# Class notes: Poisson regression and variance stabilizing transformations

## 1 Poisson distribution

$$Y \sim Pois(\lambda) \;\; \Rightarrow \;\; P(Y = k) = \exp(-\lambda)\frac{\lambda^k}{k!} \;, \;\; k = 0, 1, \dots \;, \;\; (\lambda > 0)$$

Facts:

- $E(Y) = var(Y) = \lambda$
- $X \sim Bin(n, p)$ with $n$ big and $p$ small then $X \dot{\sim} Pois(np)$
- Memoryless renewal process  
  $\Leftrightarrow$ time to event is exponentially distributed  
  $\Leftrightarrow$ number of events in time $T$ is Poisson
- $Y_i \sim Pois(\lambda_i)$ independent $\Rightarrow \; \sum_i Y_i \sim Pois(\sum_i \lambda_i)$

Very useful in "real life". Examples (under proper assumptions):

1. Number of customers arriving at bank teller in an hour
2. Number of grades a Netflix movie gets in a year
3. Number of mutations in a genomic locus in X generations (or sum over genome)

## 2 Poisson regression

Like Gaussian and Binomial (logistic) regression, we assume:

$$Y|X = x \sim Pois(\lambda(x))$$

Like in Binomial we can try to assume $\lambda(x) = x^t\beta$ but does not guarantee $\lambda > 0$.
Solution is to use link functions and assume $\log(\lambda(x)) = x^t\beta$.

## 3 Variance stabilizing transformations

Assume we insist on using square error loss for modeling or (especially) evaluation. Probabilistically squared error corresponds to Gaussian log likelihood, of homoskedastic error, i.e.,

- Symmetric.
- $Var(Y|X)$ is fixed throughout covariate space.

Second assumption especially is problematic. Say $Y|X \sim Pois(\lambda(X))$ and $\lambda$ is large, then:

- Normal appx. is not a problem: $Pois(\lambda) \approx N(\lambda, \lambda)$
- But variance linearly depends on mean $\Rightarrow$ homoskedasticity is a problem

Can we transform $Y$ in such a way as to solve this problem?

General setup:

$$E(Y) = \mu \ , \quad Var(Y) = \sigma^2 = \Omega(\mu)$$

Examples:

1. Gaussian: $\sigma^2$ is an independent parameter, can assume $\Omega(\mu)$ =constant.
2. Bernoulli: $\Omega(\mu) = \mu(1-\mu)$
3. Poisson: $\Omega(\mu) = \mu$

We are looking for $f(Y)$ such that $Var(f(Y))$ will be roughly constant (independent of $\mu$), like in the normal case. Taylor expansion:

$$\begin{aligned} f(Y) &= f(\mu) + (Y-\mu)f'(\mu) + O((Y-\mu)^2) \\ (f(Y) - f(\mu))^2 &\approx (Y-\mu)^2 (f'(\mu))^2 \end{aligned}$$

Abusing additional probability law (which one?) we write:

$$Var(f(Y)) \approx Var(Y)(f'(\mu))^2$$

So to (approximately) stabilize variance we want:

$$\begin{array}{rl} & (f'(\mu))^2 = 1/\Omega(\mu) \\ \text{Poisson:} & (f'(\mu))^2 = 1/\mu \Rightarrow \ f(\mu) = 2\sqrt{\mu} \\ \Rightarrow & Var(\sqrt{Y}) \approx 1/4 \end{array}$$

Binomial variance stabilizing transformation:

$$X \sim Bin(n,p) \ \Rightarrow \ var(\arcsin(\sqrt{(}X/n))) \approx 1/2$$