

## 4. Regression Discontinuity

PhD Applied Methods

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Spring 2026

# What is regression discontinuity?

- Regression discontinuity design (RDD) is one of the most powerful and credible research designs for causal inference
- The core idea: take advantage of **institutional features** that generate a **discontinuous change** in treatment at some threshold
- Examples:
  - Scholarship eligibility based on income threshold
  - Election outcomes determined by vote share
  - Class size rules based on enrollment thresholds
  - Program eligibility based on age cutoffs

## Example 1: Financial aid and college enrollment

**Research question:** Does receiving financial aid increase college enrollment?

**Setting:** Many scholarship programs have sharp income cutoffs

- Example: Students from families earning below \$30,000 receive a \$1,500 scholarship
- Students from families earning \$30,001 receive nothing

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**Key insight:** Students just below vs. just above the income threshold are likely very similar in all respects *except* scholarship receipt

If enrollment rates differ discontinuously at the threshold, this difference can be attributed to the scholarship

## Example 2: Electoral advantage and incumbency

**Research question:** Does barely winning an election give a party an advantage in future elections?

**Setting:** Close elections (Lee, 2008)

- A Democratic candidate wins if they get  $> 50\%$  of the vote
- They lose if they get  $< 50\%$  of the vote

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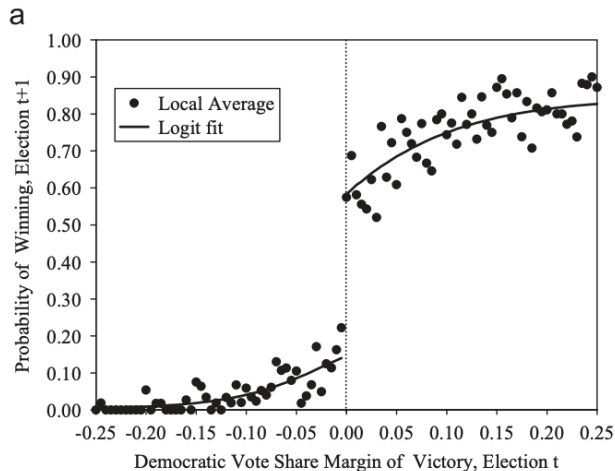
- A Democratic candidate wins if they get  $> 50\%$  of the vote
- They lose if they get  $< 50\%$  of the vote

**Key insight:** Elections decided by a very small margin (e.g., 50.1% vs 49.9%) are essentially random

- The parties competing in such close races should be very similar
- Any discontinuous change in future electoral success at the 50% threshold reveals the causal effect of incumbency

# Graphical intuition

*D.S. Lee / Journal of Econometrics 142 (2008) 675–697*





# Why is RDD so popular?

RDD has **exploded in popularity** in empirical economics. Key advantages:

- **Credibility:** Exploits institutional rules, not researcher assumptions
  - Often considered nearly as credible as randomized experiments
- **Transparency:** Visual evidence makes results compelling and hard to manipulate
  - The "eyeball test" is very informative
- **Policy relevance:** Treatment itself is often the policy of direct interest
  - Can also be used as an instrument (fuzzy RDD = IV setup)

# Outline

1. Motivation

2. Identification

3. Sharp vs. Fuzzy RDD

4. Estimation

5. Bandwidth selection

6. Threats to validity

7. Conclusion

## Setup: Notation

Using the potential outcomes framework from our first lecture:

- $Y_i(0), Y_i(1)$ : potential outcomes for individual  $i$
- $D_i \in \{0, 1\}$ : treatment status
- Observed outcome:  $Y_i = D_i Y_i(1) + (1 - D_i) Y_i(0)$

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**New element:** The **running variable** (or **forcing variable**)  $Z_i$

- Also called the "assignment variable" or "score"
- Examples: test score, age, income, vote share
- Treatment assignment determined by cutoff value  $z^*$

# The forcing variable

**Key assumption:** Treatment status  $D_i$  is determined (at least partly) by whether  $Z_i$  crosses a threshold  $z^*$

**Two cases:**

- **Sharp RDD:** Treatment changes *deterministically* at  $z^*$ 
  - Everyone with  $Z_i \geq z^*$  is treated; everyone with  $Z_i < z^*$  is untreated
- **Fuzzy RDD:** Treatment *probability* changes at  $z^*$ 
  - Crossing  $z^*$  increases the chance of treatment, but doesn't guarantee it

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We'll first derive the **general identification result** that applies to both cases, then distinguish between them

# The identifying assumption

**Core identification assumption:** The conditional expectation functions  $\mathbb{E}[Y_i(0)|Z_i = z]$  and  $\mathbb{E}[Y_i(1)|Z_i = z]$  are **continuous** in  $z$  at the cutoff  $z = z^*$

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## What does this mean?

