

Lesson 5: Simple Logistic Regression

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Learning Objectives

1. Recognize why the tests we've learned so far are not flexible enough for continuous covariates or multiple covariates.
2. Recognize why linear regression cannot be applied to categorical outcomes with two levels
3. Identify the simple logistic regression model and define key notation in statistics language
4. Connect linear and logistic regression to the larger group of models, generalized linear model
5. Determine coefficient estimates using maximum likelihood estimation (MLE) and apply it in R

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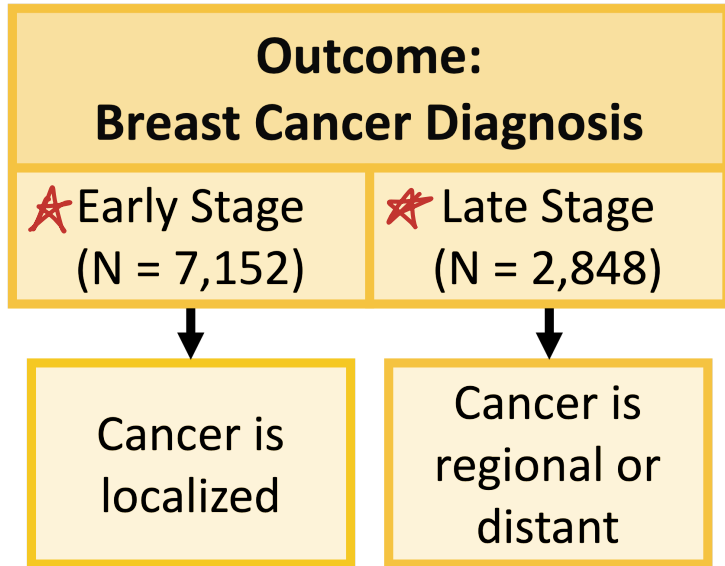
Health disparities in breast cancer diagnosis: working example

- **Question:** Is race/ethnicity and/or age associated with an individual's diagnosed stage of breast cancer?
 - For now, consider each covariate separately
- **Population:** individuals who are assigned female at birth who have been diagnosed with breast cancer in the United States
- Data from the Surveillance, Epidemiology, and End Results (SEER) Program (2014-2018)

Please note that this question has been answered

- You can take a look at the Breast Cancer Research Foundation's page: [Understanding Breast Cancer Racial Disparities](#)
- Big contributors to racial disparities include:
 - Underrepresentation in clinical trials
 - Access to healthcare
 - More aggressive cancers more likely in people of Native American, African, Hispanic, and Latin American descent
- Our analysis will not be new, but this kind of work has shed light on the importance of focused research on people of color to better serve people of color who develop breast cancer
 - Dr. Davis focuses research on genomics and tumor microenvironment in African and African American patients
 - Dr. Ambrosone focuses research on how immune cells differ between patients. Specifically on the DARC gene, which is an evolved gene that helps fight malaria, that is found at a higher rate in people with African descent
 - More public health work focused on access to healthcare and patient-doctor relationships

Example: Health disparities in breast cancer diagnosis (1/2)



Example: Health disparities in breast cancer diagnosis (2/2)

Outcome: Breast Cancer Diagnosis	
Early Stage (N = 7,152)	Late Stage (N = 2,848)



Cancer is
localized

Cancer is
regional or
distant

Covariate: Age
Continuous, range: 22-75 years old

Covariate: Race/Ethnicity	
Hispanic-Latinx (N = 846)	Non-Hispanic American Indian/Alaska Native (N = 23)
Non-Hispanic Asian/Pacific Islander (N = 790)	Non-Hispanic Black (N = 1,040)
Non-Hispanic White (N = 7,301)	

Poll Everywhere Question 1

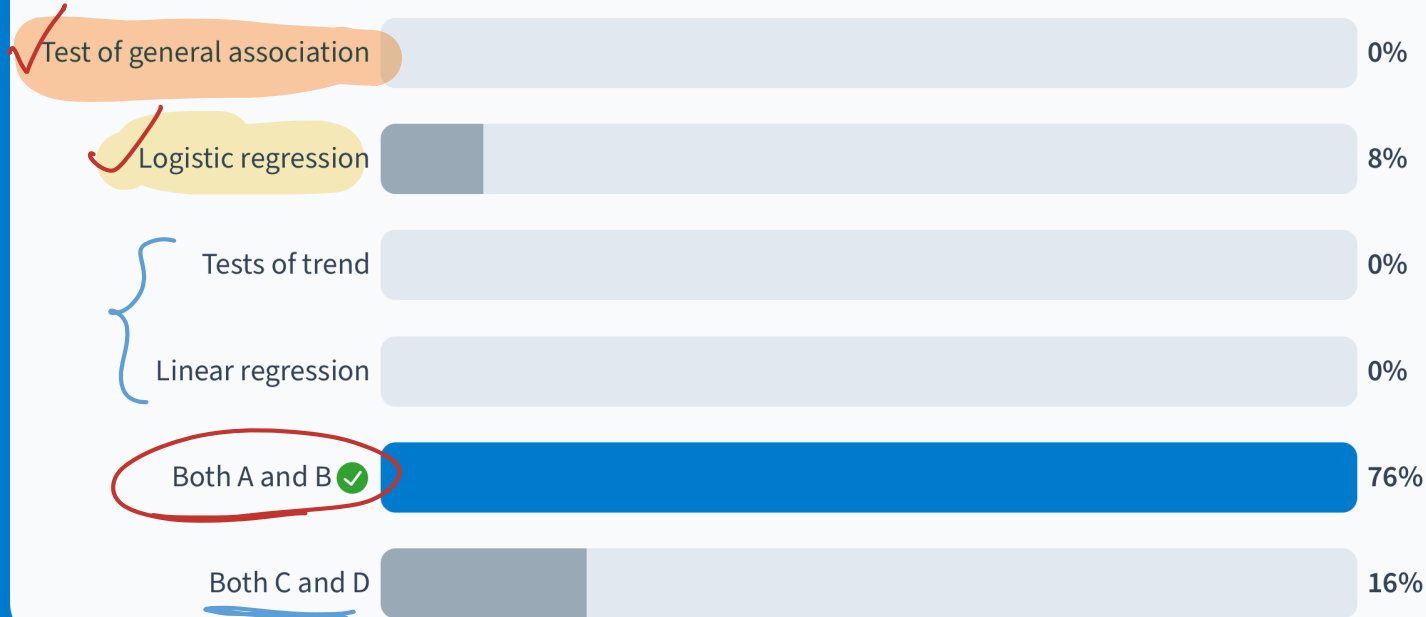
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How do we investigate the association between diagnosis stage and race/ethnicity?



