

STATS305C: Applied Statistics III

Lecture 16: Poisson processes

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Outline

- ▶ Defining properties of a Poisson process
- ▶ Four ways to sample a Poisson process
- ▶ Beyond Poisson: Doubly stochastic processes

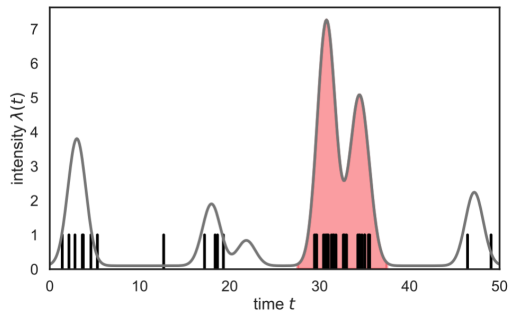
Defining properties of a Poisson process

- Poisson processes are **stochastic processes** that generate **random sets of points** $\{\mathbf{x}_n\}_{n=1}^N \subset \mathcal{X}$.
- Poisson processes are governed by an **intensity function**, $\lambda(\mathbf{x}) : \mathcal{X} \rightarrow \mathbb{R}_+$.
- **Property #1:** The number of points in any interval is a Poisson random variable,

$$N(\mathcal{A}) \sim \text{Po} \left(\int_{\mathcal{A}} \lambda(\mathbf{x}) d\mathbf{x} \right) \quad (1)$$

- **Property #2:** Disjoint intervals are independent,

$$N(\mathcal{A}) \perp N(\mathcal{B}) \iff \mathcal{A} \cap \mathcal{B} = \emptyset \quad (2)$$



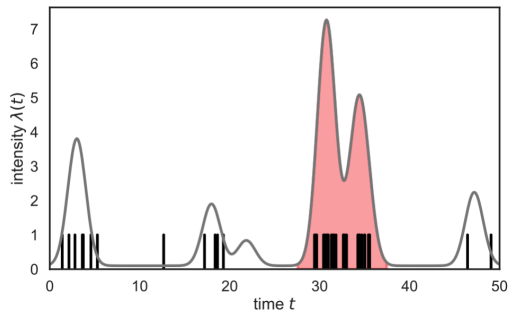
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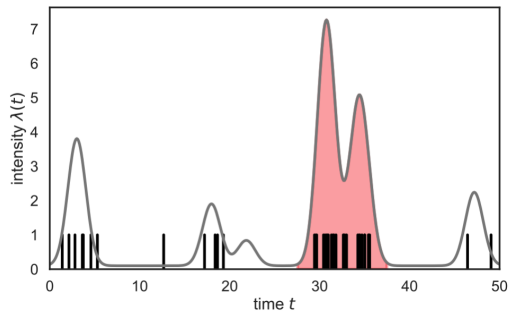
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Example applications of Poisson processes

- ▶ Modeling neural firing rates
- ▶ Locations of trees in a forest
- ▶ Locations of stars in astronomical surveys
- ▶ Arrival times of customers in a queue (or HTTP requests to a server)
- ▶ Locations of bombs in London during World War II
- ▶ Times of photon detections on a light sensor
- ▶ Others?

Four ways to sample a Poisson process

1. The top-down approach
2. The interval approach
3. The time-rescaling approach
4. The thinning approach

Top-down sampling of a Poisson process

Given $\lambda(\mathbf{x})$ (and a domain \mathcal{X}):

1. Sample the **total number of points**

$$N \sim \text{Po} \left(\int_{\mathcal{X}} \lambda(\mathbf{x}) \, d\mathbf{x} \right) \quad (3)$$

2. Sample the **locations** of the points

$$\mathbf{x}_n \stackrel{\text{iid}}{\sim} \frac{\lambda(\mathbf{x})}{\int_{\mathcal{X}} \lambda(\mathbf{x}') \, d\mathbf{x}'} \quad (4)$$

for $n = 1, \dots, N$.