- The average potential outcomes change **smoothly** as  $Z_i$  changes
- There are no **other factors** that jump discontinuously at  $Z_i = z^*$
- The only thing that changes discontinuously at the threshold is treatment  $D_i$



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**Intuition:** People just below vs. just above the threshold are essentially identical *except* for their treatment status

## Identification: The Wald estimand

Define the limits of the conditional expectation of  $Y$  on either side of the cutoff:

$$Y^+ := \lim_{z \rightarrow (z^*)^+} \mathbb{E}[Y_i | Z_i = z] \quad (1)$$

$$Y^- := \lim_{z \rightarrow (z^*)^-} \mathbb{E}[Y_i | Z_i = z] \quad (2)$$

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Similarly for treatment:

$$D^+ := \lim_{z \rightarrow (z^*)^+} \mathbb{E}[D_i | Z_i = z] \quad (3)$$

$$D^- := \lim_{z \rightarrow (z^*)^-} \mathbb{E}[D_i | Z_i = z] \quad (4)$$

## Identification: The Wald estimand

Under our model  $Y_i = Y_i(0) + D_i(Y_i(1) - Y_i(0))$  and the continuity assumption:

$$Y^+ = \lim_{z \rightarrow (z^*)^+} \mathbb{E}[Y_i(0) + D_i(Y_i(1) - Y_i(0)) | Z_i = z] \quad (5)$$

$$= \lim_{z \rightarrow (z^*)^+} \mathbb{E}[Y_i(0) | Z_i = z] + D^+ \cdot \mathbb{E}[Y_i(1) - Y_i(0) | Z_i = z^*] \quad (6)$$

$$= \mathbb{E}[Y_i(0) | Z_i = z^*] + D^+ \cdot \tau \quad (7)$$

where  $\tau = \mathbb{E}[Y_i(1) - Y_i(0) | Z_i = z^*]$  is the treatment effect at the cutoff

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Similarly:

$$Y^- = \mathbb{E}[Y_i(0) | Z_i = z^*] + D^- \cdot \tau \quad (8)$$

## Identification: The Wald estimand

Taking the difference:

$$Y^+ - Y^- = \mathbb{E}[Y_i(0)|Z_i = z^*] + D^+ \cdot \tau - \mathbb{E}[Y_i(0)|Z_i = z^*] - D^- \cdot \tau \quad (9)$$

$$= (D^+ - D^-) \cdot \tau \quad (10)$$

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$$= (D^+ - D^-) \cdot \tau \quad (10)$$

Therefore, the treatment effect at the cutoff is:

$$\tau = \frac{Y^+ - Y^-}{D^+ - D^-}$$

This is the **Wald estimand** - the ratio of the jump in outcomes to the jump in treatment

# What are we identifying?

The Wald formula identifies the **local average treatment effect** at the cutoff:

$$\tau_{RDD} = \mathbb{E}[Y_i(1) - Y_i(0) | Z_i = z^*] \quad (11)$$



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**Interpretation depends on sharp vs. fuzzy:**

- **Sharp RDD:** This is the ATE for everyone at the cutoff (since everyone's treatment changes)
- **Fuzzy RDD:** This is the LATE for compliers at the cutoff (those induced to take treatment by crossing  $z^*$ )

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**Key limitation:** Very local parameter (measure-zero set of population)

# RDD for reduced form vs. as an instrument

## Important distinction

### 1. RDD for direct/reduced form effects:

- Interested in effect of treatment  $D$  itself on outcome  $Y$
- Example: Effect of scholarship receipt on college enrollment
- Example: Effect of winning election on policy outcomes

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### 2. RDD as an instrument:

- Treatment  $D$  is not ultimate interest; it affects some other variable  $S$
- Use RDD assignment as instrument for  $S$  to estimate effect of  $S$  on  $Y$
- Example: Scholarship  $\rightarrow$  years of education  $\rightarrow$  labor outcomes
- RDD identifies effect of years of education (not just scholarship)

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**Both uses can occur in sharp or fuzzy RDD!**

