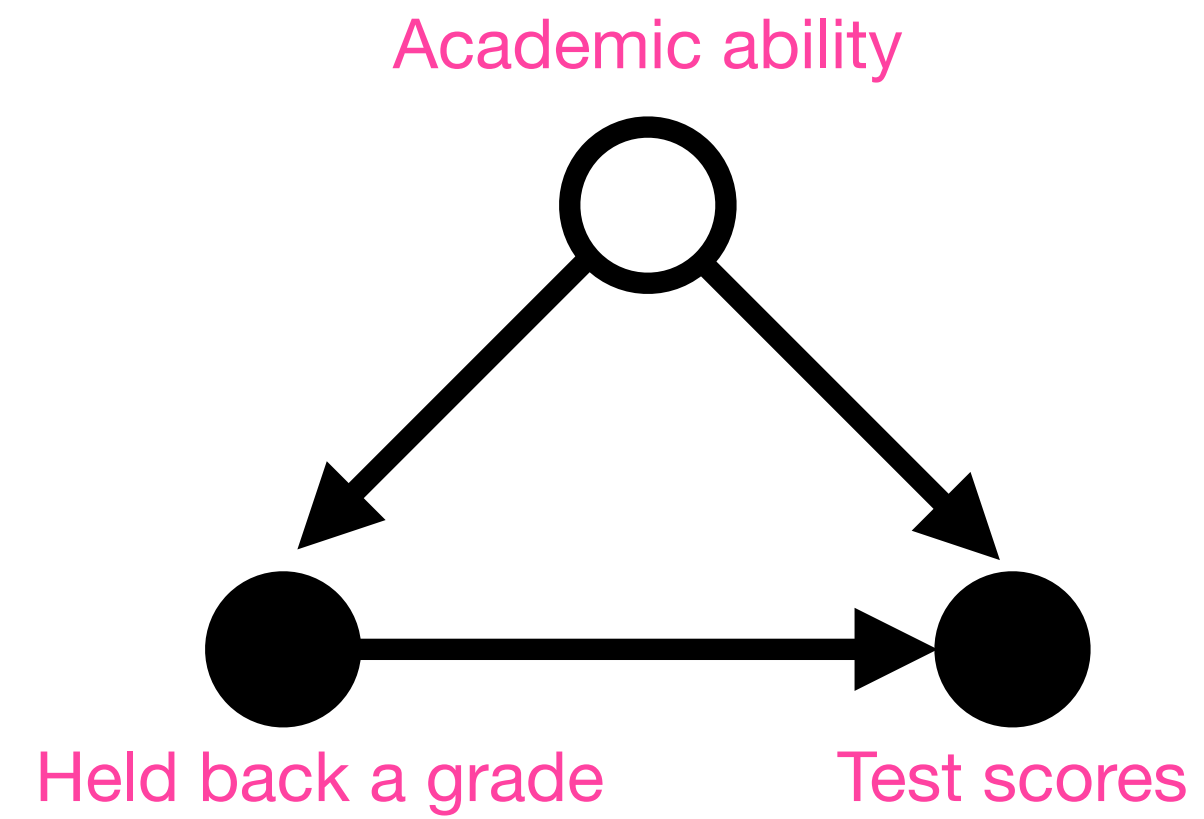


Proximal Causal Learning with Kernels: Two-Stage Estimation and Moment Restriction

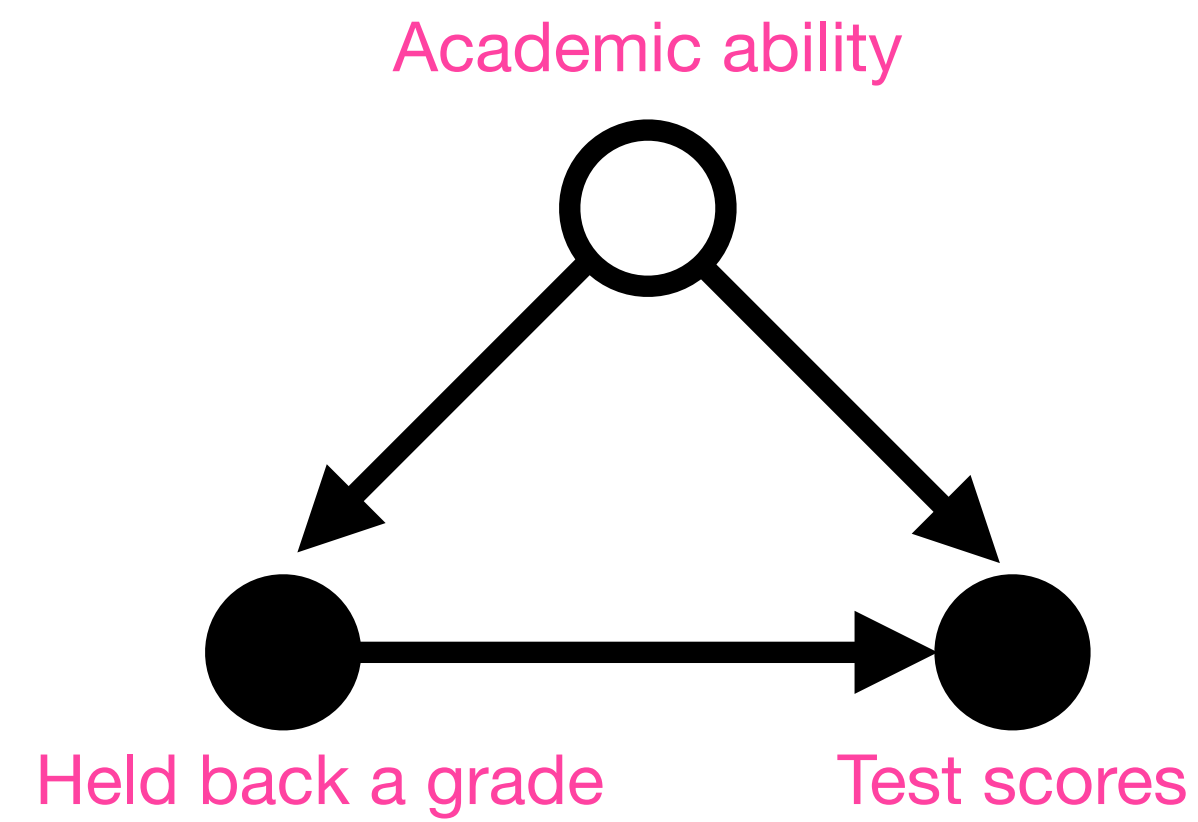
Afsaneh Mastouri*, Yuchen Zhu*, Limor Gultchin, Anna Korba, Ricardo Silva, Matt Kusner
Arthur Gretton[^], Krikamol Muandet[^]



