

# Lecture 7: GLM Theory — Link Functions

## MATH3823 Generalised Linear Models

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**Course notes:** Chapter 3, Sections 3.5–3.6

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## Recall: The Role of the Link Function

**Problem:** The mean  $\mu$  may be constrained:

- Poisson:  $\mu > 0$
- Binomial:  $0 < \mu/m < 1$

**But:** The linear predictor  $\eta = \mathbf{x}'\boldsymbol{\beta}$  is unconstrained.

**Solution:** Use a link function  $g$  such that:

$$\eta = g(\mu) \in \mathbb{R}$$

The inverse  $h = g^{-1}$  maps  $\eta$  back to the valid range of  $\mu$ .

## Canonical Links Revisited

**Recall:** The canonical link sets  $\eta = \theta$  (natural parameter).

Distribution	Canonical Link	$g(\mu)$
Normal	Identity	$\mu$
Poisson	Log	$\log(\mu)$
Binomial	Logit	$\log \frac{p}{1-p}$
Gamma	Reciprocal	$-1/\mu$

**Property:** With canonical link,

$$g'(\mu) = \frac{1}{b''(\theta)} = \frac{1}{V(\mu)}$$

# Advantages of Canonical Links

## ① Sufficient statistics:

$$S_j = \sum_{i=1}^n y_i x_{ij}$$

contain all information about  $\beta_j$ .

## ② Simple score equations: MLE satisfies

$$\sum_{i=1}^n (y_i - \hat{\mu}_i) x_{ij} = 0$$

## ③ Computational efficiency: Algorithms converge reliably.

**However:** Other links may be more interpretable or provide a better fit.

## Link Functions for Binomial Data

For proportions/probabilities  $p \in (0, 1)$ :

Name	Link $g(p)$	Inverse $h(\eta)$
Logit	$\log \frac{p}{1-p}$	$\frac{e^\eta}{1+e^\eta}$
Probit	$\Phi^{-1}(p)$	$\Phi(\eta)$
Cloglog	$\log(-\log(1-p))$	$1 - e^{-e^\eta}$
Cauchit	$\tan(\pi(p - 0.5))$	$0.5 + \frac{1}{\pi} \arctan(\eta)$

where  $\Phi$  is the standard normal CDF.

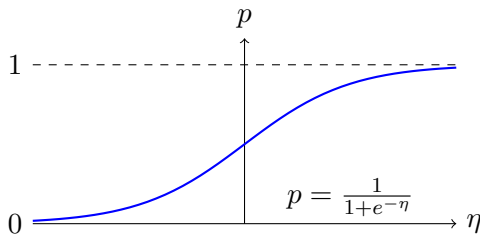
# The Logit Link

**Definition:**

$$\text{logit}(p) = \log \frac{p}{1-p} = \log(\text{odds})$$

**Inverse (logistic function):**

$$p = \frac{e^{\eta}}{1 + e^{\eta}} = \frac{1}{1 + e^{-\eta}}$$



# The Probit Link

## Definition:

$$\text{probit}(p) = \Phi^{-1}(p)$$

where  $\Phi$  is the standard normal CDF.

## Inverse:

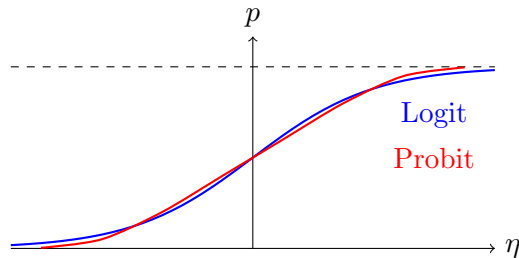
$$p = \Phi(\eta)$$

## Interpretation:

- If there's a latent normal variable  $Z = \eta + \epsilon$ ,  $\epsilon \sim \mathcal{N}(0, 1)$
- Then  $\mathbb{P}(Z > 0) = \Phi(\eta)$
- Probit link arises naturally from latent variable models



# Comparing Logit and Probit



## Key points:

- Very similar for moderate probabilities
- Logit has slightly heavier tails
- In practice, results are often nearly identical
- Logit preferred for interpretability (odds ratios)