Question: what assumptions are necessary for this procedure to be tractable?

Deriving the Poisson process likelihood

Exercise: from the top-down sampling process, derive the Poisson process likelihood,

$$p(\{\mathbf{x}_n\}_{n=1}^N \mid \lambda(\mathbf{x})) = \quad (5)$$

Intervals of a homogeneous Poisson process

- ▶ A Poisson process is **homogeneous** if its intensity is constant, $\lambda(\mathbf{x}) \equiv \lambda$.
- ▶ **Property #3:** A homogeneous Poisson process on $[0, T] \subset \mathbb{R}$ (e.g. where points correspond to arrival times) has **independent, exponentially distributed intervals**,

$$\Delta_n = x_n - x_{n-1} \stackrel{\text{iid}}{\sim} \text{Exp}(\lambda) \quad (6)$$

- ▶ **Property #4:** A homogeneous Poisson process is **memoryless** – the amount of time until the next point arrives is independent of the time elapsed since the previous point arrived.

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Sampling a homogeneous Poisson process by simulating intervals

We can sample a homogeneous Poisson process on $[0, T]$ by simulating intervals as follows:

1. Initialize $\mathbf{X} = \emptyset$ and $x_0 = 0$
2. For $n = 1, 2, \dots$:
 - ▶ Sample $\Delta_n \sim \text{Exp}(\lambda)$.
 - ▶ Set $x_n = x_{n-1} + \Delta_n$.
 - ▶ If $x_n > T$, break and return \mathbf{X} ,
 - ▶ Else, set $\mathbf{X} \leftarrow \mathbf{X} \cup \{x_n\}$.

Deriving the likelihood of a homogeneous Poisson process

Exercise: from the interval sampling process, derive the likelihood of a homogeneous Poisson process. Show that it is the same as what you derived from the top-down sampling process.

Sampling an inhomogeneous Poisson process by time-rescaling

- ▶ Now consider an **inhomogeneous** Poisson process on $[0, T]$; i.e. one with a non-constant intensity.
- ▶ Apply the change of variables,

$$x \mapsto \int_0^x \lambda(t) dt \triangleq \Lambda(x) \quad (7)$$

Note that this is an **invertible transformation** when $\lambda(x) > 0$.

- ▶ Sample a homogeneous Poisson process with unit rate on $[0, \Lambda(T)]$ to get points $\mathbf{U} = \{u_n\}_{n=1}^N$. Then set,

$$\mathbf{X} = \{\Lambda^{-1}(u_n) : u_n \in \mathbf{U}\}. \quad (8)$$

- ▶ **Sanity check:** what is the expected value of N ?

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Sampling an inhomogeneous Poisson process by time-rescaling, in pictures

Note: this is the analog of **inverse-CDF** sampling.

A Goodness of fit test for inhomogeneous Poisson processes

- ▶ Brown et al. [2002] used the time-rescaling sampling procedure to develop a goodness-of-fit test for inhomogeneous Poisson processes.
- ▶ Suppose you observe a set of points $\{x_n\}_{n=1}^N \subset [0, T]$ and you want to test whether they are well-modeled by an inhomogeneous Poisson process with rate $\lambda(x)$.
- ▶ Let $\Delta_n = \Lambda(x_n) - \Lambda(x_{n-1})$ with $\Lambda(x_0) = 0$. If the model is a good fit, then $\Delta_n \stackrel{\text{iid}}{\sim} \text{Exp}(1)$.
- ▶ Perform a further transformation $z_n = 1 - e^{-\Delta_n}$. Then $z_n \stackrel{\text{iid}}{\sim} \text{Unif}([0, 1])$.
- ▶ Now sort the z_n 's in increasing order into $(z_{(1)}, \dots, z_{(N)})$, so $z_{(1)}$ is the smallest value.
- ▶ Intuitively, the points $(\frac{n-1/2}{N}, z_{(n)})$ should lie along a 45° line.

