^\Omega \rightarrow \mathbf{D}X$

NB:

- ▶ Dirac kernel $\delta_- : X \rightarrow \mathbf{D}X$
- ▶ Kock integration
 $\oint : \mathbf{D}X \times (\mathbf{D}Y)^{\mathbf{D}X} \rightarrow \mathbf{D}Y$

Standard vocabulary

- ▶ Joint and marginal distributions
- ▶ Independence
- ▶ Distribution/probability preservation and invariance
- ▶ Density and absolute continuity
- ▶ Almost certain/sure properties

Lecture plan

Lecture 1: discrete model (today)

- ▶ Motivation
- ▶ Language of probability and distribution
- ▶ Discrete model
- ▶ Simply-typed probability
- ▶ Dependently-typed probability



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Lecture 2: the full model

- ▶ Borel sets and measurable spaces
- ▶ Quasi-Borel spaces
- ▶ Type structure & standard Borel spaces
- ▶ Integration & random variables



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Type dependencies

Example: Binomial kernels

We've defined, for every $n \in \mathbb{N}$, the binomial kernel:

$$\vdash \mathbf{B}_n : \mathbb{I} \rightsquigarrow \mathbf{Fin}(1 + n)$$

We will now look at **dependent-type** structure which allows us to view these as one kernel internally:

$$n : \mathbb{N} \vdash \mathbf{B}_n : \mathbb{I} \rightsquigarrow \mathbf{Fin}(1 + n)$$

Family model

Family over an indexing set I

consists of a sequence $X_ = (X_i)_{i \in I}$ of sets.

We call each set X_i the **fibre over i** .

Family F

a pair $F = (I, X_)$ consisting of (indexing) set I and a family $X_$ over it.

Notation: $F = I \vdash X_$

$= i : I \vdash X_i$.

Example

The family $n : \mathbb{N} \vdash \mathbf{Fin} n$ has \mathbb{N} as the indexing set. The fibre over $n \in \mathbb{N}$ is:

$$\mathbf{Fin} n := \{0, 1, \dots, n - 1\}$$

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Family map

$(\theta, f_) : (I \vdash X_) \rightarrow (J \vdash Y_)$ is a pair of a function between the indexing sets and a sequence of functions between the corresponding fibres:

$$\theta : I \rightarrow J \quad (f_i : X_i \rightarrow Y_{\theta i})_{i \in I}$$

Notation: $\theta \vdash f_$. We won't use these maps explicitly, but they are the foundation.

Terms in context

Dependent elements $i : I \vdash M : X_i$

in family $i : I \vdash X_i$ are I -indexed sequences of elements from the corresponding fibres:

$$(M \in X_i)_{i \in I}$$

Example

We have the elements:

$$n : \mathbb{N} \vdash 0, \dots, n - 1 : \mathbf{Fin}\,n$$

Subsumption

Every simple type becomes a family by ignoring the dependency through the constant family, e.g., $i : I \vdash \mathbb{N}$ and $i : I \vdash 42 : \mathbb{N}$.

Simple functions

Fibred exponential

of two families over the same indexing set $i : I \vdash X_i, Y_i$ is the family:

Family of distributions

$$i : I \vdash X_i \rightarrow Y_i$$

over a family $i : I \vdash X_i$ is the family:

$$i : I \vdash \mathbf{D}X_i$$

Its sub-family of fibred **probability** distributions:

$$i : I \vdash \mathbf{P}X_i$$

Both have a **Dirac** distribution:

$$i : I \vdash \delta_- : X_i \rightarrow \mathbf{D}X_i \quad i : I \vdash \delta_- : X_i \rightarrow \mathbf{P}X_i$$

Extension and dependent pairs

Extension

of indexing set I by a **variable** of the family $i : I \vdash X_i$ is the (indexing) set:

$$\coprod_{i \in I} X_i \coloneqq \bigcup_{i \in I} \{i\} \times X_i = \left\{ (i, x) \in I \times \bigcup_{i \in I} X_i \mid x \in X_i \right\}$$

Notation: $(i : I, x : X_i) \coloneqq \coprod_{i \in I} X_i$ and we'll often write i, x instead of (i, x) .