# The Complementary Log-Log Link

**Definition:**

$$\text{cloglog}(p) = \log(-\log(1 - p))$$

**Inverse:**

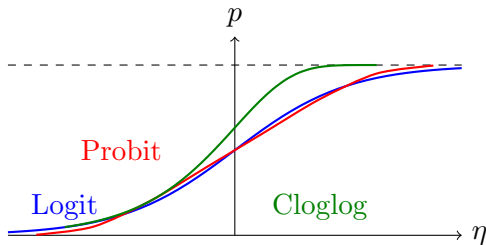
$$p = 1 - \exp(-e^\eta)$$

**Key property: Asymmetric** — behaves differently near 0 and 1.

**Use when:**

- Probability of an event increases steeply then levels off
- Complementary to the log-log link:  $\log(-\log(p))$
- Arises from extreme value distributions

## Comparing Link Functions



**Note:** Cloglog approaches 1 faster but 0 slower than logit/probit.

Fit logistic regression with different link functions:

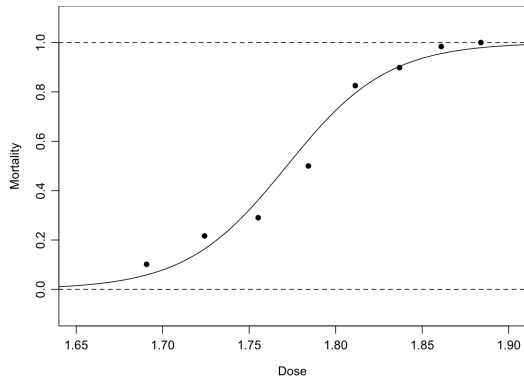
```
# Logit link (default)
glm(y ~ dose, family = binomial(link = "logit"))

# Probit link
glm(y ~ dose, family = binomial(link = "probit"))

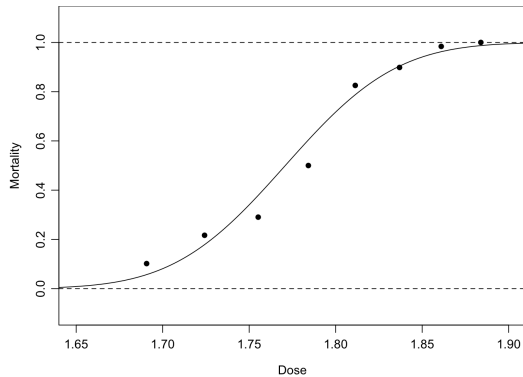
# Complementary log-log link
glm(y ~ dose, family = binomial(link = "cloglog"))
```

Compare using residual deviance, AIC, and residual plots.

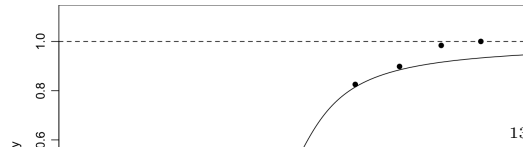
# Beetle Data: Fitted Curves with Different Links



Logit



Probit



## Link Functions for Poisson Data

For count data with  $\mu > 0$ :

Name	Link $g(\mu)$	Ensures $\mu > 0$ ?
Log (canonical)	$\log(\mu)$	Yes, $\mu = e^\eta > 0$
Square root	$\sqrt{\mu}$	Need $\eta > 0$
Identity	$\mu$	Need $\eta > 0$

**Log link is almost always used:**

- Ensures positive fitted values
- Coefficients have multiplicative interpretation
- $e^{\beta_j}$  = rate ratio for unit increase in  $x_j$

## Considerations:

- ① **Theoretical:** Does a particular link arise from the science?
  - Probit from latent normal models
  - Cloglog from survival/extreme value theory
- ② **Interpretability:**
  - Logit gives odds ratios
  - Log gives rate ratios
- ③ **Empirical fit:**
  - Compare deviances/AIC
  - Check residual patterns

## R: Specifying Link Functions

```
# Binomial family with different links
glm(y ~ x, family = binomial(link = "logit"))
glm(y ~ x, family = binomial(link = "probit"))
glm(y ~ x, family = binomial(link = "cloglog"))

# Poisson family with different links
glm(y ~ x, family = poisson(link = "log"))
glm(y ~ x, family = poisson(link = "sqrt"))

# Gaussian family
glm(y ~ x, family = gaussian(link = "identity"))
glm(y ~ x, family = gaussian(link = "log"))
```



## Key points:

- Link functions map constrained  $\mu$  to unconstrained  $\eta$
- Canonical links have computational advantages
- For binomial: logit, probit, cloglog are common choices
- Logit and probit give similar results; logit is more interpretable
- Cloglog is asymmetric — useful for specific applications
- For Poisson: log link is standard
- Choose based on theory, interpretability, and fit

**Next lecture:** Maximum likelihood estimation for GLMs.