Reliable Decision Making

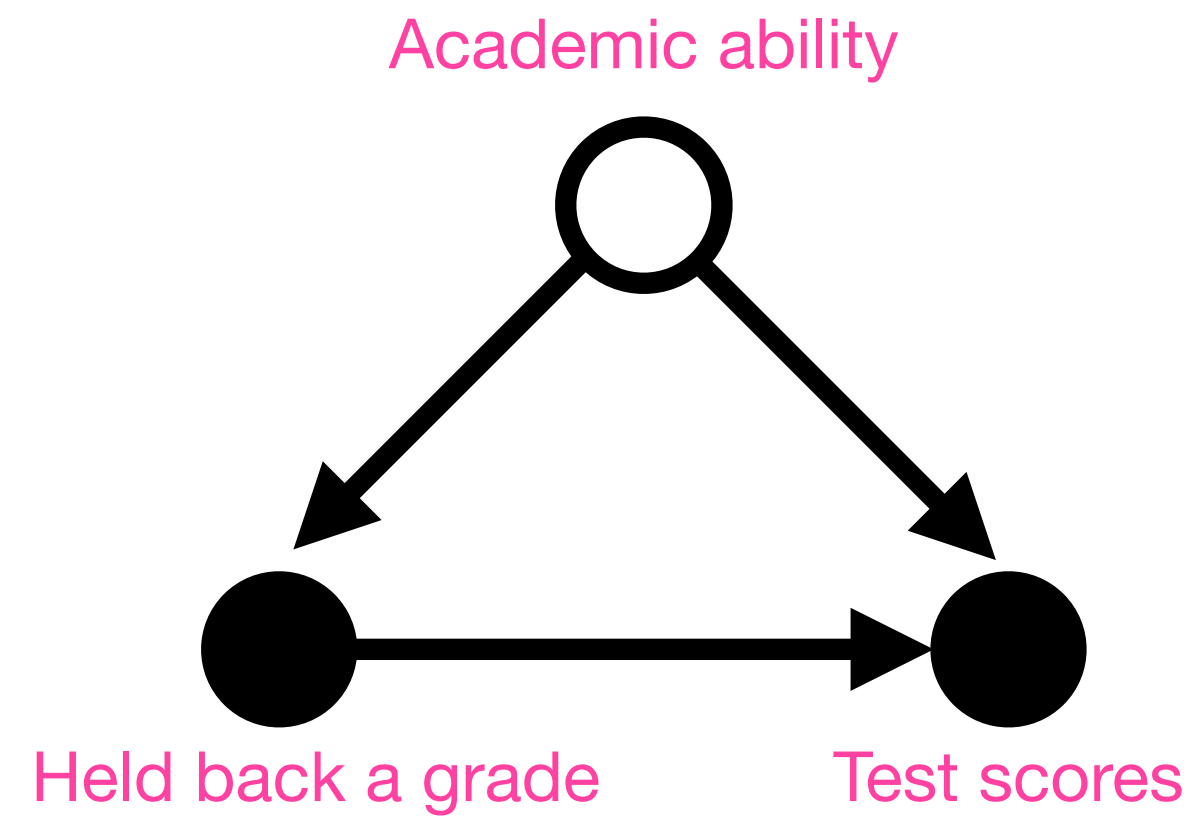


Reliable Decision Making



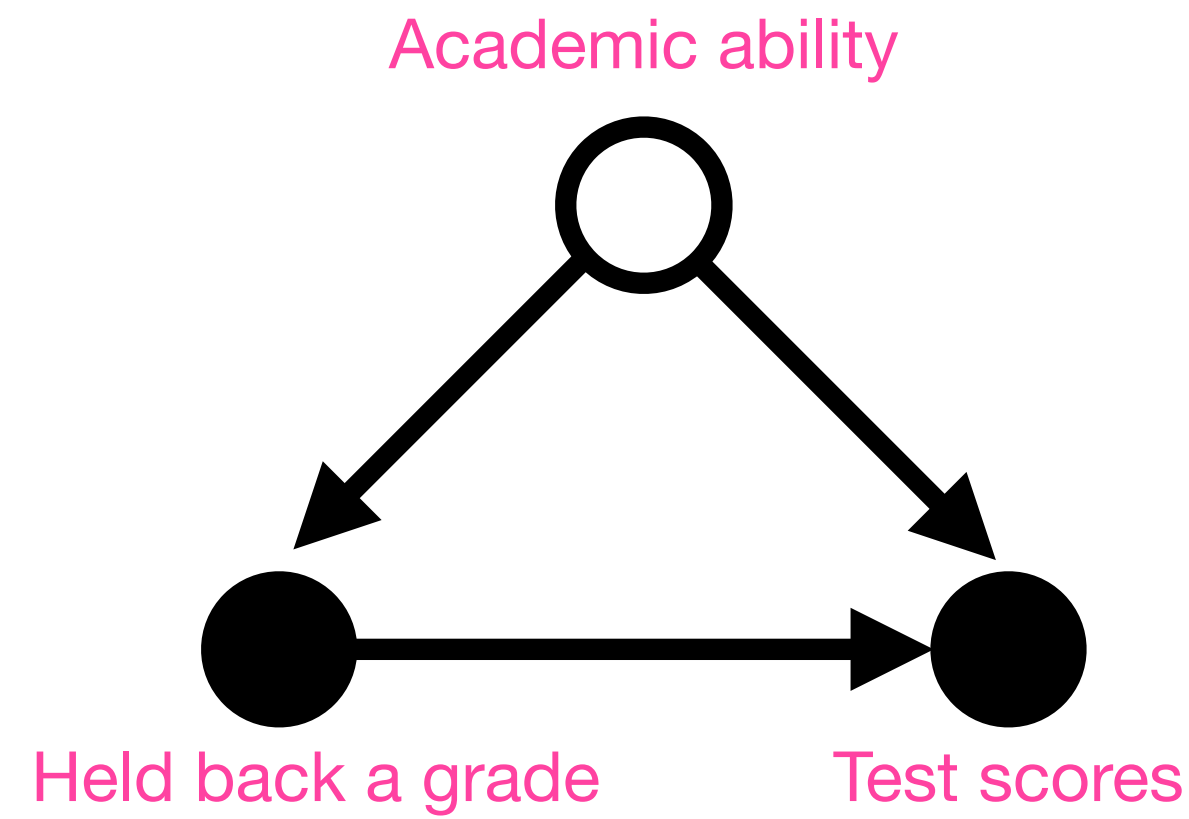
- Machine learning allows us to create models that excel at making **prediction**.