## RDD as a local randomized experiment

**Alternative interpretation:** Think of RDD as a randomized experiment in a neighborhood of the cutoff

- For individuals very close to  $Z_i = z^*$ , whether they end up just above or just below the threshold is essentially random
- Example: In a close election with  $Z_i = \text{vote margin}$ , whether you get 50.01% or 49.99% is basically random
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- This makes treated and untreated individuals near the cutoff comparable
- This "local randomization" interpretation is increasingly popular
- Helps with thinking about inference and design

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## Sharp regression discontinuity

**Definition:** In a **sharp RDD**, treatment status changes *deterministically* at the cutoff

Treatment assignment is a **deterministic function** of the running variable:

$$D_i = \begin{cases} 1 & \text{if } Z_i \geq z^* \\ 0 & \text{if } Z_i < z^* \end{cases} \quad (12)$$

This means:  $D^+ = 1$  and  $D^- = 0$

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The Wald formula simplifies:

$$\tau^{Sharp} = \frac{Y^+ - Y^-}{D^+ - D^-} = \frac{Y^+ - Y^-}{1 - 0} = Y^+ - Y^- \quad (13)$$

**The treatment effect is simply the jump in outcomes!**

# Sharp RDD: Examples

- **Age-based eligibility:** Pension eligibility at age 65
  - $Z_i = \text{age}$ , cutoff at 65
  - Everyone 65+ receives pension, nobody under 65 does
- **Test score cutoff:** Admission to selective program
  - $Z_i = \text{test score}$ , cutoff at 70
  - Everyone scoring  $\geq 70$  admitted, everyone below rejected
- **Electoral threshold:** Winning an election
  - $Z_i = \text{vote share} - 50\%$
  - Above 50%: you win; below 50%: you lose

## Fuzzy regression discontinuity

**Definition:** In a **fuzzy RDD**, the *probability* of treatment changes discontinuously at the cutoff, but not from 0 to 1

Treatment probability jumps, but not perfectly:

$$\mathbb{P}(D_i = 1|Z_i) = \begin{cases} P_1(Z_i) & \text{if } Z_i \geq z^* \\ P_0(Z_i) & \text{if } Z_i < z^* \end{cases} \quad (14)$$

where  $P_1(z^*) > P_0(z^*)$  but the jump is not from 0 to 1

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Equivalently:  $0 < D^+ - D^- < 1$

**This has the structure of instrumental variables:**

- Eligibility: Crossing the cutoff  $\mathbb{1}\{Z_i \geq z^*\}$
- Treatment: Actual treatment receipt  $D_i$

# Why does fuzzy RDD arise?

**Reasons we see fuzzy rather than sharp:**

**Non-compliance** (most common): Eligibility  $\neq$  actual treatment

- Not everyone eligible takes up the program
- Some ineligible gain access through exceptions
- Example: Scholarship eligibility vs. actual receipt

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**When you have fuzzy RDD:** Think of it as IV, where crossing  $z^*$  is an instrument for treatment  $D_i$

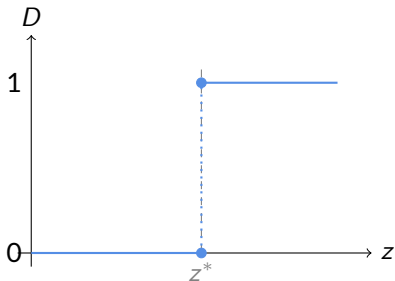
# Fuzzy RDD: Examples

- **Scholarship eligibility:**
  - $Z_i$  = family income, cutoff at \$30,000
  - Not everyone eligible applies for or receives the scholarship
  - Some ineligible students receive aid from other sources
- **Class size rules:**
  - $Z_i$  = enrollment, cutoff triggers new class
  - Rules may not be perfectly enforced
  - Some schools may combine classes despite the rule
- **Medicaid eligibility:**
  - $Z_i$  = income relative to poverty line
  - Not all eligible enroll
  - Some ineligible may be covered through other programs