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A Goodness of fit test for inhomogeneous Poisson processes II

- ▶ We can check for significant departures from the 45° line using a simple visual test.
- ▶ The order statistics $z_{(n)}$ are marginally beta distributed,

$$z_{(n)} \sim \text{Beta}(n, N - n + 1) \quad (9)$$

The mean is $\frac{n}{N+1}$ and its mode is $\frac{n-1}{N-1}$.

- ▶ Then, use the 2.5% and 97.5% quantiles of the beta distribution to obtain confidence intervals around the 45° line.

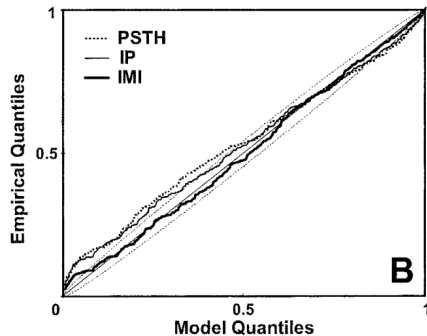


Figure: Figure 1 from Brown et al. [2002].

The Poisson Superposition Principle

- **Property #5:** The union (a.k.a. superposition) of independent Poisson processes is also a Poisson process.
- Suppose we have two independent Poisson processes on the same domain \mathcal{X} ,

$$\{\mathbf{x}_n\}_{n=1}^N \sim \text{PP}(\lambda_1(\mathbf{x})) \quad (10)$$

$$\{\mathbf{x}'_m\}_{m=1}^M \sim \text{PP}(\lambda_2(\mathbf{x})) \quad (11)$$

Then

$$\{\mathbf{x}_n\}_{n=1}^N \cup \{\mathbf{x}'_m\}_{m=1}^M \sim \text{PP}(\lambda_1(\mathbf{x}) + \lambda_2(\mathbf{x})) \quad (12)$$

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Poisson thinning

- ▶ The opposite of Poisson superposition is **Poisson thinning**.
- ▶ Suppose we have points $\{\mathbf{x}_n\}_{n=1}^N \sim \text{PP}(\lambda(\mathbf{x}))$ where $\lambda(\mathbf{x}) = \lambda_1(\mathbf{x}) + \lambda_2(\mathbf{x})$.
- ▶ Sample independent binary variables

$$z_n \sim \text{Bern}\left(\frac{\lambda_1(\mathbf{x}_n)}{\lambda_1(\mathbf{x}_n) + \lambda_2(\mathbf{x}_n)}\right). \quad (13)$$

- ▶ Then $\{\mathbf{x}_n : z_n = 1\} \sim \text{PP}(\lambda_1(\mathbf{x}))$ and $\{\mathbf{x}_n : z_n = 0\} \sim \text{PP}(\lambda_2(\mathbf{x}))$.

Sampling a Poisson process by thinning

Exercise: Use Poisson thinning to sample an inhomogeneous Poisson process with a bounded intensity, $\lambda(\mathbf{x}) \leq \lambda_{\max}$.

Question: What Monte Carlo sampling method is this akin to?

Outline

- ▶ Defining properties of a Poisson process
- ▶ Four ways to sample a Poisson process
- ▶ **Beyond Poisson**

What's not to love about Poisson processes?

Conditional intensity functions

- ▶ One way of introducing dependence is via an **autoregressive model**. Consider a point process on a time interval $[0, T]$.
- ▶ Let $\lambda(t \mid \mathcal{H}_t)$ denote a **conditional intensity function** where \mathcal{H}_t is the **history** of points before time t .
- ▶ Technically, \mathcal{H}_t is a **filtration** in the language of stochastic processes.
- ▶ Allowing past points to influence the intensity function enables more complex, non-Poisson models.

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Hawkes processes

- ▶ Hawkes processes [Hawkes, 1971] are **self-exciting point processes**.