Reliable Decision Making



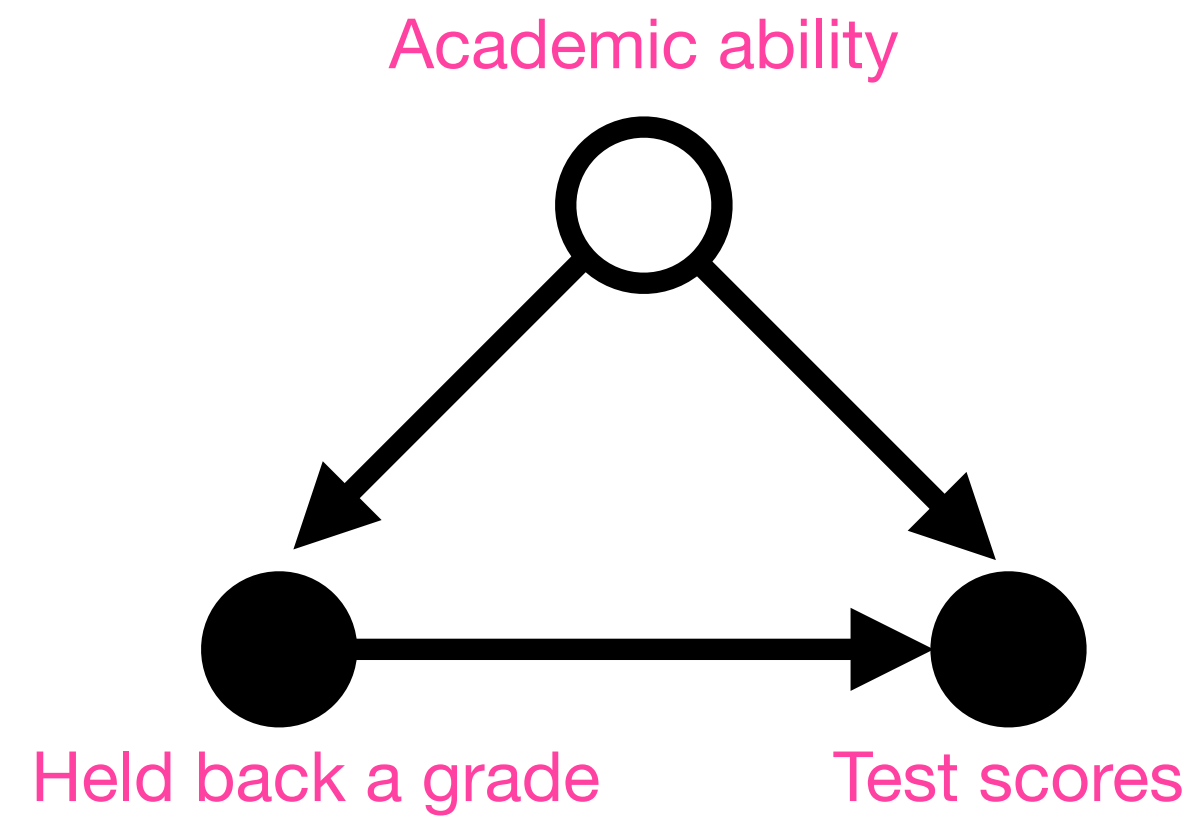
- Machine learning allows us to create models that excel at making **prediction**.
- We aim to predict an outcome of some **intervention**.

Reliable Decision Making



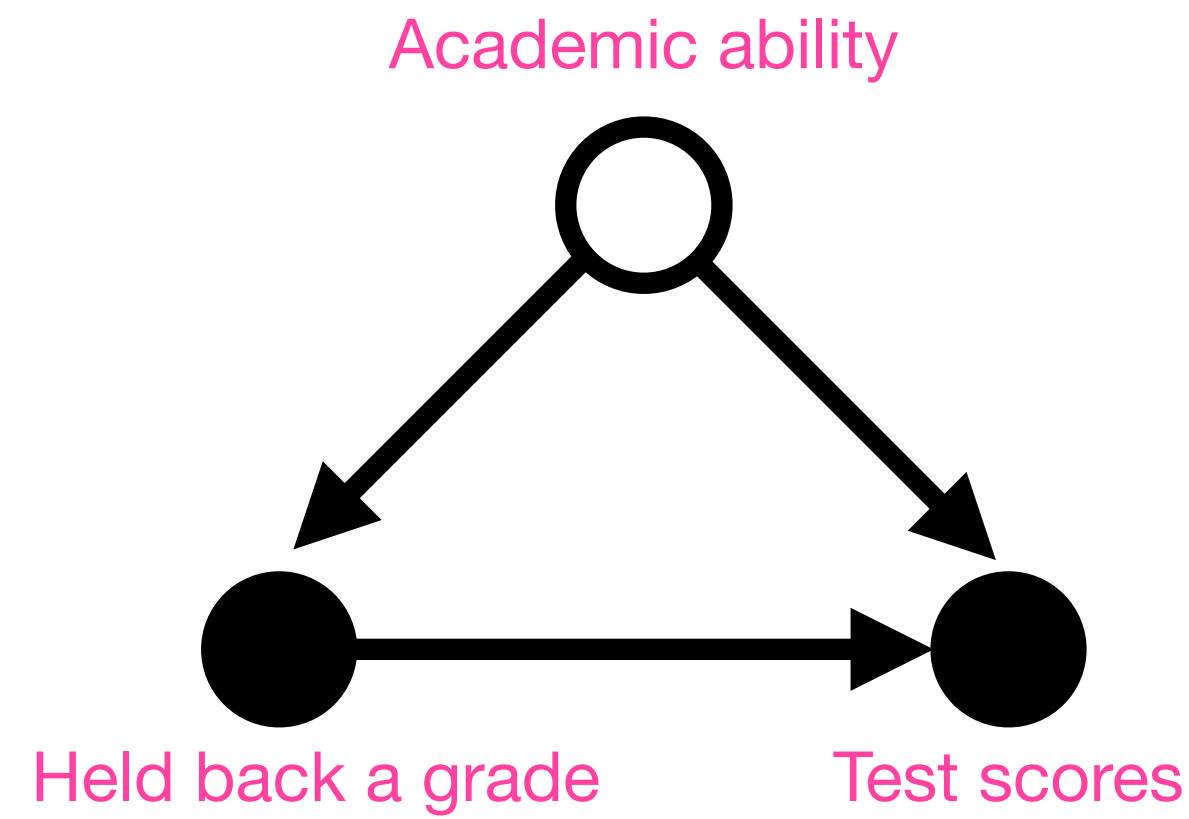
- Machine learning allows us to create models that excel at making **prediction**.
- We aim to predict an outcome of some **intervention**.
 - Will holding back a grade, improve the test scores of students?

Reliable Decision Making

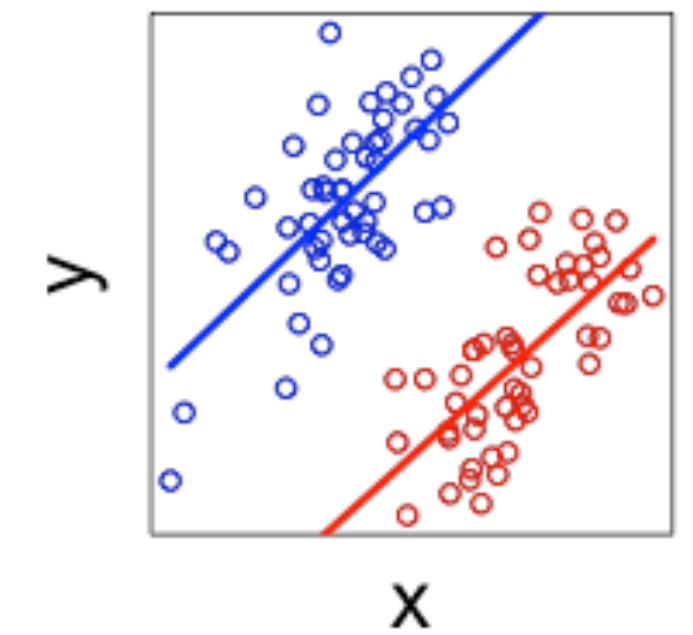
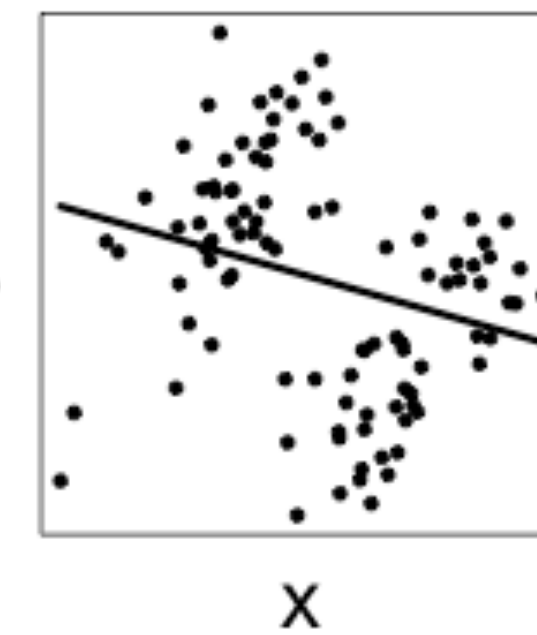


- Machine learning allows us to create models that excel at making **prediction**.
- We aim to predict an outcome of some **intervention**.
 - Will holding back a grade, improve the test scores of students?
- **Experimental** data are not available. Only **Observational**.

