Lecture 18

Logistic Regression

STAT 8020 Statistical Methods II
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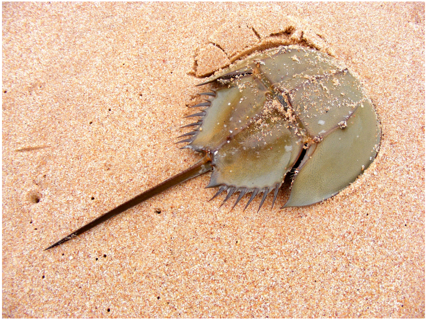
Whitney Huang
Clemson University

A Motivating Example: Horseshoe Crab Malting [Brockmann, 1996, Agresti, 2013]



sat	y	weight	width
8	1	3.05	28.3
0	0	1.55	22.5
9	1	2.30	26.0
0	0	2.10	24.8
4	1	2.60	26.0
0	0	2.10	23.8
0	0	2.35	26.5
0	0	1.90	24.7
0	0	1.95	23.7
0	0	2.15	25.6

Source: `https://www.britannica.com/story/horseshoe-crab-a-key-player-in-ecology-medicine-and-more`

In the rest of today's lecture, we are going to use this data set to illustrate logistic regression. The response variable is y: whether there are males clustering around the female

Logistic Regression

Let $\mathrm{P}(Y = 1) = \pi \in [0, 1]$, and x be the predictor (`weight` in the previous example). In SLR we have

$$\pi(x) = \beta_0 + \beta_1 x,$$

which will lead to invalid estimate of π (i.e., > 1 or < 0).

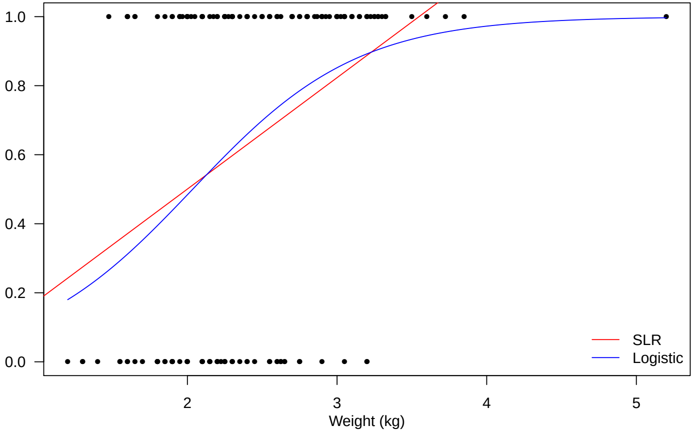
Logistic Regression

$$\log(\frac{\pi}{1-\pi}) = \beta_0 + \beta_1 x.$$

- $\log(\frac{\pi}{1-\pi})$: the log-odds or the logit
- $\pi(x) = \frac{e^{\beta_0+\beta_1 x}}{1+e^{\beta_0+\beta_1 x}} \in (0, 1)$

Logistic Regression Fit

$$\hat{\pi}(x) = \frac{e^{\hat{\beta}_0 + \hat{\beta}_1 x}}{1 + e^{\hat{\beta}_0 + \hat{\beta}_1 x}},\ \hat{\beta}_0 = -3.6947(0.8802),\ \hat{\beta}_1 = 1.8151(0.3767).$$



Properties

- Similar to SLR, Sign of β_1 indicates whether $\pi(x) \uparrow$ or $\downarrow$ as $x \uparrow$
- If $\beta_1 = 0$, then $\pi(x) = e^{\beta_0}/(1 + e^{\beta 0})$ is a constant w.r.t x (i.e., π does not depend on x)
- Curve can be approximated at fixed x by straight line to describe rate of change: $\frac{d\pi(x)}{dx} = \beta_1 \pi(x)(1 - \pi(x))$
- $\pi(-\beta_0/\beta_1) = 0.5$, and $1/\beta_1 \approx$ the distance of x values with $\pi(x) = 0.5$ and $\pi(x) = 0.75$ (or $\pi(x) = 0.25$)

Odds Ratio Interpretation

Recall $\log(\frac{\pi(x)}{1-\pi(x)}) = \beta_0 + \beta_1 x$, we have the odds

$$\frac{\pi(x)}{1-\pi(x)} = \exp(\beta_0 + \beta_1 x).$$

If we increase x by 1 unit, the the odds becomes

$$\exp(\beta_0 + \beta_1(x+1)) = \exp(\beta_1) \times \exp(\beta_0 + \beta_1 x).$$

$$\Rightarrow \frac{\text{Odds at } x+1}{\text{Odds at } x} = \exp(\beta_1), \forall x$$

Example: In the horseshoe crab example, we have $\hat{\beta}_1 = 1.8151 \Rightarrow e^{1.8151} = 6.14 \Rightarrow$ Estimated odds of satellite multiply by 6.1 for 1 kg increase in weight.

Parameter Estimation

In logistic regression we use maximum likelihood estimation to estimate the parameters:

- **Statistical model**: $Y_i \sim \text{Bernoulli}(\pi(x_i))$ where $\pi(x_i) = \frac{\exp(\beta_0+\beta_1 x_i)}{1+\exp(\beta_0+\beta_1 x_i)}$.
- **Likelihood function**: We can write the joint probability density of the data $\{x_i, y_i\}_{i=1}^n$ as

  $$\prod_{i=1}^{n} \pi(x_i)^{y_i}(1-\pi(x_i))^{(1-y_i)}.$$

  We treat this as a function of parameters (β_0, β_1) given data.
- **Maximum likelihood estimate**: The maximizer $\hat{\beta}_0, \hat{\beta}_1$ is the maximum likelihood estimate (MLE). This maximization can only be solved numerically.