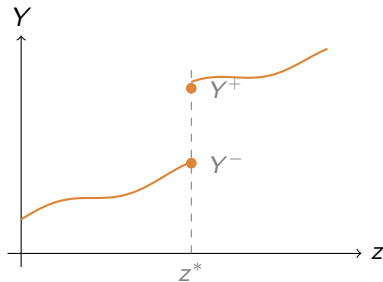


# Sharp RDD: Visual representation

## Treatment assignment



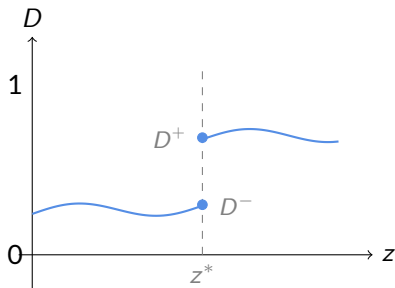
## Outcome



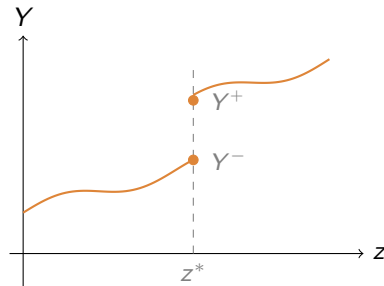
Left: Treatment status jumps from 0 to 1 at cutoff. Right: Outcome shows discontinuous jump.

# Fuzzy RDD: Visual representation

## Treatment probability



## Outcome



Left: Treatment probability jumps but not from 0 to 1. Right: Outcome shows discontinuous jump.

## Fuzzy RDD and LATE

Since fuzzy RDD has IV structure (eligibility vs. take-up), all the IV results apply!

The Wald formula  $\tau = \frac{Y^+ - Y^-}{D^+ - D^-}$  identifies a **Local Average Treatment Effect (LATE)**:

- Effect for **compliers**: those induced to take treatment by crossing  $z^*$
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### Compliers in fuzzy RDD:

- Would take treatment if  $Z_i \geq z^*$  (eligible)
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**Standard IV assumptions needed:** Relevance, exclusion, monotonicity

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## No exact empirical counterpart to the limit

**Important practical issue:** We want to estimate limits as  $z \rightarrow z^*$ , but:

- We only have a **finite sample** of observations
- We may not observe anyone *exactly* at  $Z_i = z^*$
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- We need to use data **away from the cutoff**

**This creates a fundamental estimation challenge:**

- How far from the cutoff should we use data?
- How do we approximate the conditional expectations near the cutoff?
- This is the focus of the next section!



# From theory to estimation

**Recall the identification formula:**

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where  $Y^+ = \lim_{z \rightarrow (z^*)^+} \mathbb{E}[Y_i | Z_i = z]$ , etc.

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**But:** We need to estimate these limits from data

**Approach:** Assume  $\mathbb{E}[Y_i | Z_i = z]$  can be approximated by a smooth function  $g(z)$  near the cutoff

## Basic regression approach

The simplest specification uses a linear function on each side:

$$Y_i = \alpha + \beta D_i + \gamma_1 Z_i + \gamma_2 D_i \cdot Z_i + \varepsilon_i \quad (16)$$

where  $D_i = \mathbb{1}\{Z_i \geq z^*\}$

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### Interpretation:

- $\alpha$ : Intercept for untreated (extrapolated to  $Z_i = z^*$ )
- $\gamma_1$ : Slope for untreated
- $\beta$ : **Treatment effect** at the cutoff
- $\gamma_2$ : Difference in slopes between treated and untreated

## Understanding the specification

The regression can be written separately on each side:

**Below the cutoff** ( $Z_i < z^*$ , so  $D_i = 0$ ):

$$\mathbb{E}[Y_i|Z_i = z] = \alpha + \gamma_1(z - z^*) \quad (17)$$

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**At the cutoff** ( $Z_i = z^*$ ):

- From below:  $Y^- = \alpha$
- From above:  $Y^+ = \alpha + \beta$
- Difference:  $\beta = Y^+ - Y^-$

## Allowing for flexible functional forms

Linear may be too restrictive! We can use **polynomial specifications**:

$$Y_i = \alpha + \beta D_i + \sum_{p=1}^P \gamma_p Z_i^p + \sum_{p=1}^P \delta_p D_i \cdot Z_i^p + \varepsilon_i \quad (19)$$



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**Common choices:**

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- $P = 2$ : Quadratic
- $P = 3$  or  $P = 4$ : Higher-order polynomials

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- $P = 2$ : Quadratic
- $P = 3$  or  $P = 4$ : Higher-order polynomials

### Trade-off:

- Higher  $P \rightarrow$  more flexible, fits data better
- But: risk of overfitting, especially near endpoints
- **Warning:** Gelman and Imbens (2019) show high-order polynomials can be problematic