- ▶ Their conditional intensity function is modeled as,

$$\lambda(t \mid \mathcal{H}_t) = \lambda_0 + \sum_{t_n \in \mathcal{H}_t} h(t - t_n), \quad (14)$$

where $h : \mathbb{R}_+ \mapsto \mathbb{R}_+$ is a positive **impulse response** or **influence function**.

- ▶ For example, the impulse responses could be modeled as exponential functions,

$$h(\Delta t) = \frac{w}{\tau} e^{-\frac{\Delta t}{\tau}} = w \cdot \text{Exp}(\Delta t; \tau), \quad (15)$$

where $\tau \in \mathbb{R}_+$ is a time-constant governing the rate of decay and $w \in \mathbb{R}_+$ is a scaling parameter such that $\int_0^\infty h(\Delta t) d\Delta t = w$.

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Hawkes processes, in pictures

Maximum likelihood estimation for Hawkes processes I

- Suppose we observe a collection of time points $\{t_n\}_{n=1}^N \subset [0, T]$ and want to estimate the parameters $\boldsymbol{\theta} = (\lambda_0, w)$ of a Hawkes process with an exponential impulse response function. (Consider τ to be fixed.)
- The Hawkes process log likelihood is just like that of a Poisson process,

$$\log p(\{t_n\}_{n=1}^N \mid \boldsymbol{\theta}) = - \int_0^T \lambda_{\boldsymbol{\theta}}(t \mid \mathcal{H}_t) dt + \sum_{n=1}^N \log \lambda_{\boldsymbol{\theta}}(t_n \mid \mathcal{H}_{t_n}) \quad (16)$$

Maximum likelihood estimation for Hawkes processes II

- Substituting in the form of the conditional intensity, we can simplify the log likelihood to,

$$\begin{aligned} \log p(\{t_n\}_{n=1}^N \mid \boldsymbol{\theta}) = & - \int_0^T \left[\lambda_0 + w \sum_{t_n \in \mathcal{H}_t} \text{Exp}(t - t_n; \tau) \right] dt \\ & + \sum_{n=1}^N \log \left(\lambda_0 + w \sum_{t_m \in \mathcal{H}_{t_n}} \text{Exp}(t_n - t_m; \tau) \right) \end{aligned} \quad (17)$$

$$\approx -\boldsymbol{\theta}^\top \boldsymbol{\phi}_0 + \sum_{n=1}^N \log \left(\boldsymbol{\theta}^\top \boldsymbol{\phi}_n \right) \quad (18)$$

where $\boldsymbol{\phi}_0 = (T, N)^\top$ and $\boldsymbol{\phi}_n = \left(1, \sum_{t_m \in \mathcal{H}_{t_n}} \text{Exp}(t_n - t_m; \tau) \right)^\top$.

- **Questions:** What approximation did we make? How would you maximize the log likelihood as a function of $\boldsymbol{\theta}$?

Marked point processes

- ▶ Now suppose we observed points from S difference **sources**.
- ▶ We can represent the points as a set of tuples, $\{(t_n, s_n)\}_{n=1}^N$ where $t_n \in [0, T]$ denotes the time and $s_n \in \{1, \dots, S\}$ denotes the source of the n -th point.
- ▶ We will model them as a **marked point process**.
- ▶ Like before, we have a (conditional) intensity function, but this time is defined over time and marks,

$$\lambda(t, s \mid \mathcal{H}_t) : [0, T] \times \{1, \dots, S\} \mapsto \mathbb{R}_+ \quad (19)$$

- ▶ When s takes on a discrete set of values, we often use the shorthand,

$$\lambda_s(t \mid \mathcal{H}_t) \triangleq \lambda(t, s \mid \mathcal{H}_t) \quad (20)$$

to denote the intensity for the s -th source.

Multivariate Hawkes processes

- ▶ A **multivariate** Hawkes process is a marked point process with **mutually excitatory** interactions.
- ▶ It is defined by the conditional intensity functions,

$$\lambda_s(t \mid \mathcal{H}_t) = \lambda_{s,0} + \sum_{(t_n, s_n) \in \mathcal{H}_t} h_{s_n, s}(t - t_n). \quad (21)$$

where $h_{s, s'}(\Delta t)$ is a **directed impulse response** from points on source s to the intensity of s' .