How do we determine differences in diagnosis? (1/2)

- Breast cancer diagnosis study: two variables that are categorical
- We could use a contingency table (or two-way table)

expl. var		outcome		
		Breast Cancer Diagnosis		
	Race/Ethnicity	Early Stage	Late Stage	Total
	Non-Hispanic White	5,321	1,980	7,301
	Non-Hispanic Black	683	357	1,040
	Non-Hispanic Asian/Pacific Islander	556	234	790
	Hispanic-Latinx	575	271	846
	Non-Hispanic American Indian/Alaska Native	17	6	23
	Total	7,152	2,848	10,000

How do we determine differences in diagnosis? (2/2)

- Contingency table does not work for...
 - Continuous covariates
 - Multiple covariates
- Logistic regression models can handle multiple covariates that are continuous or categorical

Individual #	Diagnosis stage	Race/Ethnicity	Age
1	Early	Non-Hispanic Black	71
2	Early	Non-Hispanic White	35
3	Late	Non-Hispanic Asian/Pacific Islander	59
4	Early	Hispanic-Latinx	68
...			



Logistic Regression
Model

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Reference: individual components

General form	Breast Cancer Diagnosis Example
i	Individual who has been diagnosed with breast cancer in the United States
$Y_i = 1$	Individual i received a <u>late-stage diagnosis</u> of breast cancer
$Y_i = 0$	Individual i <u>did not</u> receive a late-stage diagnosis of breast cancer (early-stage diagnosis)
$P(Y_i = 1 X_i) = \pi(X_i)$ <i>given</i>	Probability that individual receives a late-stage diagnosis of breast cancer given their observed covariates
$P(Y_i = 0 X_i) = 1 - \pi(X_i)$	Probability that individual <u>does not</u> receive a late-stage diagnosis of breast cancer given their observed covariates
$X_{1,i}$ $X_{2,i}$	$R_{E1,i}$ (race/ethnicity) for individual i or- Age_i for individual i

Building towards simple logistic regression

- **Goal:** model the probability of our outcome ($\pi(X)$) with the covariate (X_1)
- In simple linear regression, we use the model in its various forms:

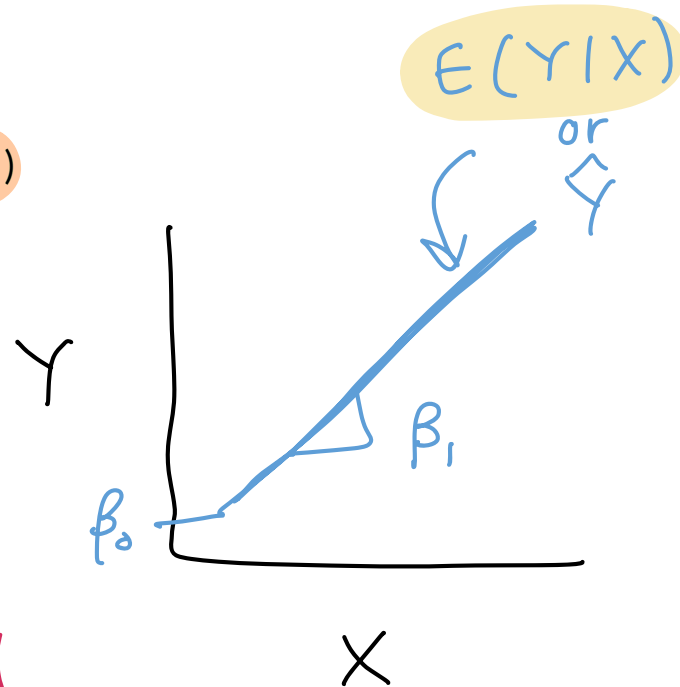
$$Y = \beta_0 + \beta_1 X_1 + \epsilon$$

$$E[Y|X] = \beta_0 + \beta_1 X_1$$

$$\hat{Y} = \beta_0 + \beta_1 X_1$$

- Potential problem? Probabilities can only take values from 0 to 1

$$Y = 0 \quad \text{or} \quad Y = 1$$



Simple Logistic Regression Model: Components

- Outcome: Y - binary (two-level) categorical variable
 - $Y = 1$ "Success"
 - $Y = 0$ "failure"
- Covariate: X_1
 - For today: simple logistic regression with one covariate
 - X_1 can be continuous or categorical
- Probability of outcome for individual with observed covariates
 - $P(Y = 1|X) = \pi(X)$
 - $P(Y = 0|X) = 1 - \pi(X)$
- Because the expected value is a weighted average, we can say:

$$\begin{aligned} E(Y|X) &= P(Y = 1|X) \cdot 1 + P(Y = 0|X) \cdot 0 \\ &= P(Y = 1|X) \cdot 1 \\ &= P(Y = 1|X) \\ &= \pi(X) \end{aligned}$$

- For categorical outcomes, $\pi(X)$ (or π for shorthand), is more widely used than $E(Y|X)$



Can we apply OLS to our binary outcome?

- Let's see if we can apply OLS/linear regression to our binary outcome
- What assumptions do our data need to meet in order to use OLS?
- Let's review OLS assumptions!

Review of simple linear regression(1/2)

The (population) regression model is denoted by:

$$Y = \beta_0 + \beta_1 X + \epsilon$$

Components

Y	response, outcome, dependent variable
-----	---------------------------------------

β_0	intercept
-----------	-----------

β_1	slope
-----------	-------

X	predictor, covariate, independent variable
-----	--

ϵ	residuals, error term
------------	-----------------------

Review of simple linear regression (2/2)

- Assumptions of the linear regression model:

- Independence: observations are independent
- Linearity: linear relationship between $E[Y|X]$ and X

$$E[Y|X] = \beta_0 + \beta_1 \cdot X$$

- Normality and homoscedasticity assumption for residuals (ϵ):