## Local linear regression

**Better approach:** Use data only *close to the cutoff* with linear specification

Estimate:

$$Y_i = \alpha + \beta D_i + \gamma_1 Z_i + \gamma_2 D_i \cdot Z_i + \varepsilon_i \quad (20)$$

but only using observations where  $|Z_i| \leq h$  for some bandwidth  $h$

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**Why is this better?**

- Linear approximation is better when we're close to the cutoff
- Avoids relying on functional form assumptions far from cutoff
- More robust to misspecification

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**Why is this better?**

- Linear approximation is better when we're close to the cutoff
- Avoids relying on functional form assumptions far from cutoff
- More robust to misspecification

**But:** How do we choose the bandwidth  $h$ ? (More on this soon!)

# Weighted local linear regression

**Possible other specification:** weight observations based on distance from cutoff

Use a **kernel function**  $K(u)$  that gives more weight to observations closer to the cutoff

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**Common kernels:**

- **Uniform:**  $K(u) = 0.5$  for  $|u| \leq 1$ , zero otherwise
- **Triangular:**  $K(u) = 1 - |u|$  for  $|u| \leq 1$
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**In practice:** Choice of kernel matters less than choice of bandwidth

## Estimation with fuzzy RDD

For **fuzzy RDD**, we use instrumental variables (2SLS):

**First stage** (treatment on eligibility):

$$D_i = \pi_0 + \pi_1 \mathbb{1}\{Z_i \geq z^*\} + \pi_2(Z_i - z^*) + \pi_3 \mathbb{1}\{Z_i \geq z^*\} \cdot (Z_i - z^*) + \nu_i \quad (21)$$

**Second stage** (outcome on predicted treatment):

$$Y_i = \alpha + \beta \hat{D}_i + \gamma_1(Z_i - z^*) + \gamma_2 \mathbb{1}\{Z_i \geq z^*\} \cdot (Z_i - z^*) + \varepsilon_i \quad (22)$$

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**Or equivalently:** Reduced form divided by first stage

$$\beta = \frac{Y^+ - Y^-}{D^+ - D^-} = \frac{\text{Reduced form effect}}{\text{First stage effect}} \quad (23)$$

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# The fundamental trade-off

**Central challenge in RDD: choosing the bandwidth  $h$**

**Narrow bandwidth (small  $h$ ):**

- **Good:** Better approximation (less bias from functional form)
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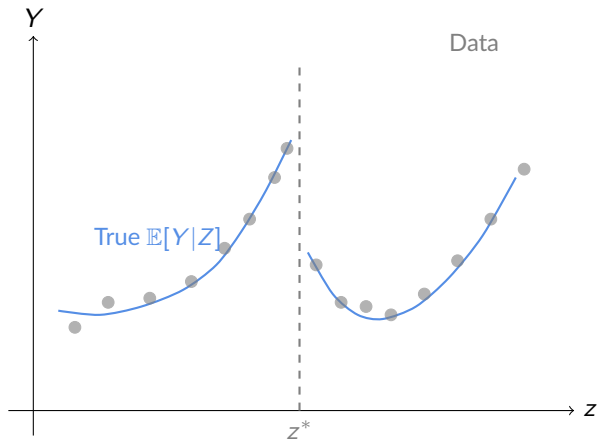
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**Wide bandwidth** (large  $h$ ):

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This is the classic **bias-variance trade-off!**