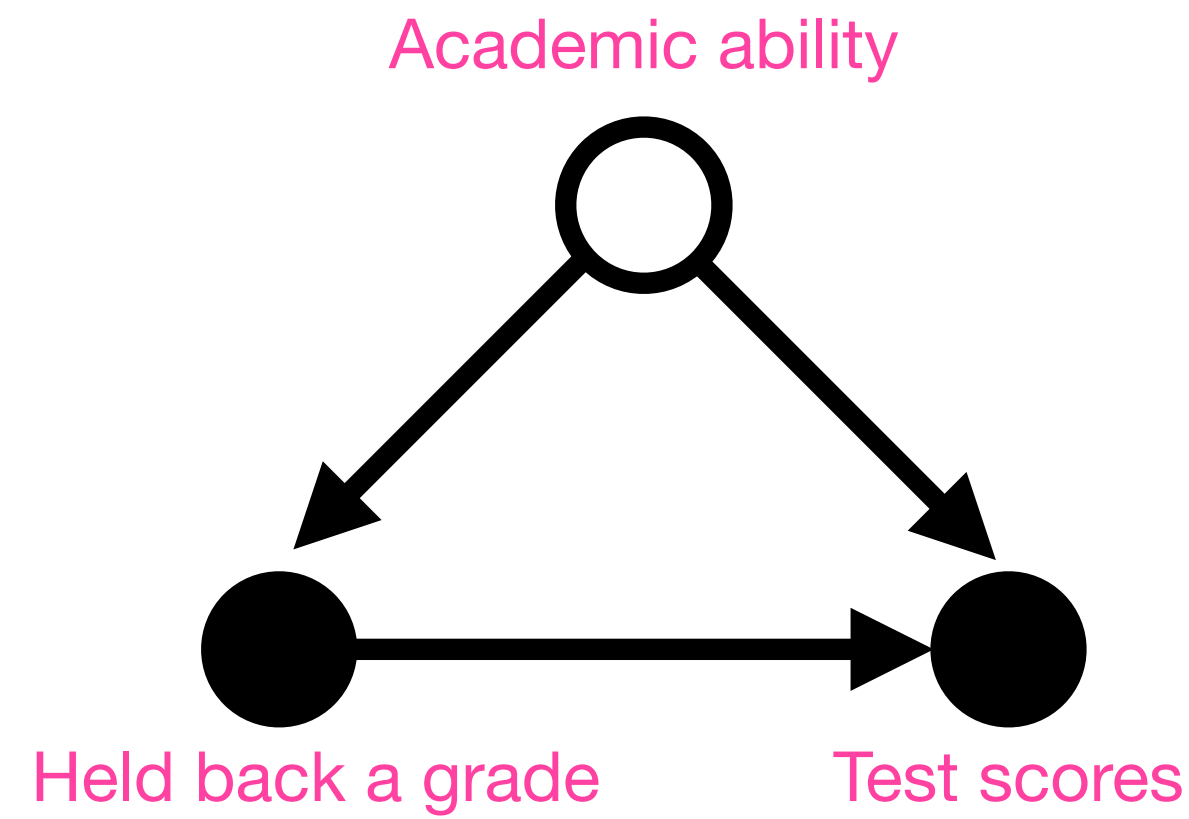
Reliable Decision Making



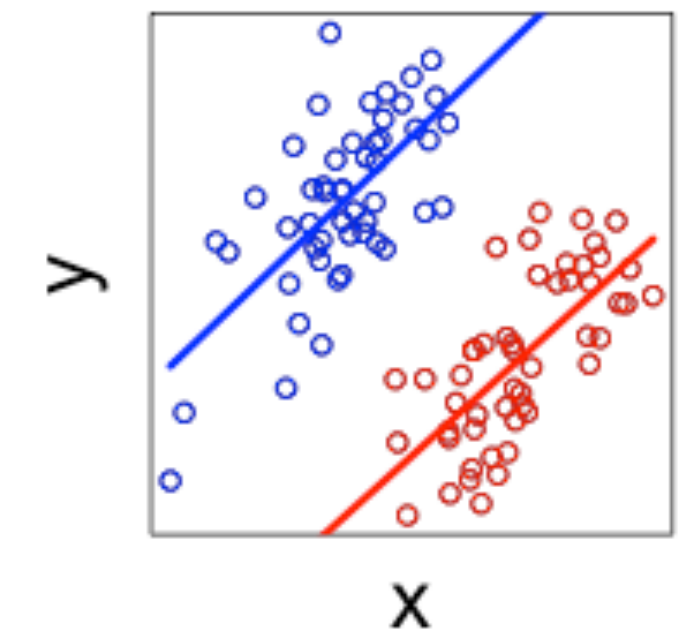
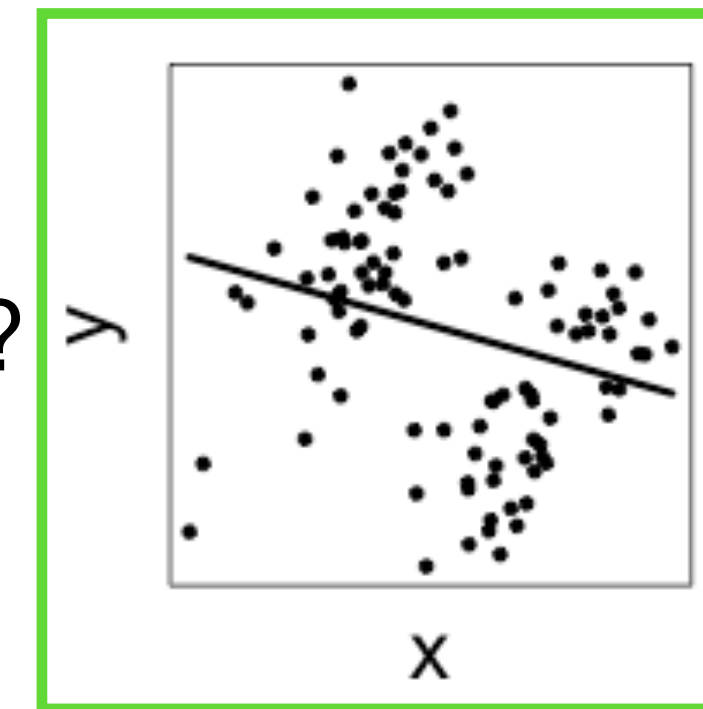
- Machine learning allows us to create models that excel at making **prediction**.
- We aim to predict an outcome of some **intervention**.
 - Will holding back a grade, improve the test scores of students? $>$
- Experimental** data are not available. Only **Observational**.
- We cannot rule out the effect of **unobserved confounders** (Simpson's paradox)