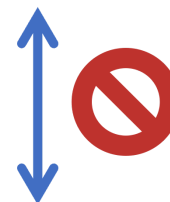
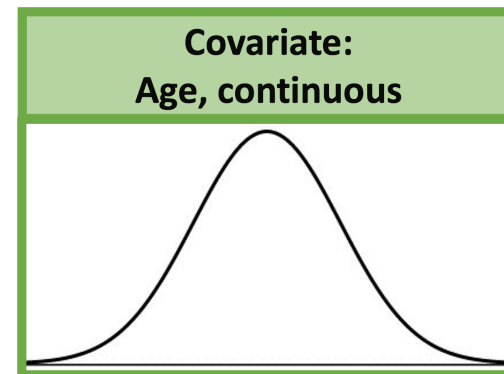
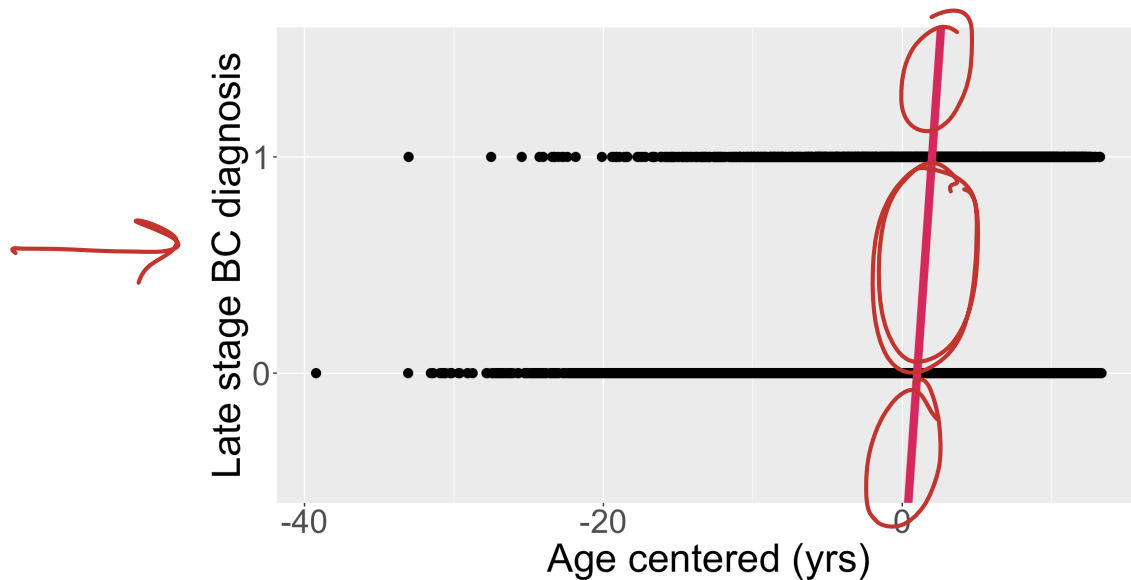
- Normality: residuals are normally distributed ($\epsilon \sim N(0, \sigma^2)$)
- Homoscedasticity (equal variance): Variance of Y given X ($\sigma_{Y|X}^2$), is the same for any X

- Which assumptions are violated if dependent variable is categorical?

- Think in terms of binary dependent variable

Violated: Linearity

- The relationship between the variables is linear (a straight line):
 - $E[Y|X]$ or $\pi(X)$, is a straight-line function of X
- The independent variable X can take any value, while $\pi(X)$ is a probability that should be bounded by $[0,1]$
 - We cannot use linear mapping to translate X to $\pi(X)$



Outcome: Breast Cancer Diagnosis	
Early Stage, $Y = 0$	Late Stage, $Y = 1$

Violated: Normality

- In linear regression, ϵ is distributed normally
- Recall that Y can take only one of the two values: 0 or 1
- And the fitted Y , $\hat{Y}$ can also only take values 0 or 1
- Thus, $\epsilon = Y - \hat{Y}$ can only take values -1, 0, or 1
*diff b/w
obs & fitted*
- Then ϵ **cannot follow a normal distribution**, which would require ϵ to have a continuum of values and no upper or lower bound

<i>obs</i> Y	<i>fitted</i> $\hat{Y}$	
	0	1
0	$\epsilon = 0 - 0 = 0$	$\epsilon = 0 - 1 = -1$
1	$\epsilon = 1 - 0 = 1$	$\epsilon = 1 - 1 = 0$

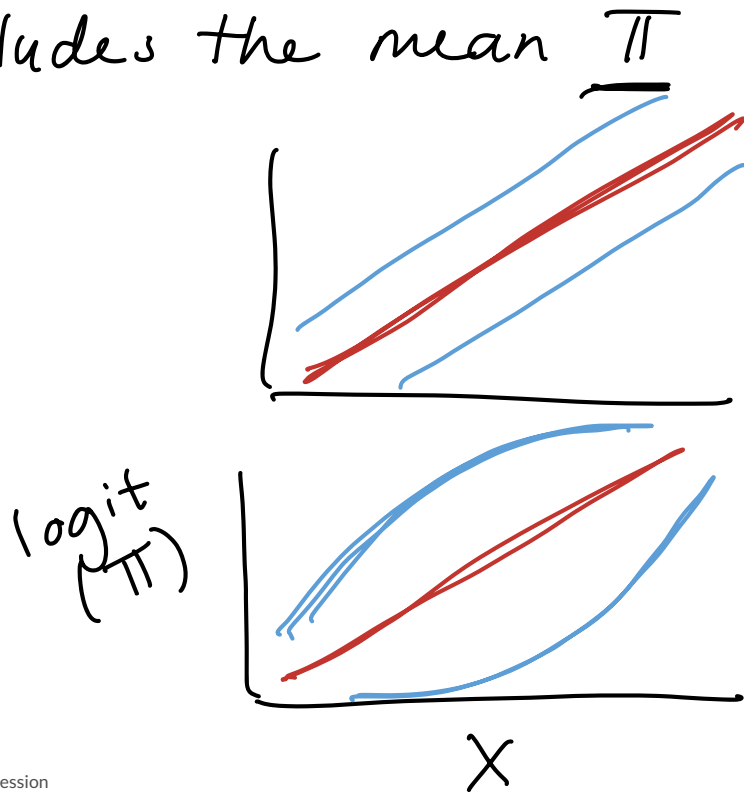
Violated: Homoscedasticity / equal variance

- In linear regression, $\text{var}(\epsilon) = \sigma^2$
 - Variance does not depend on $X \rightarrow$ result of normal dist

- When Y is a binary outcome variance includes the mean π

$$\begin{aligned}\text{var}(Y) &= \pi(1 - \pi) \\ &= (\beta_0 + \beta_1 X)(1 - \beta_0 - \beta_1 X)\end{aligned}$$

- Variance depends on X
- Because variance depends on X : no homoscedasticity
 - Variance will not be equal across X -values



Poll Everywhere Question 2

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82%



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Which, if any, of the below equations appropriately models our categorical outcome (Y) with our covariate (X_1)?