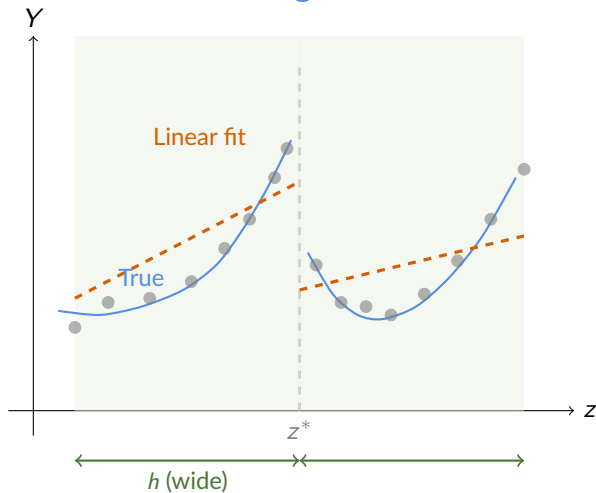
## Visualizing the trade-off: True CEF



True conditional expectation function with curvature and observed data points

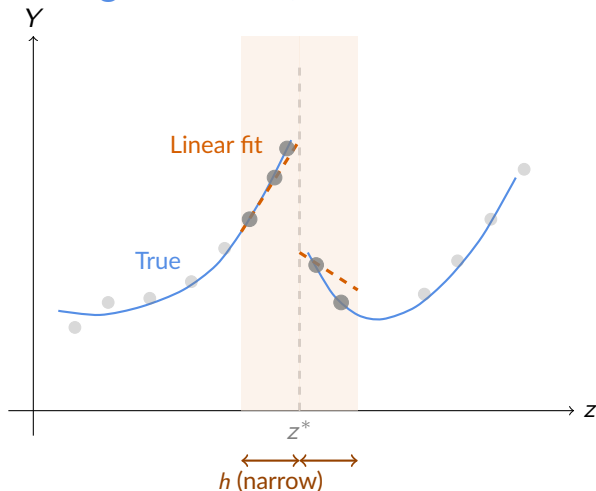


## Wide bandwidth: Low variance, high bias



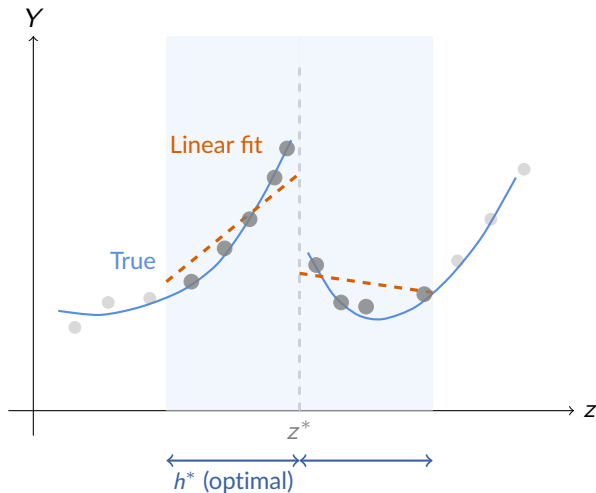
Many observations used, but poor approximation due to curvature

## Narrow bandwidth: High variance, low bias



Few observations used, but good local approximation

# Optimal bandwidth: Balance bias and variance



Optimal  $h^*$  balances moderate sample size with reasonable approximation

# Optimal bandwidth selection

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**Yes!** Modern approaches minimize mean squared error (MSE):

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**Key insight:**

- Bias typically grows with  $h^{p+1}$  (where  $p$  is polynomial order)
- Variance typically shrinks with  $1/(nh)$  (where  $n$  is sample size)
- Optimal  $h$  balances these two

# Practical bandwidth selection

**In practice:** Use data-driven bandwidth selection

**Popular methods:**

- **rdrobust** (Calonico, Cattaneo, Titiunik): Most common, includes bias correction
- **RDHonest** (Kolesar, Rothe): For discrete running variables
- Cross-validation approaches

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**Important:** Always show **robustness** to bandwidth choice!

- Plot estimates for a range of bandwidths
- Show that results are not driven by one specific choice



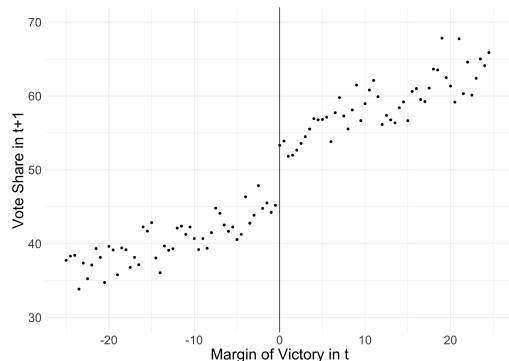
# Graphical presentation: Choosing bin size

## Similar trade-off for graphical presentation:

- Too many bins → noisy (hard to interpret)
- Too few bins → masks true pattern
- Need to find the right balance

### Ideally: Plot binned means

- Similar intuition to binscatter
- But how do we choose bins?



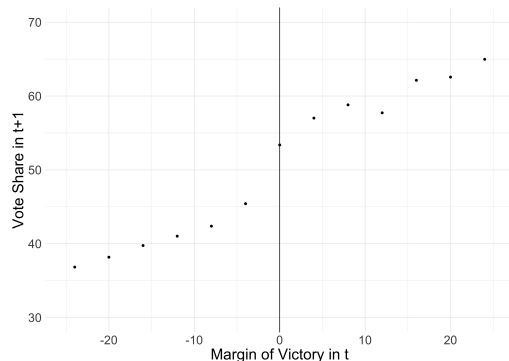
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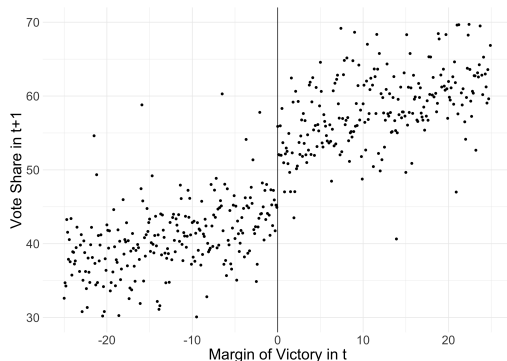
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# Graphical presentation: Optimal bin selection