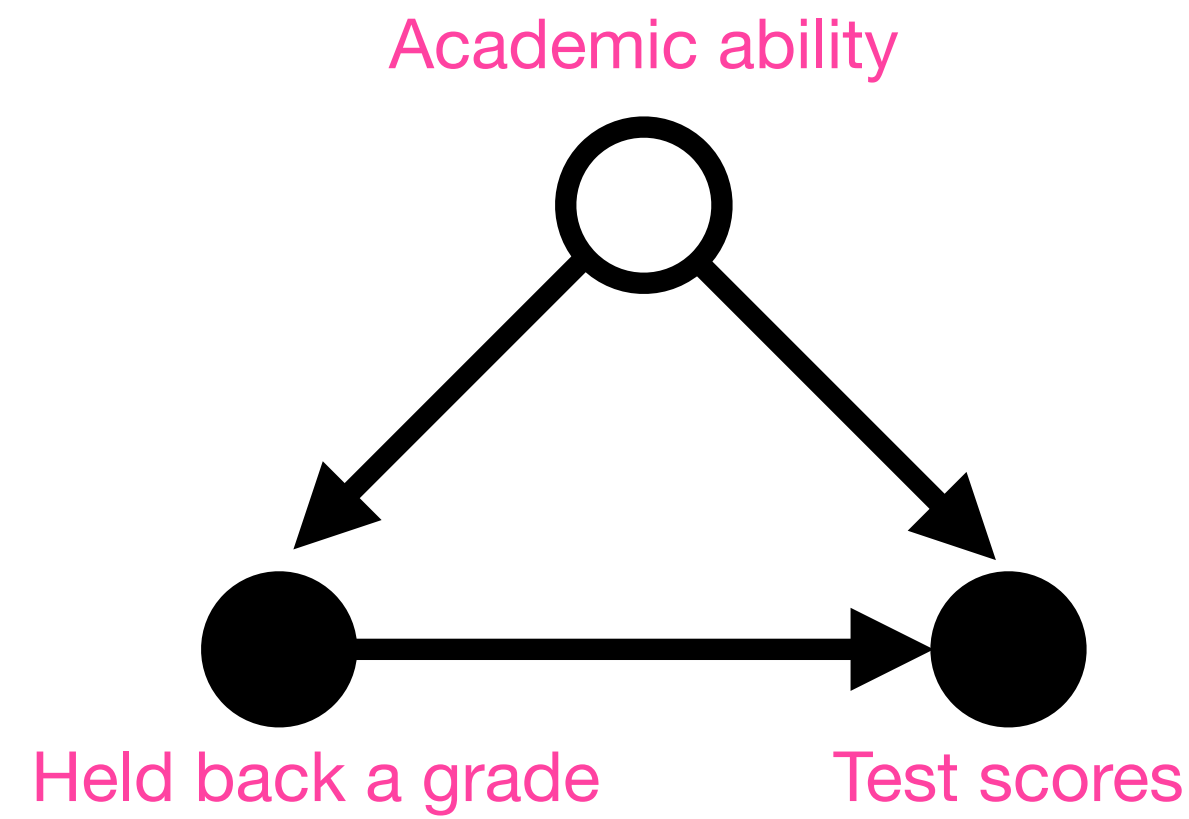
Reliable Decision Making



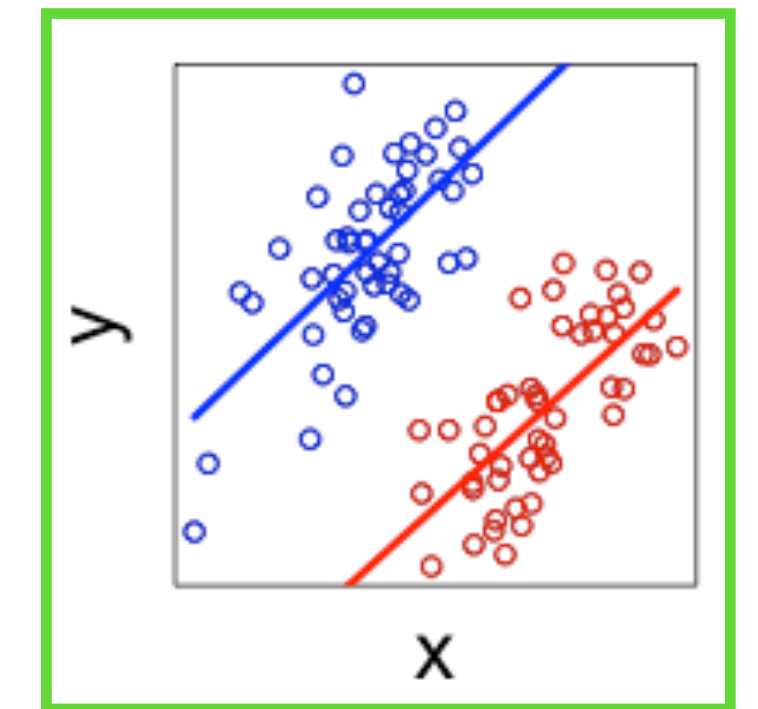
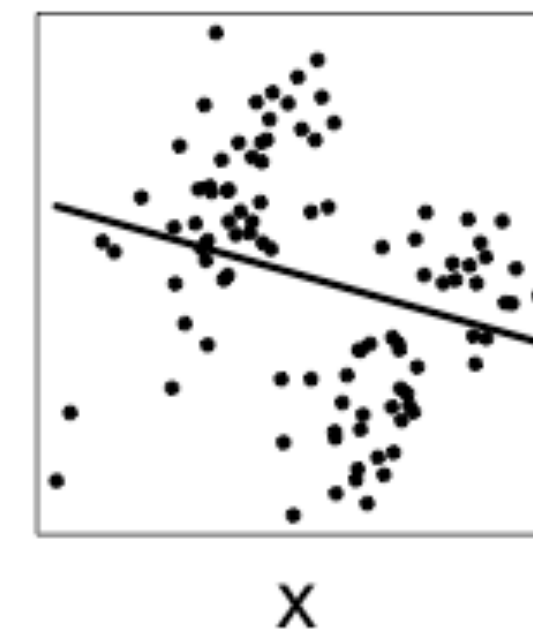
- Machine learning allows us to create models that excel at making **prediction**.
- We aim to predict an outcome of some **intervention**.
 - Will holding back a grade, improve the test scores of students?
- **Experimental** data are not available. Only **Observational**.
- We cannot rule out the effect of **unobserved confounders** (Simpson's paradox)