01

$$Y = \beta_0 + \beta_1 X_1$$

15%

$$P(Y = 1) = \beta_0 + \beta_1 X_1$$

23%

$[0, 1]$

$$\pi = \beta_0 + \beta_1 X_1$$

12%

Both B and C are correct

42%

None of the above ✓

8%

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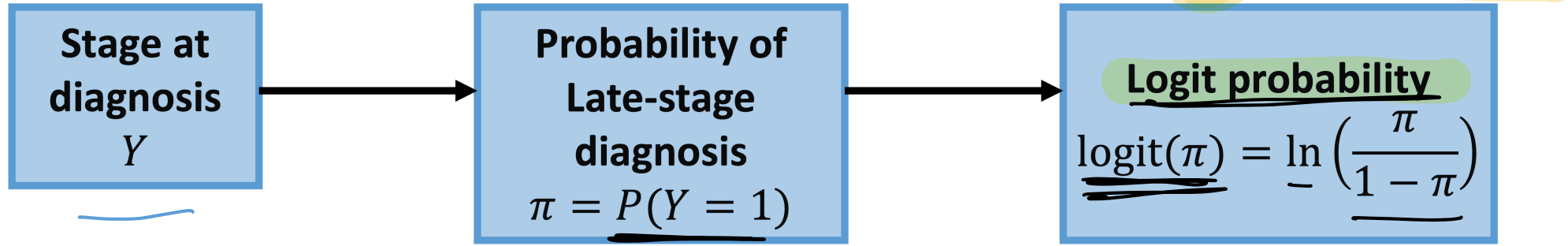
How do we fix these violations?

- **Question:** How do we manipulate our response variable so that we fix these violations?

$$(-\infty, \infty)$$

- **Answer:** We need to *transform the outcome* so we can map differences in covariates to the two levels
 - Will discuss in a few slides: called link function

How do we transform our outcome? (1/2)



Two levels:

$$Y = 0$$

$$Y = 1$$

Range of probabilities:

$$0 \leq \pi \leq 1$$

Range of logit values:

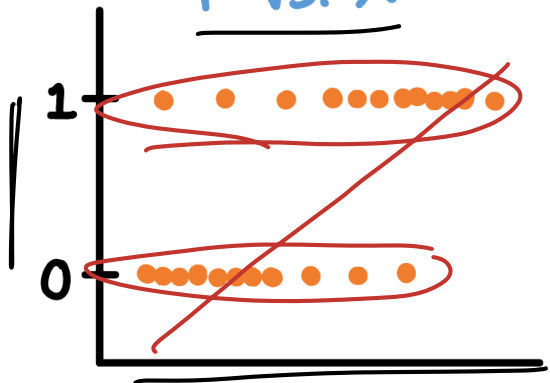
$$-\infty \leq \text{logit}(\pi) \leq \infty$$

Note: people use π (or p)
to mean $\pi(X)$

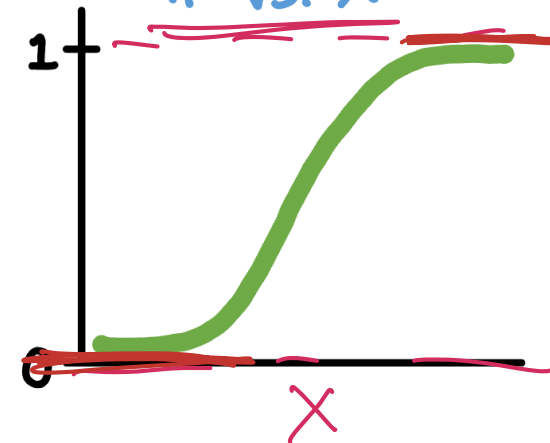
$$\hookrightarrow \pi(X) = P(Y=1|X)$$

How do we transform our outcome? (2/2)