**Modern approach:** Choose bins optimally

Cattaneo et al. (2020) propose two approaches:

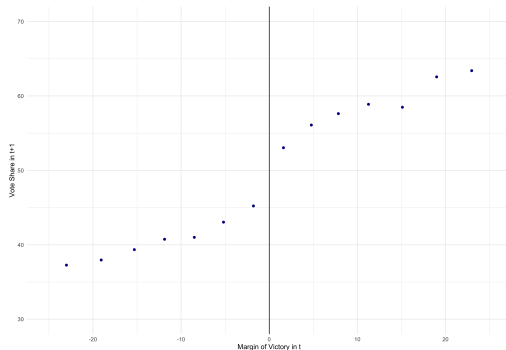
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- Trades off bias vs. variance over whole range

## 2. Mimicking-variance ( $\propto n/\log(n)^2$ bins)

- Matches variance of raw data in binned plots
- Typically more bins

**Software:** `rdplot` in `rdrobust` (Stata/R)



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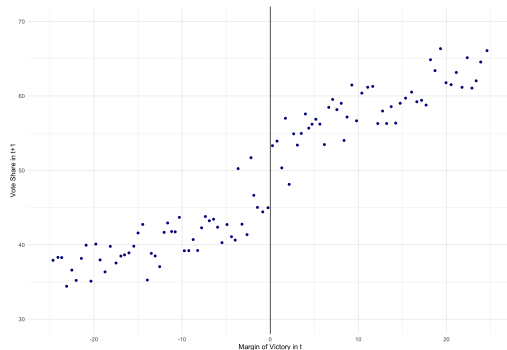
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## Graphical presentation: Bin placement

**Other decision to make:** How to place bins: equal-spaced vs. quantile

- Quantile binning more transparent
- Equal-spaced can mask underlying density

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# Validating the RDD

**Recall:** RDD relies on the assumption that potential outcomes are continuous at the cutoff

**This assumption is not directly testable!**

- We never observe both  $Y_i(0)$  and  $Y_i(1)$  for same individual
- Cannot verify continuity of counterfactuals



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**But:** We can test **implications** of the assumption

Main threats to validity:

- ① **Manipulation/sorting** of the running variable
- ② **Imbalance** in covariates at cutoff
- ③ **Other discontinuities** at the same threshold

## Threat 1: Manipulation and bunching

**Problem:** If individuals can manipulate their value of  $Z_i$  to cross the threshold, then treated and untreated are no longer comparable

**Example** (McCrary, 2008):

- Government announces income support for those earning  $< \$14,000$
- Some people might underreport income to qualify
- Would see "bunching" just below the cutoff

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**Why is this a problem?**

- Those who manipulate may be systematically different
- Example: More sophisticated, more desperate, etc.
- Violates continuity assumption

## Testing for manipulation: McCrary density test

**McCrary (2008) test:** Test whether the *density* of the running variable is continuous at the cutoff

### Intuition:

- If no manipulation, density should be smooth through cutoff
- Manipulation creates a "jump" or "hole" in the density

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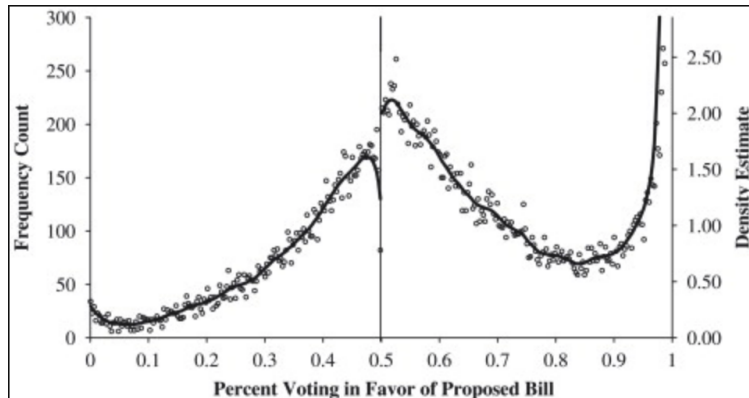
### Intuition:

- If no manipulation, density should be smooth through cutoff
- Manipulation creates a "jump" or "hole" in the density

### Implementation:

- Estimate density on each side of cutoff (using kernel methods)
- Test for discontinuity at  $Z_i = z^*$
- Software: `rddensity` (Cattaneo, Jansson, Ma, 2020)

## McCrary test: Example



Lee (2008): No evidence of manipulation in close elections

# When manipulation happens anyway...

## What if there IS bunching?

### Option 1: Bounds on treatment effects

- Gerard, Rokkanen, and Rothe (2020): rdbounds
- Even with sorting, can bound the magnitude of effects
- Asks: how much could sorting explain the results?

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- Asks: how much could sorting explain the results?

### Option 2: Donut-hole RDD

- Exclude observations very close to cutoff
- If manipulation only affects those right at threshold
- But: loses precision, changes estimand



## Threat 2: Covariate imbalance

**Covariate balance test:** Check whether predetermined covariates change discontinuously at cutoff

**Idea:** If RDD is valid, things that were determined *before* treatment assignment shouldn't jump at the cutoff

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### What to test:

- Demographic characteristics (age, gender, race, etc.)
- Baseline/lagged outcomes (outcomes before treatment)
- Other predetermined variables

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### What to test:

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**Implementation:** Run the same RDD regression, but use covariate as outcome

$$X_i = \alpha + \beta \mathbb{1}\{Z_i \geq z^*\} + \gamma_1(Z_i - z^*) + \gamma_2 \mathbb{1}\{Z_i \geq z^*\} \cdot (Z_i - z^*) + \varepsilon_i \quad (25)$$

Test  $H_0: \beta = 0$  for each covariate

## Threat 3: Other discontinuities at cutoff

**Problem:** If *other things* besides treatment change at the cutoff, we can't isolate the treatment effect

**Example:** Retirement age

- At age 65: eligibility for pension, Medicare, mandatory retirement, etc.
- Hard to say which one drives any outcome changes

## Threat 3: Other discontinuities at cutoff

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**Solutions:**

- Find a setting where only one thing changes
- Try to measure all the things that change
- Focus on outcomes that should only be affected by one channel

## Additional robustness tests

### Placebo cutoffs:

- Test for discontinuities at points *other than* the true cutoff
- If you find effects at fake cutoffs, something's wrong!
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### Alternative specifications:

- Different polynomial orders
- Different bandwidths
- With/without covariates



## External validity: The local nature of RDD

**Key limitation:** RDD identifies  $\tau_{RDD} = \mathbb{E}[Y_i(1) - Y_i(0)|Z_i = z^*]$  - a **very local** parameter

### When is this a problem?

- Treatment effects are heterogeneous (marginal vs. inframarginal individuals)
- Policy question is about broader population, not just at cutoff
- Example: Class size effect at 41 vs. 40 may not apply to 30 vs. 20

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### When is it less of a concern?

- Marginal policy changes (moving the cutoff slightly)
- Effect at cutoff IS the policy-relevant parameter
- Using RDD to understand mechanisms, not for extrapolation

# RDD estimation checklist

A credible RDD paper should present:

- 1 **Graphical evidence:** Plot outcome vs. running variable with discontinuity clearly visible (rdplot)
- 2 **Density test:** McCrary/`rddensity` test to rule out manipulation at cutoff
- 3 **Covariate balance:** Test for discontinuities in predetermined variables
- 4 **Main estimates:** Use local linear with MSE-optimal bandwidth (`rdrobust`)
  - For fuzzy RDD: report first stage (check  $F\text{-stat} > 10$ )
- 5 **Robustness:** Show sensitivity to bandwidth, polynomial order, covariates
- 6 **Placebo tests:** Check for effects at fake cutoffs, lagged outcomes, donut-hole

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# Summary

## Key takeaways:

- RDD exploits discontinuous changes in treatment at a threshold
- **Identification:** Relies on continuity of potential outcomes at cutoff
- **Sharp vs. Fuzzy:** Deterministic vs. probabilistic treatment assignment
- **Estimation:** Local linear regression with optimal bandwidth
- **Validity:** Test for manipulation, covariate balance, other discontinuities
- **External validity:** Effects are local to the cutoff