- ▶ Again, it is common to model the impulse responses as weighted probability densities; e.g.,

$$h_{s, s'}(\Delta t) = w_{s, s'} \cdot \text{Exp}(\Delta t; \tau_{s, s'}) \quad (22)$$

where $w_{s, s'}$ is the weight.

- ▶ Like before, the weights can be estimated using maximum likelihood estimation.

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- ▶ It is defined by the conditional intensity functions,

$$\lambda_s(t \mid \mathcal{H}_t) = \lambda_{s,0} + \sum_{(t_n, s_n) \in \mathcal{H}_t} h_{s_n, s}(t - t_n). \quad (21)$$

where $h_{s, s'}(\Delta t)$ is a **directed impulse response** from points on source s to the intensity of s' .

- ▶ Again, it is common to model the impulse responses as weighted probability densities; e.g.,

$$h_{s, s'}(\Delta t) = w_{s, s'} \cdot \text{Exp}(\Delta t; \tau_{s, s'}) \quad (22)$$

where $w_{s, s'}$ is the weight.

- ▶ Like before, the weights can be estimated using maximum likelihood estimation.

Multivariate Hawkes processes

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Multivariate Hawkes Processes II

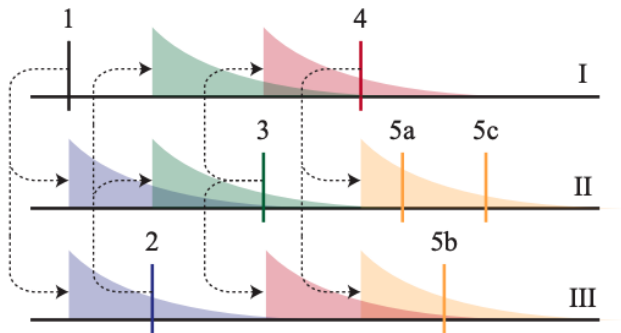


Figure 1: Illustration of a Hawkes process. Events induce impulse responses on connected processes and spawn “child” events. See the main text for a complete description.

From Linderman and Adams [2014].

Discovering latent network structure in point process data

- We can think of the weights as defining a **directed network**,

$$\mathbf{W} = \begin{bmatrix} w_{1,1} & \dots & w_{1,S} \\ \vdots & & \vdots \\ w_{S,1} & \dots & w_{S,S} \end{bmatrix} \quad (23)$$

where $w_{s,s'} \in \mathbb{R}_+$ is the strength of influence that events (points) on source s induce on the intensity of source s' .

- However, we don't directly observe the network. We only observed it indirectly through the point process.
- **Question:** when is a multivariate Hawkes process stable, in that the intensity tends to a finite value in the infinite time limit?

Multivariate Hawkes processes as Poisson clustering processes

- Note that the conditional intensity in eq. (21) is a sum of a background intensity and a bunch of non-negative impulse responses.

$$\lambda_s(t \mid \mathcal{H}_t) = \lambda_{0,s} + \sum_{(t_n, s_n) \in \mathcal{H}_t} h_{s_n, s}(t - t_n). \quad (24)$$

- **Question:** which property of Poisson processes applied to such intensities?

Multivariate Hawkes processes as Poisson clustering processes

- Note that the conditional intensity is a sum of a background intensity and a bunch of non-negative impulse responses,

$$\lambda_s(t \mid \mathcal{H}_t) = \lambda_{s,0} + \sum_{(t_n, s_n) \in \mathcal{H}_t} h_{s_n, s}(t - t_n). \quad (25)$$

- **Question:** which property of Poisson processes applied to such intensities?
- Using the **Poisson superposition principle**, we can partition the points $\mathcal{T}_s = \{t_n : s_n = s\}$ from source s into **clusters** attributed to either the background or to one of the impulse responses.