Y vs. X

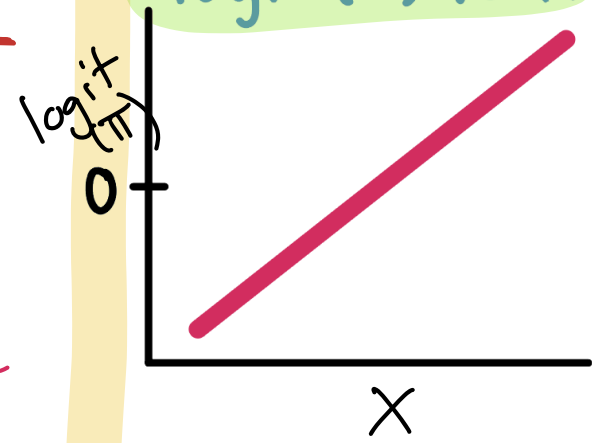


π vs. X

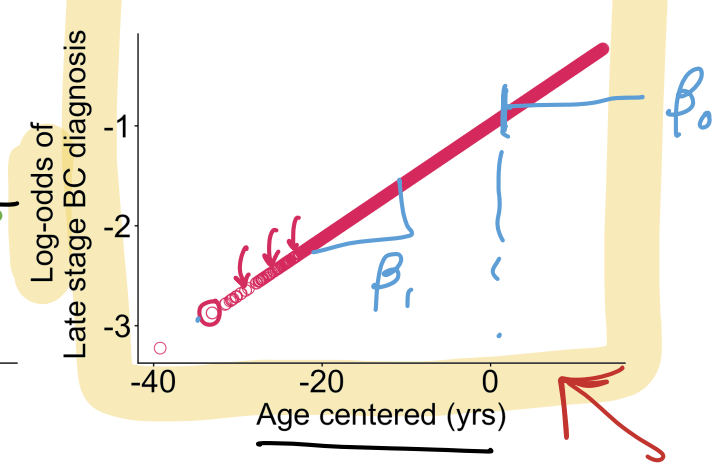
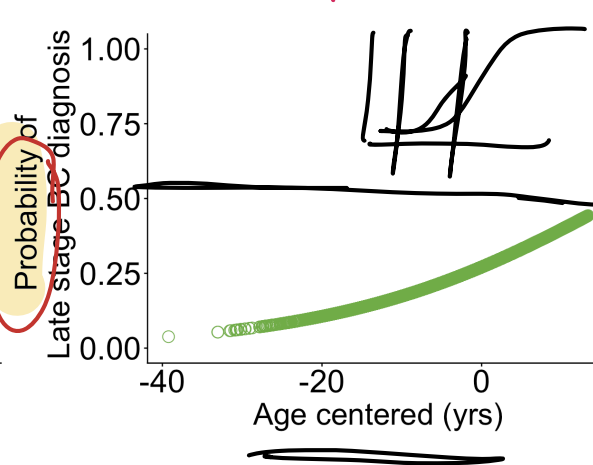
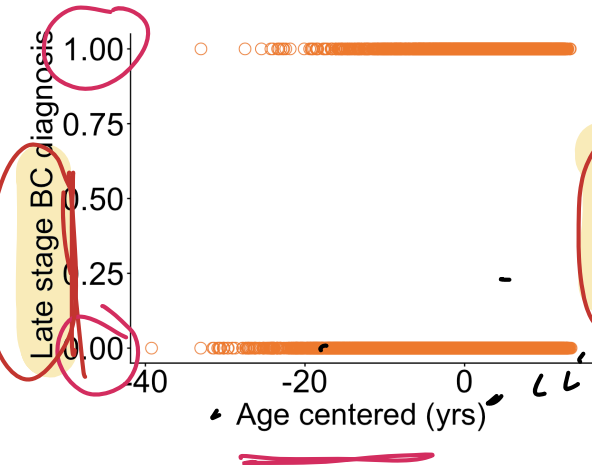


(or $\ln$) $\log \left(\frac{\pi}{1-\pi} \right)$

logit(π) vs. X



fit regression on this scale



Simple Logistic Regression Model

The (population) regression model is denoted by:

$$\text{logit}(\pi) = \beta_0 + \beta_1 X$$

Components

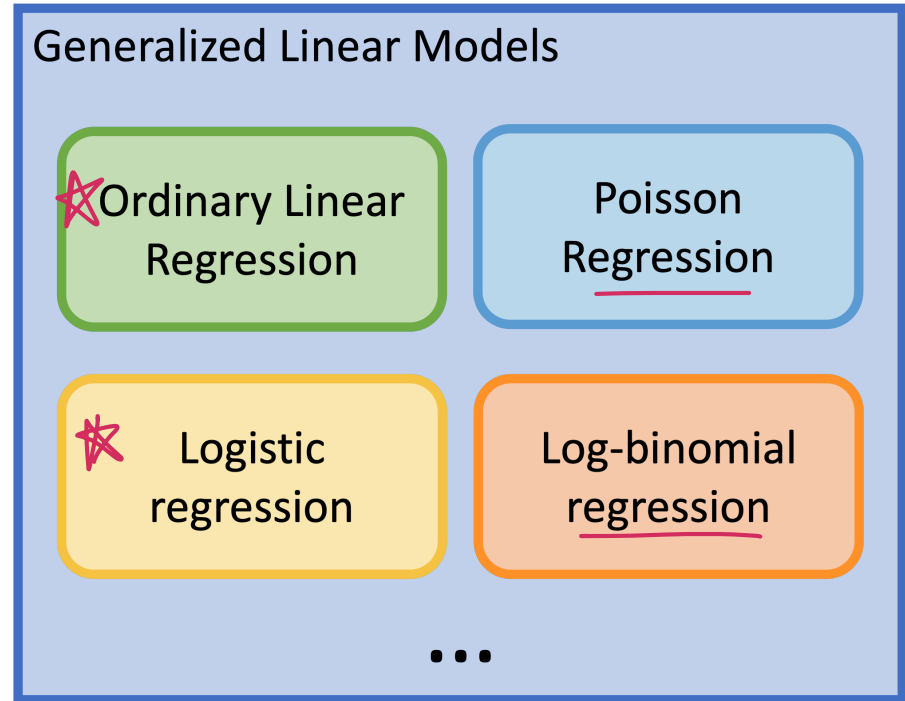
→ π	probability that the outcome occurs ($Y = 1$) given X
β_0	intercept
β_1	slope
X	predictor, covariate, independent variable

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Generalized Linear Models (GLMs) (1/2)

- **Generalized Linear Models** are a class of models that includes regression models for **continuous and categorical responses**
 - Responses follow exponential family distribution
 - Helps us set up other types of regressions using each outcome's needed transformations
- Here we will focus on the GLMs for **categorical/count data**
 - **Logistic regression** is just a one type of GLM
 - **Poisson regression** – for counts
 - **Log-binomial** can be used to focus on prevalence/risk ratio



Poll Everywhere Question 3

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78%



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What type of response variable could we model with a generalized linear model?

✓ *linear reg*
Continuous normal variable

7%

logistic
Binary categorical variable

4%

poiss
Count variable

4%

exp
Continuous exponential variable

4%

All of the above ✓

81%

Generalized Linear Models (GLMs) (2/2)

Generalized Linear Models

Random component

- Identify the response variable Y
- Specify a suitable (presumably) distribution for it

distribution of
outcome type

Systematic component

- Specify the explanatory variable(s) for the model

$$\beta_0 + \beta_1 X$$

Link function

- Specify a functional form of $E(Y)$ that is related to the explanatory variables through a prediction equation in linear form

transform of
 Y

GLM: Random Component

- The random component specifies the response variable Y and identifies a probability distribution for it
- Basically, we are just identifying the distribution for our outcome
 - If Y is binary: assumes a binomial distribution of Y
 - If Y is count: assumes Poisson or negative binomial distribution of Y
 - If Y is continuous: assume a Normal distribution of Y

GLM: Systematic Component

- The systematic component specifies the explanatory variables, which enter linearly as predictors

$$\beta_0 + \beta_1 X_1 + \dots + \beta_k X_k$$

- Above equation includes:

- Centered variables
- Interactions
- Transformations of variables (like squares)