Horseshoe Crab Logistic Regression Fit

```
> logitFit <- glm(y ~ weight, data = crab, family = "binomial")
> summary(logitFit)

Call:
glm(formula = y ~ weight, family = "binomial", data = crab)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.1108  -1.0749   0.5426   0.9122   1.6285

Coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  -3.6947     0.8802  -4.198 2.70e-05 ***
weight        1.8151     0.3767   4.819 1.45e-06 ***
---
Signif. codes:
0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 225.76  on 172  degrees of freedom
Residual deviance: 195.74  on 171  degrees of freedom
AIC: 199.74

Number of Fisher Scoring iterations: 4
```

Inference: Confidence Interval

A 95% confidence interval of the parameter β_i is

$$\hat{\beta}_i \pm z_{0.025} \times \mathrm{SE}_{\hat{\beta}_i}, \quad i = 0, 1$$

Horseshoe Crab Example
A 95% (Wald) confidence interval of β_1 is

$$1.8151 \pm 1.96 \times 0.3767 = [1.077, 2.553]$$

Therefore a 95% CI of e^{β_1}, the multiplicative effect on odds of 1-unit increase in x, is

$$[e^{1.077}, e^{2.553}] = [2.94, 12.85]$$

Inference: Hypothesis Test

Null and Alternative Hypotheses:

$$H_0 : \beta_1 = 0 \Rightarrow Y \text{ is independent of } X \Rightarrow \pi(x) \text{ is a constant}$$
$$H_a : \beta_1 \neq 0$$

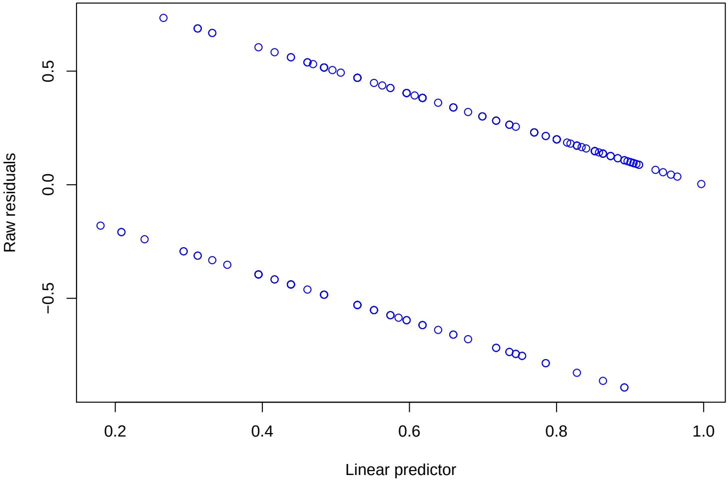
Test Statistics:

$$z_{obs} = \frac{\hat{\beta}_1}{\mathrm{SE}_{\hat{\beta}_1}} = \frac{1.8151}{0.3767} = 4.819.$$

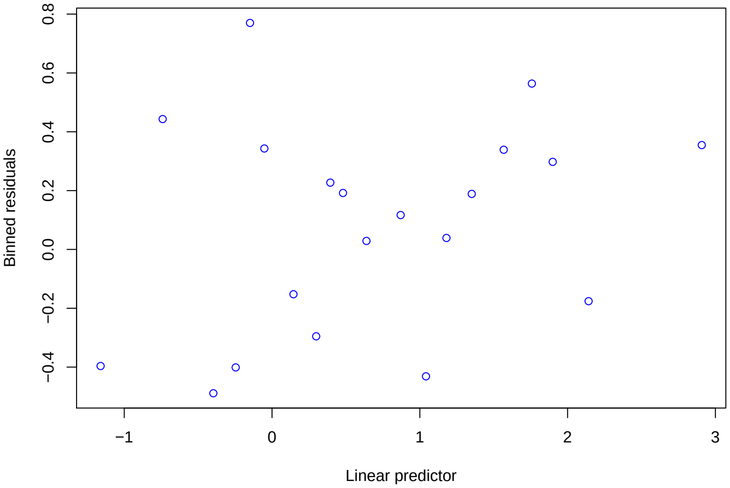
P-value $= 1.45 \times 10^{-6}$

> We have sufficient evidence that `weight` has positive effect on π, the probability of having satellite male horseshoe crabs

Diagnostic: Raw Residual Plot



Diagnostic: Binned Residual Plot



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Model Selection

```
> logitFit2 <- glm(y ~ weight + width, data = crab, family = "binomial")
> step(logitFit2)
Start:  AIC=198.89
y ~ weight + width

         Df Deviance    AIC
- weight  1   194.45 198.45
<none>        192.89 198.89
- width   1   195.74 199.74

Step:  AIC=198.45
y ~ width

        Df Deviance    AIC
<none>       194.45 198.45
- width  1   225.76 227.76

Call:  glm(formula = y ~ width, family = "binomial", data = crab)

Coefficients:
(Intercept)        width
   -12.3508       0.4972

Degrees of Freedom: 172 Total (i.e. Null);  171 Residual
Null Deviance:      225.8
Residual Deviance: 194.5        AIC: 198.5
```