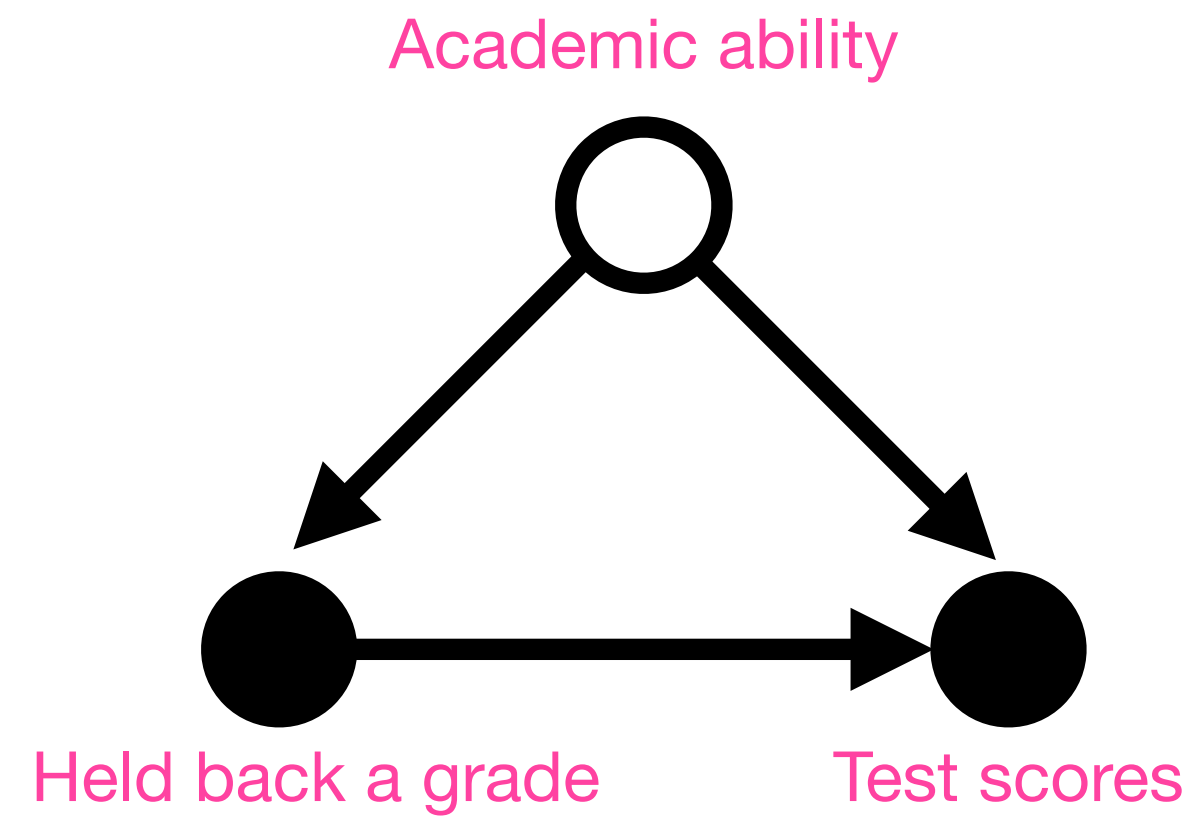
Reliable Decision Making



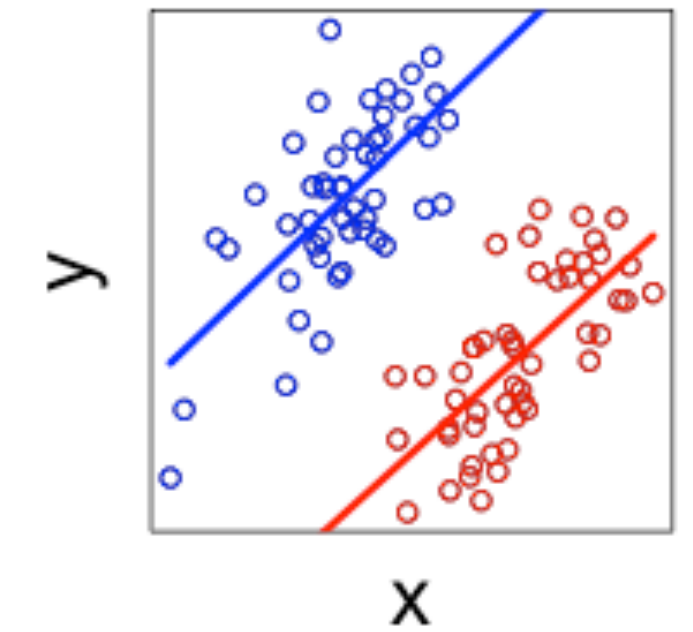
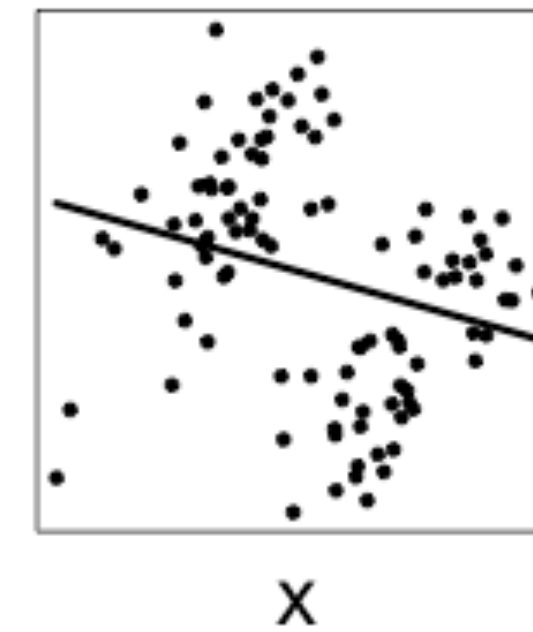
- Machine learning allows us to create models that excel at making **prediction**.
- We aim to predict an outcome of some **intervention**.
 - Will holding back a grade, improve the test scores of students? $>$
- **Experimental** data are not available. Only **Observational**.
- We cannot rule out the effect of **unobserved confounders** (Simpson's paradox)