- Systematic component is the **same** as what we learned in Linear Models

GLM: Link Function

- If $\mu = E(Y)$, then the link function specifies a function $g(\cdot)$ that relates μ to the linear predictors
 - $g(\mu)$ is the transformation we make to $E(Y)$ (aka μ) so that the linear predictors (right side of equation) can be linked to the outcome
↳ in binary $Y: E(Y) = \pi$
 - AKA: link function connects the random component with the systematic component
- So the general form of a regression equation looks like:

link fn $\leftarrow g(\mu) = \beta_0 + \beta_1 X_1 + \dots + \beta_k X_k$ *sys comp*

logit(μ)

and $g(\mu)$ is the placeholder for the transformation we make to mean μ

- For logistic regression, $g(\mu) = \text{logit}(\mu)$, so the regression equation is $\text{logit}(\mu) = \beta_0 + \beta_1 X_1 + \dots + \beta_k X_k$
- For linear regression, $g(\mu) = \mu$ and so the regression equation is $\mu = \beta_0 + \beta_1 X_1 + \dots + \beta_k X_k$
- Can also think of this of equation with inverse of g :

$\mu = g^{-1}(\beta_0 + \beta_1 X_1 + \dots + \beta_k X_k)$

logistic: μ aka $\pi = \text{logit}^{-1}(\beta_0 + \beta_1 X_1 + \dots)$

$$\frac{Y}{\text{link fn}} = \frac{\beta_0 + \beta_1 X}{\text{sys}}$$

$g(\mu) = \mu$

GLM: Link Function

Link	Link function	Type of response variable	Type of regression
<u>Identity link</u>	<u>$g(\mu) = 1 \times \mu$</u>	<u>Continuous response variables</u>	<u>Linear regression</u>
<u>Log link</u>	<u>$g(\mu) = \log(\mu)$</u>	<u>Discrete count response variable</u>	<u>Poisson regression</u>
Logit link	$g(\mu) = \text{logit}(\mu)$ $= \log \left[\frac{\mu}{1 - \mu} \right]$	<u>Categorical response variable</u>	<u>Logistic regression</u>
<u>Log link</u>	<u>$g(\mu) = \log(\mu)$</u>	<u>Categorical response variable</u>	<u>Log-binomial regression</u>

★
epi
Risk ratios

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Reminder: Simple Logistic Regression Model

The (population) regression model is denoted by:

$$\text{logit}(\pi) = \beta_0 + \beta_1 X$$

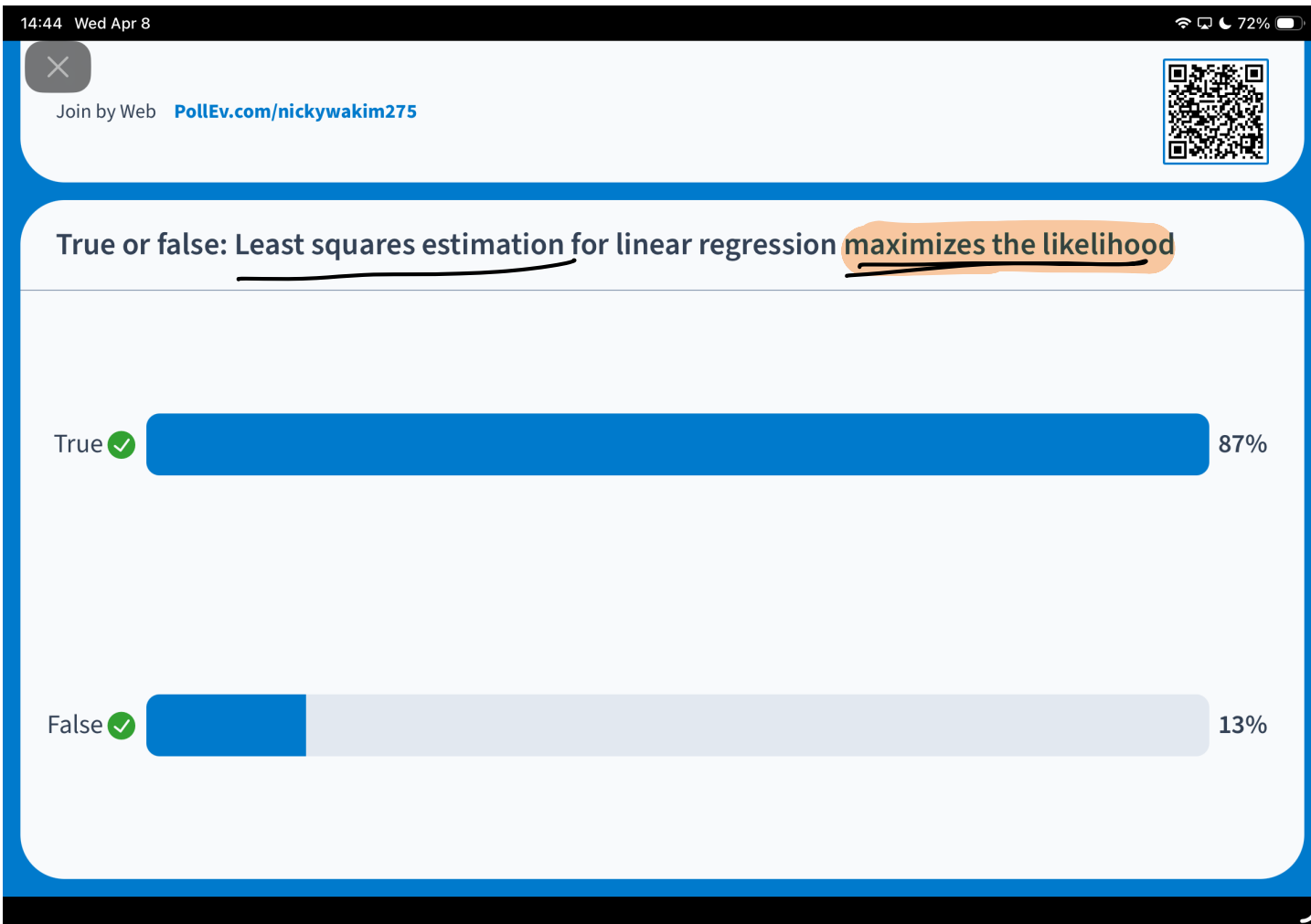
Components

π	probability that the outcome occurs ($Y = 1$) given X
β_0	intercept
β_1	slope
X	predictor, covariate, independent variable

Estimation for Logistic Regression Model

- Same as linear regression model: we need to estimate the values of β_0 and β_1
- **Maximum likelihood**: yields estimates for the unknown parameters that maximize the probability of obtaining observed set of data
 - In linear regression, this leads to least squares estimation (OLS) $\rightarrow$ minimize $\sum \epsilon_i^2$
SSE
 - But we can't use OLS in all types of regression
 - Maximum likelihood estimators (MLE): values of parameters that maximize likelihood
- **Likelihood function**: expresses the probability of the observed data as a function of the unknown parameters

Poll Everywhere Question 4



OLS results
for $\hat{\beta}_0$ $\hat{\beta}_1$

=

MLE results
for $\hat{\beta}_0$ $\hat{\beta}_1$

process OLS
≠

process MLE

How to find Maximum Likelihood Estimator (MLE)?