$$\mathcal{T}_s = \bigcup_{n=0}^N \mathcal{T}_{s,n} \quad (26)$$

where

$$\mathcal{T}_{s,0} \sim \text{PP}(\lambda_{s,0}) \quad [\text{background points}] \quad (27)$$

$$\mathcal{T}_{s,n} \sim \text{PP}(h_{s_n, s}(t - t_n)) \quad [\text{points induced by } (t_n, s_n)] \quad (28)$$

Multivariate Hawkes processes as Poisson clustering processes

- Now the weights have an intuitive interpretation. Plugging in the definition of the impulse response,

$$\mathcal{T}_{s,n} \sim \text{PP}\left(w_{s_n,s} \cdot \text{Exp}(t - t_n; \tau_{s_n,s})\right). \quad (29)$$

- **Question:** What is the expected number of points induced by this impulse response, i.e. $\mathbb{E}[|\mathcal{T}_{s,n}|]$?

Conjugate Bayesian inference for multivariate Hawkes processes

- Let's put a gamma prior on the weights,

$$w_{s,s'} \sim \text{Ga}(\alpha, \beta). \quad (30)$$

- **Question:** suppose we know the partition of points; i.e. we knew the clusters $\mathcal{T}_{s,n}$. What is the conditional distribution,

$$p(w_{s,s'} \mid \{\{\mathcal{T}_{s,n}\}_{n=0}^N\}_{s=1}^S) = \quad (31)$$

Conjugate Bayesian inference for multivariate Hawkes processes II

- ▶ We don't know the partition of spikes in general, but we do know its conditional distribution!
- ▶ Let $z_n \in \{0, \dots, n-1\}$ denote the cluster to which the n -th spike is assigned, with $z_n = 0$ denoting the background cluster. With this notation,

$$\mathcal{T}_{s,n} = \{(t_{n'}, s_{n'}) : s_{n'} = s \wedge z_{n'} = n\}. \quad (32)$$

- ▶ **Question:** what is the conditional distribution of the cluster assignment,

$$p(z_n \mid \{(t_n, s_n)\}_{n=1}^N; \theta) = \quad (33)$$

- ▶ Using these two conditional distributions, we can derive a simple Gibbs sampling algorithm that alternates between sampling the weights given the clusters and the clusters given the weights.

Beyond Poisson: Doubly stochastic processes

- ▶ Hawkes processes are only one way of going beyond Poisson processes.
- ▶ Whereas Hawkes processes take an autoregressive approach, **doubly stochastic point processes** (a.k.a. **Cox processes**) take a latent variable approach.

- ▶ In these models, the intensity itself is modeled as a stochastic process,

$$\lambda(\mathbf{x}) \sim p(\lambda). \quad (34)$$

- ▶ For example, consider the model,

$$\lambda(\mathbf{x}) = g(f(\mathbf{x})) \quad \text{where} \quad f \sim \text{GP}(\mu(\cdot), K(\cdot, \cdot)). \quad (35)$$

When g is the exponential function, this is called a **log Gaussian Cox process**. When g is the sigmoid function, this is called a **sigmoidal Gaussian Cox process** [Adams et al., 2009].

- ▶ Alternatively, take λ to be a convolution of a Poisson process with a non-negative kernel; this is called a Neyman-Scott process [Wang et al., 2022, e.g.].

Conclusion

- ▶ Poisson processes are stochastic processes that generate discrete sets of points.
- ▶ They are defined by an intensity function $\lambda(\mathbf{x})$, which specifies the expected number of points in each interval of time or space.
- ▶ We can build in dependencies by conditioning on past points or introducing latent variables.
- ▶ Poisson process modeling boils down to inferring the intensity. We can take various parametric and nonparametric approaches.
- ▶ The hardness comes about when the integral in the Poisson process likelihood is intractable.
- ▶ As we will see next time, Poisson processes are also mathematical building blocks for Bayesian nonparametric models with random measures.

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