Dependent pairs

$$\frac{i : I \vdash X_i \quad i : I, x : X_i \vdash Y_{i,x}}{i : I \vdash (x : X_i) \times (Y_{i,x}) \coloneqq \coprod_{x \in X_i} Y_{i,x}}$$

Functions and kernels

Dependent functions

we identify a function f with a tuple $(fx)_x$ as usual:

$$\frac{i : I \vdash X_i \quad i : I, x : X_i \vdash Y_{i,x}}{i : I \vdash ((x : X) \rightarrow Y_{i,x}) \coloneqq \prod_{x \in X} Y_{i,x}}$$

Dependent kernels $i : I \vdash k : (x : X_i) \rightsquigarrow Y_{i,x}$

are dependent elements:

$$i : I \vdash k : (x : X_i) \rightarrow \mathsf{D}Y_{i,x}$$

Dependent **stochastic** kernels $i : I \vdash k : (x : X_i) \rightsquigarrow Y_{i,x}$ are similarly:

$$i : I \vdash k : (x : X_i) \rightarrow \mathsf{P}Y_{i,x}$$

Integration

Dependent Kock integral

$$i : I, \mu : \mathbf{D}X_i, k : (x : X_i) \rightsquigarrow Y_{i,x} \vdash \oint d\mu k : \mathbf{D}Y_{i,x}$$

and in the **discrete model** we define it for i, μ, k as in the simply-typed case:

$$(\oint d\mu k)y \coloneqq \sum_{x \in X_i} \mu x \cdot k(x; y) : \mathbb{W}$$

Through the identification $\mathbb{W} \cong \mathbf{D}\mathbb{1}$ and characteristic functions, we reduce dependent Lebesgue integration and measurement to dependent Kock integration:

$$i : I, \mu : \mathbf{D}X_i, f : (x : X_i) \rightarrow \mathbb{W} \vdash \int d\mu f : \mathbb{W} \quad i : I, \mu : \mathbf{D}X_i, E : \mathcal{B}_{X_i} \vdash \text{Ce}_\mu [E] : \mathbb{W}$$
$$\int d\mu f = \sum_{x \in X} \mu x \cdot f x \quad \text{Ce}_\mu [E] = \sum_{x \in E} \mu x$$

Random variables

Let $\overline{\mathbb{R}} := [-\infty, \infty]$ be the extended real line.

Signed and unsigned random variable

in a probability space (Ω, μ) are random elements $\alpha : \Omega \rightarrow \overline{\mathbb{R}}$ and $\alpha : \Omega \rightarrow \mathbb{W}$.

The **positive** and **negative parts** are unsigned random variables $\alpha^\pm : \overline{\mathbb{R}}^\Omega \rightarrow \mathbb{W}^\Omega$:

$$\alpha^+ := \lambda \omega. \max(\alpha \omega, 0) = [\alpha \geq 0] \cdot |\alpha| \quad \alpha^- := \lambda \omega. -\min(\alpha \omega, 0) = [\alpha \leq 0] \cdot |\alpha|$$

An unsigned r.v. α is **Lebesgue integrable** when its Lebesgue integral is finite:

$$\int d\mu \alpha < \infty.$$

For a (signed) r.v. α , when either α^+ or α^- is Lebesgue integrable, we define:

$$\mu : \mathbf{DX}, \alpha : \overline{\mathbb{R}}^X, \int d\mu \alpha^+, \int d\mu \alpha^- < \infty \vdash \int d\mu \alpha := \int d\mu \alpha^+ - \int d\mu \alpha^-$$

A signed variable is **Lebesgue integrable** when both its parts are Lebesgue integrable.

Random variable spaces

Lebesgue integrability is a Boolean property:

$$\mu : \text{DX}, \alpha : X \rightarrow \bar{\mathbb{R}} \vdash \alpha \text{ integrable} := \int d\mu \alpha^+ < \infty \wedge \int d\mu \alpha^- < \infty : \mathbb{B}$$

Lebesgue spaces ensemble

is the family:

$$i : I, p : [1, \infty), \mu : \mathsf{P}X_i \vdash \mathcal{L}_p(X_i, \mu) := \{\alpha : X_i \rightarrow \bar{\mathbb{R}} \mid \alpha^p \text{ integrable}\}$$