1. Construct a likelihood function for an individual
2. Construct the likelihood function across the sample
3. Convert to log-likelihood
4. Find parameter estimates that maximize log-likelihood: MLEs

1. Construct a likelihood function for an individual

- Within a dataset with n subjects, for the i th subject:
 - if $Y_i = 1$, the contribution to the likelihood function is $\pi(X_i)$
 - if $Y_i = 0$, the contribution to the likelihood function is $1 - \pi(X_i)$
- The **contribution from the i th subject** to the likelihood function can be expressed as:

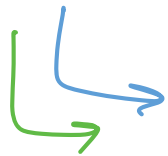
Recall

- Y_i : Response variable of the i th subject
- X_i : Independent variable for the i th subject
- $\pi(X_i) = \Pr(Y_i = 1 | X_i)$
- $1 - \pi(X_i) = \Pr(Y_i = 0 | X_i)$

$$\pi(X_i)^{Y_i} [1 - \pi(X_i)]^{1-Y_i}$$

$p^Y (1-p)^{1-Y}$

- Because...



if $Y = 1$:

if $Y = 0$:

$$\pi(X_i)^1 (1 - \pi(X_i))^{1-1} = \pi(X_i) \cdot 1$$

$$\frac{P(Y=1)^1 P(Y=0)^0}{P(Y=1)^0 P(Y=0)^1} = \frac{P(Y=1)}{P(Y=0)}$$

$$\pi(X_i)^0 (1 - \pi(X_i))^{1-0} = (1 - \pi(X_i))$$

2. Construct the likelihood function across the sample

- Since there are n subjects in the data, and **each subject is considered independent of each other**, the likelihood function for the whole data can be expressed as:

$$l(\beta_0, \beta_1) = \prod_{i=1}^n (\pi(X_i))^{Y_i} (1 - \pi(X_i))^{1-Y_i}$$

ind likelihoods

- The likelihood for the whole sample is the likelihood for each individual multiplied together (result of independence assumption)

Recall

- Y_i : Response variable of the i th subject
- X_i : Independent variable for the i th subject
- $\pi(X_i) = \Pr(Y_i = 1 | X_i)$
- $1 - \pi(X_i) = \Pr(Y_i = 0 | X_i)$

$$\underbrace{p^{Y_1}(1-p)^{1-Y_1}}_1 \times \underbrace{p^{Y_2}(1-p)^{1-Y_2}}_2 \times \underbrace{p^{Y_3}(1-p)^{1-Y_3}}_3$$

mult likelihoods for ind 1, 2, and 3 to get their total likel

3. Convert to log-likelihood

- Mathematically, it is easier to work with the **log likelihood** function for maximization
- The log-likelihood function is:

$$L(\beta_0, \beta_1) = \log(l(\beta_0, \beta_1))$$
$$= \sum_{i=1}^n \left[Y_i \cdot \ln[\pi(X_i)] + (1 - Y_i) \cdot \ln[1 - \pi(X_i)] \right]$$

log likelihood of individuals

Recall

- Y_i : Response variable of the i th subject
- X_i : Independent variable for the i th subject
- $\pi(X_i) = \Pr(Y_i = 1 | X_i)$
- $1 - \pi(X_i) = \Pr(Y_i = 0 | X_i)$

4. Find MLEs that maximize log-likelihood

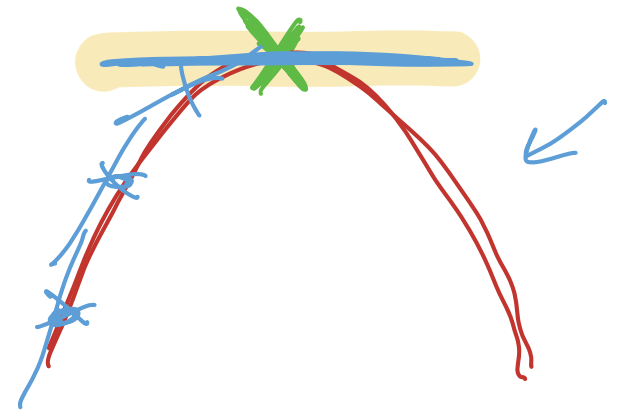
- To find β_0 and β_1 that maximizes $L(\beta_0, \beta_1)$:

- We **differentiate** $L(\beta_0, \beta_1)$ with respect to β_0 and β_1 ...
- And **set the resulting expression to zero**

- Such equations are called likelihood equations: result of differentiation and setting to 0

$$\left[\begin{array}{l} \sum [Y_i - \pi(X_i)] = 0 \\ \sum X_i [Y_i - \pi(X_i)] = 0 \end{array} \right] \left. \vphantom{\sum} \right\} \text{if solve, find max}$$

- In logistic regression, there is no “closed form” solution to the above equations
 - Meaning we cannot manipulate the math to find the solution
- Need to use iterative algorithm, such as iteratively reweighted least squares (IRLS) algorithm, should be used to find the MLEs for logistic regression