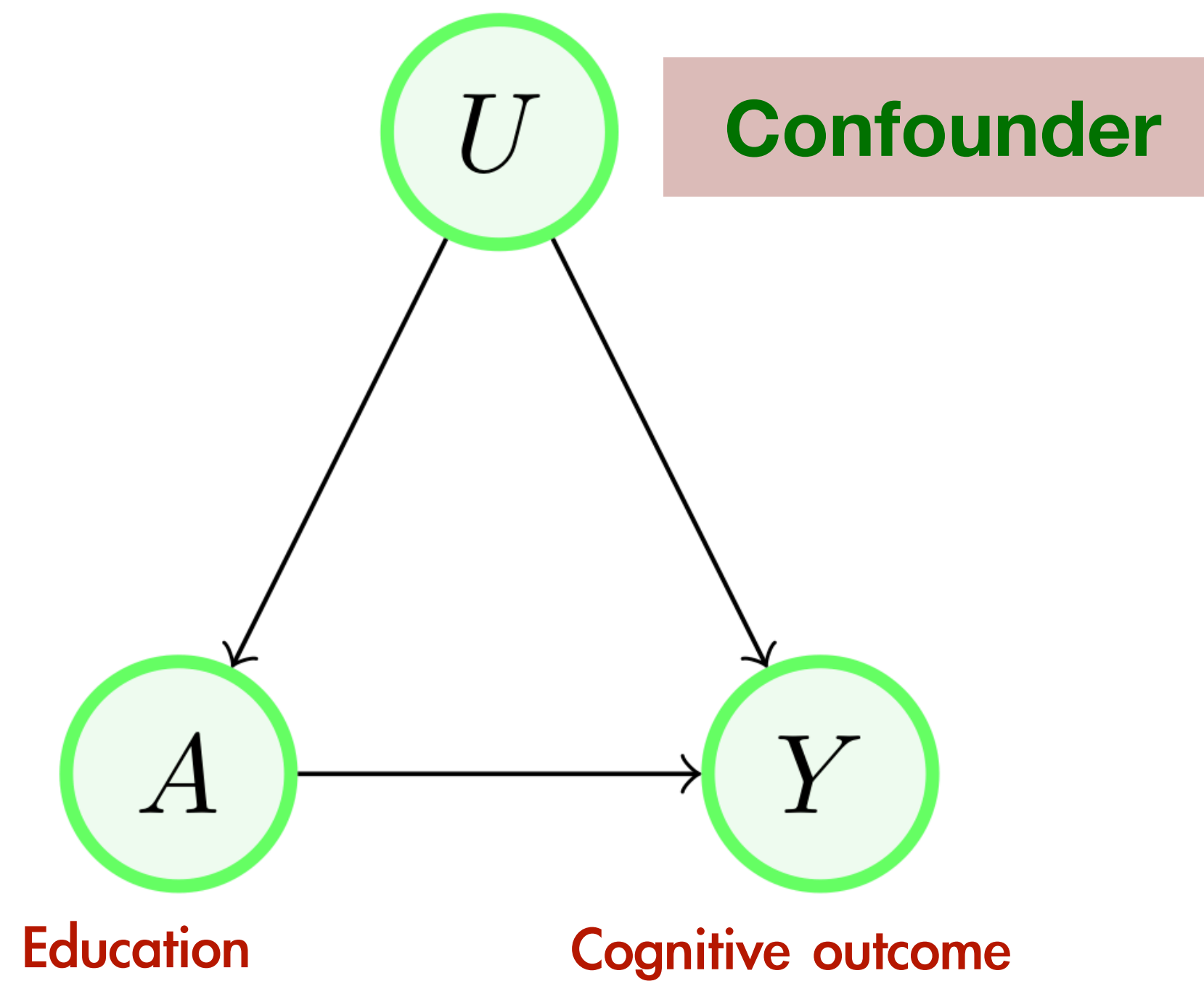
Reliable Decision Making



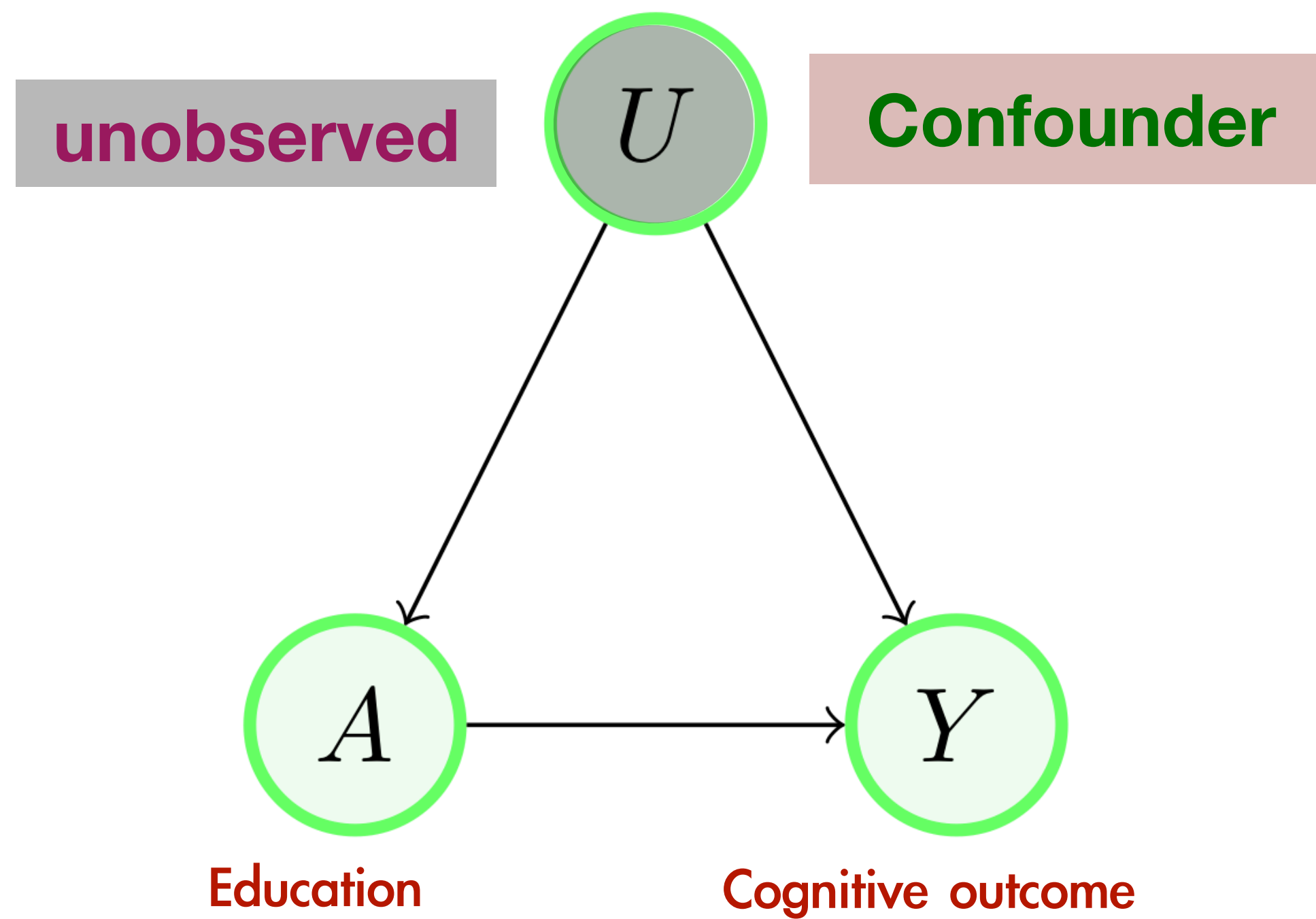
- Machine learning allows us to create models that excel at making **prediction**.
- We aim to predict an outcome of some **intervention**.
 - Will holding back a grade, improve the test scores of students? $>$
- **Experimental** data are not available. Only **Observational**.
- We cannot rule out the effect of **unobserved confounders** (Simpson's paradox)