Every fibre has a vector space structure and a norm (almost a Banach space!):

$$i : I, p : [1, \infty), \mu : \mathsf{P}X_i, \alpha : \mathcal{L}_p(X_i, \mu) \vdash \|\alpha\|_p := \sqrt[p]{\mathbb{E}_\mu [\|\alpha\|^p]} : \mathbb{W}$$

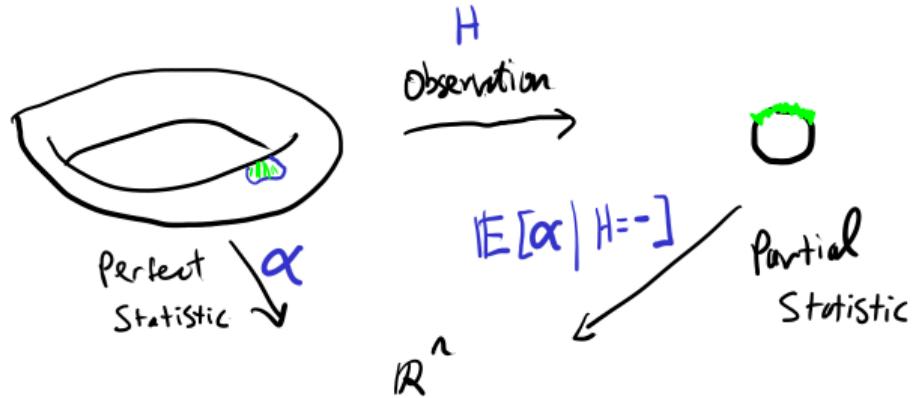
and the fibre 2 has an inner product (almost a Hilbert space!):

$$i : I, \mu : \mathsf{P}X_i, \alpha, \beta : \mathcal{L}_2(X_i, \mu) \vdash (\alpha, \beta) := \sqrt{\mathbb{E}_\mu [\alpha \cdot \beta]} : \mathbb{W}$$

Conditioning

Situation:

- ▶ Statistical model $\mu : D\Omega$
(voters in the next election)
- ▶ Perfect statistic $\alpha : \Omega \rightarrow \mathbb{R}$
(expected winning candidate)
- ▶ Observation $H : D \rightarrow X$
(poll voting intention)



Conditional expectation of α along H w.r.t μ

Statistic $\beta : X \rightarrow \mathbb{R}$ that 'best' approximates $H \circ \alpha$ statistically. Halmos and Doob's definition: any measurement we make of β agrees with measurement of α :

$$\mu : D\Omega, H : \Omega \rightarrow X, \alpha : \mathcal{L}_1(\Omega, \mu), \beta : \mathcal{L}_1(X, \mu_H) \vdash$$

$$\left(\beta = \underset{\mu}{\mathbb{E}} [\alpha | H = -] \right) \doteq \left(\forall \varphi : \mathcal{L}_1 X, \mu_H. \int d\mu_H \beta \cdot \varphi = \int d\mu \alpha (\varphi \circ H) \right) \quad : \text{Prop}$$

Conditioning

Theorem (Kolmogorov)

Every random variable has a conditional expectation:

$$\mu : \mathsf{D}\Omega, H : \Omega \rightarrow X, \alpha : \mathcal{L}_1(\Omega, \mu) \vdash \exists \beta : \mathcal{L}_1(X, \mu_H). \beta = \underset{\mu}{\mathbb{E}} [\alpha | H = -]$$

Therefore:

Corollary (Internal conditional expectation)

In the **discrete model** we have a dependent function:

$$\mathbb{E}_- [- | - = -] :$$

$$(\mu : \mathsf{D}\Omega) \rightarrow (H : \Omega \rightarrow X) \rightarrow (\alpha : \mathcal{L}_1(\Omega, \mu)) \rightarrow \left\{ \beta : \mathcal{L}_1(X, \mu_H) \middle| \beta = \underset{\mu}{\mathbb{E}} [\alpha | H = -] \right\}$$

Conditioning

Conditional probability

$$\Pr_{\underline{-}}[-|-\underline{=} -] \coloneqq \lambda \mu, H, x. \mathbb{E}_{\mu} [[-=x]|H=-] : \\ (\mu : \mathsf{D}\Omega) \rightarrow (H : \Omega \rightarrow X) \rightarrow (x : X) \rightarrow \mathsf{P} \{\omega \in \Omega | H\omega = x\}$$

when the conditional expectation internalises.

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