Poll Everywhere Question 5

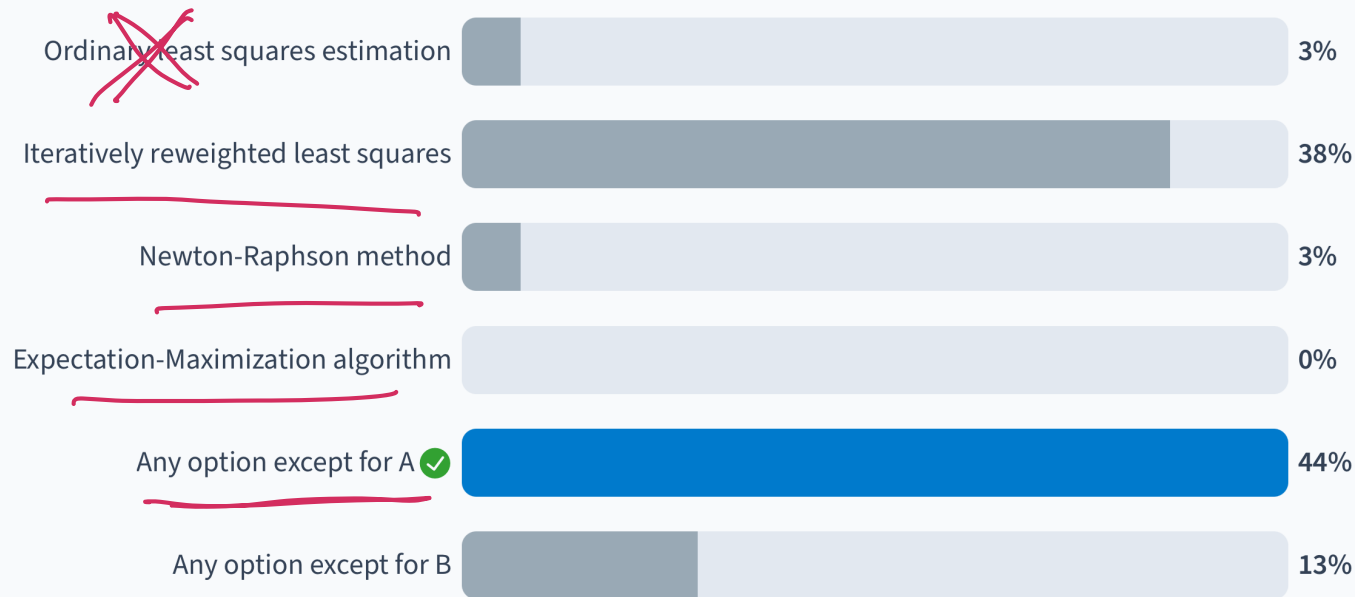
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Which algorithm can we use to maximize the likelihood for logistic regression?



methods to
maximize
likelihood
fn

How do perform MLE in R?

- `glm()` function automatically does MLE for you
 - For logistic regression with a binary outcome, we need to set the `family` within `glm()` to "binomial" which will automatically set the logit link $\rightarrow \text{logit}(\pi)$
- You can explore other algorithms (other than IRLS) to maximize the likelihood
 - Pretty good [Cross Validated](#) post on algorithms in `glm()`

$Y = 0$ or $Y = 1$



Example: Breast cancer diagnosis (1/3)

- Let's start with simple logistic regression with late stage breast cancer diagnosis as the outcome and age as our independent variable

- We want to fit:

$$\pi(Age) = P(Y=1 | Age)$$
$$\text{logit}(\pi(Age)) = \beta_0 + \beta_1 \cdot Age$$

- Don't forget: $\pi(Age) = P(Y = 1 | Age) = P(\text{Late stage BC diagnosis} | Age)$

Example: Breast cancer diagnosis (2/3)

```
1 bc_reg = glm(Late_stage_diag ~ Age_c, data = bc, family = binomial)
2 summary(bc_reg)
```

Call:

```
glm(formula = Late_stage_diag ~ Age_c, family = binomial, data = bc)
```

Coefficients:

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-0.989422	0.023205	-42.64	<2e-16 ***
Age_c	0.056965	0.003204	17.78	<2e-16 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 11861 on 9999 degrees of freedom
Residual deviance: 11510 on 9998 degrees of freedom
AIC: 11514

Number of Fisher Scoring iterations: 4

bc %>%

*glm(formula =
Late_stage
diag
~ Age,
family =
binomial)*

Example: Breast cancer diagnosis (3/3)

- Translate the results back to an equation!
- Just going to pull the coefficients so I have a reference as I create the fitted regression model:

```
1 summary(bc_reg)$coefficients
```

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-0.9894225	0.0232055	-42.63742	0.000000e+00
Age_c	0.0569645	0.0032039	17.77974	1.014557e-70

- Fitted logistic regression model:

$$\text{logit}(\hat{\pi}(\text{Age})) = \underbrace{-0.989}_{\hat{\beta}_0} + \underbrace{0.057}_{\hat{\beta}_1} \cdot \text{Age}$$

Example: Breast cancer diagnosis (3/3)

- Translate the results back to an equation!
- Just going to pull the coefficients so I have a reference as I create the fitted regression model:

```
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	Estimate	Std. Error	z value	Pr(> z)
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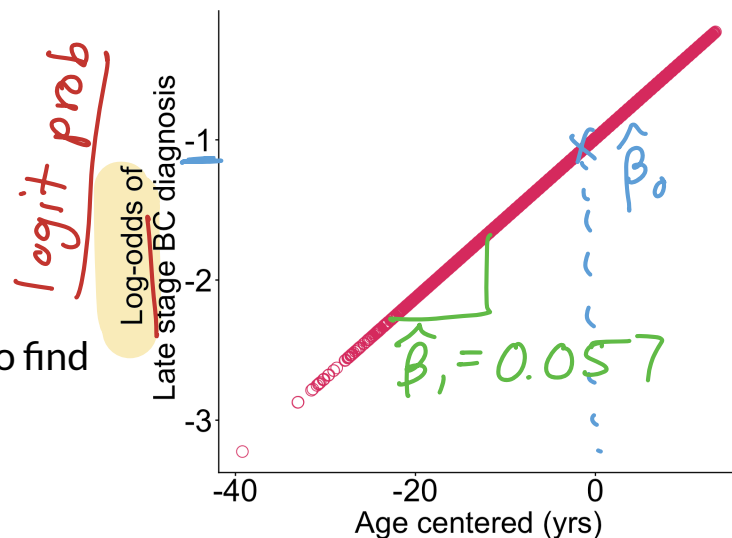
- Fitted logistic regression model:

$$\text{logit}(\hat{\pi}(\text{Age})) = -0.989 + 0.057 \cdot \text{Age}$$

We will need to reverse the transformation process in slide 24-25 to find the odds ratios

- Will do in next week's lessons

- This is the fitted line:



Learning Objectives

1. Recognize why the tests we've learned so far are not flexible enough for continuous covariates or multiple covariates.
2. Recognize why linear regression cannot be applied to categorical outcomes with two levels
3. Identify the simple logistic regression model and define key notation in statistics language
4. Connect linear and logistic regression to the larger group of models, generalized linear model
5. Determine coefficient estimates using maximum likelihood estimation (MLE) and apply it in R