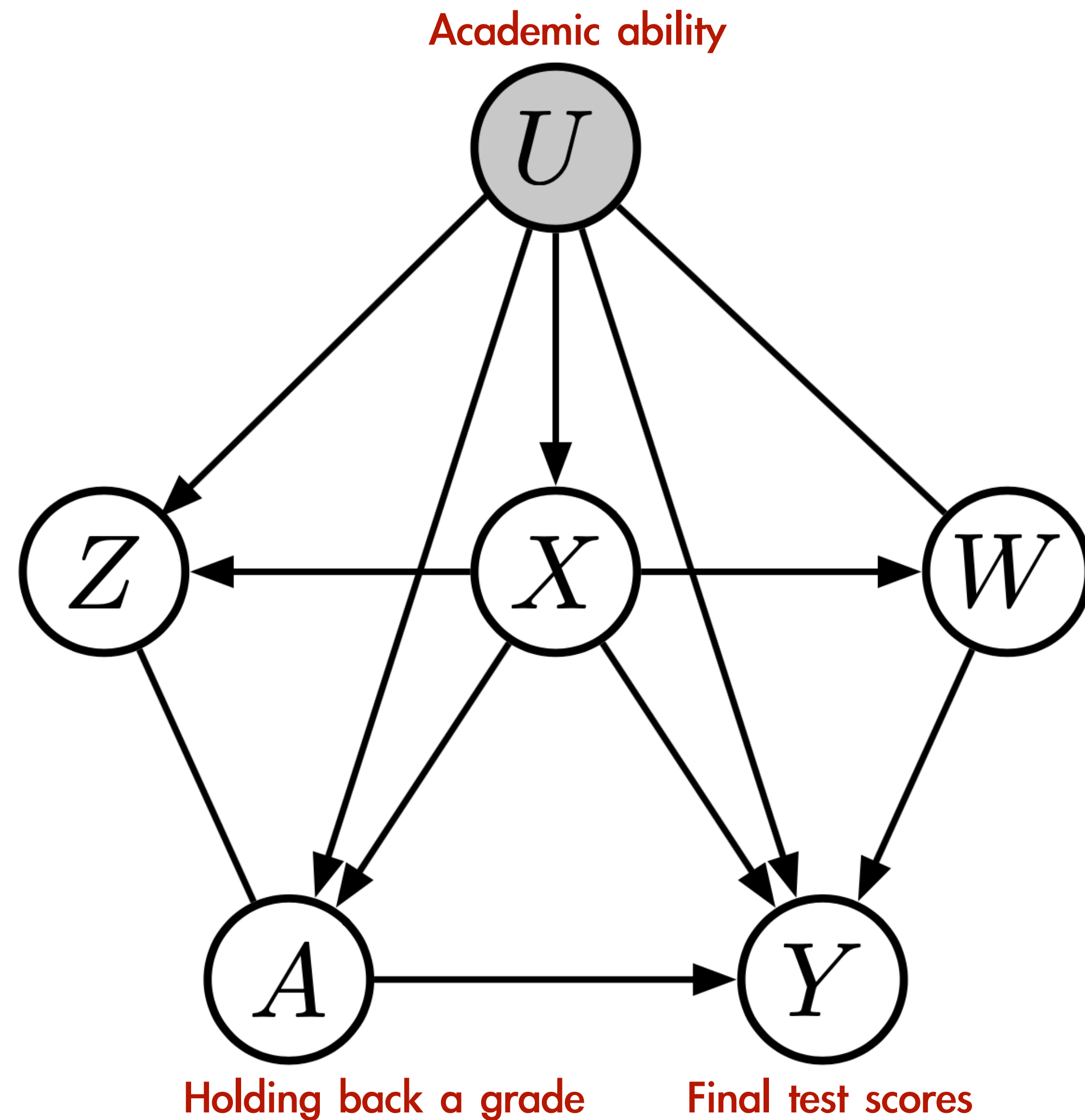
How to resolve **unobserved** confounding?



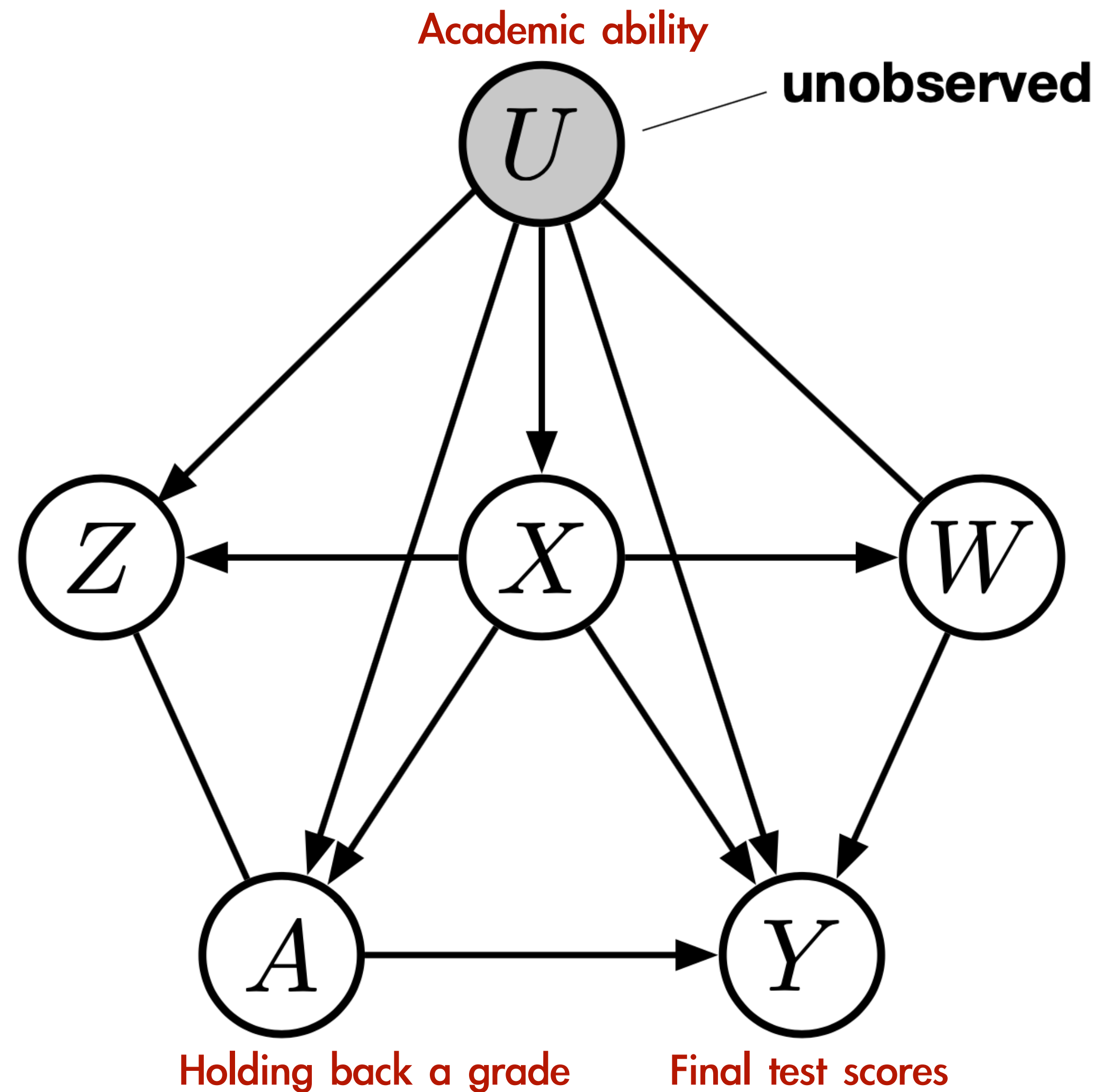
How to resolve **unobserved** confounding?



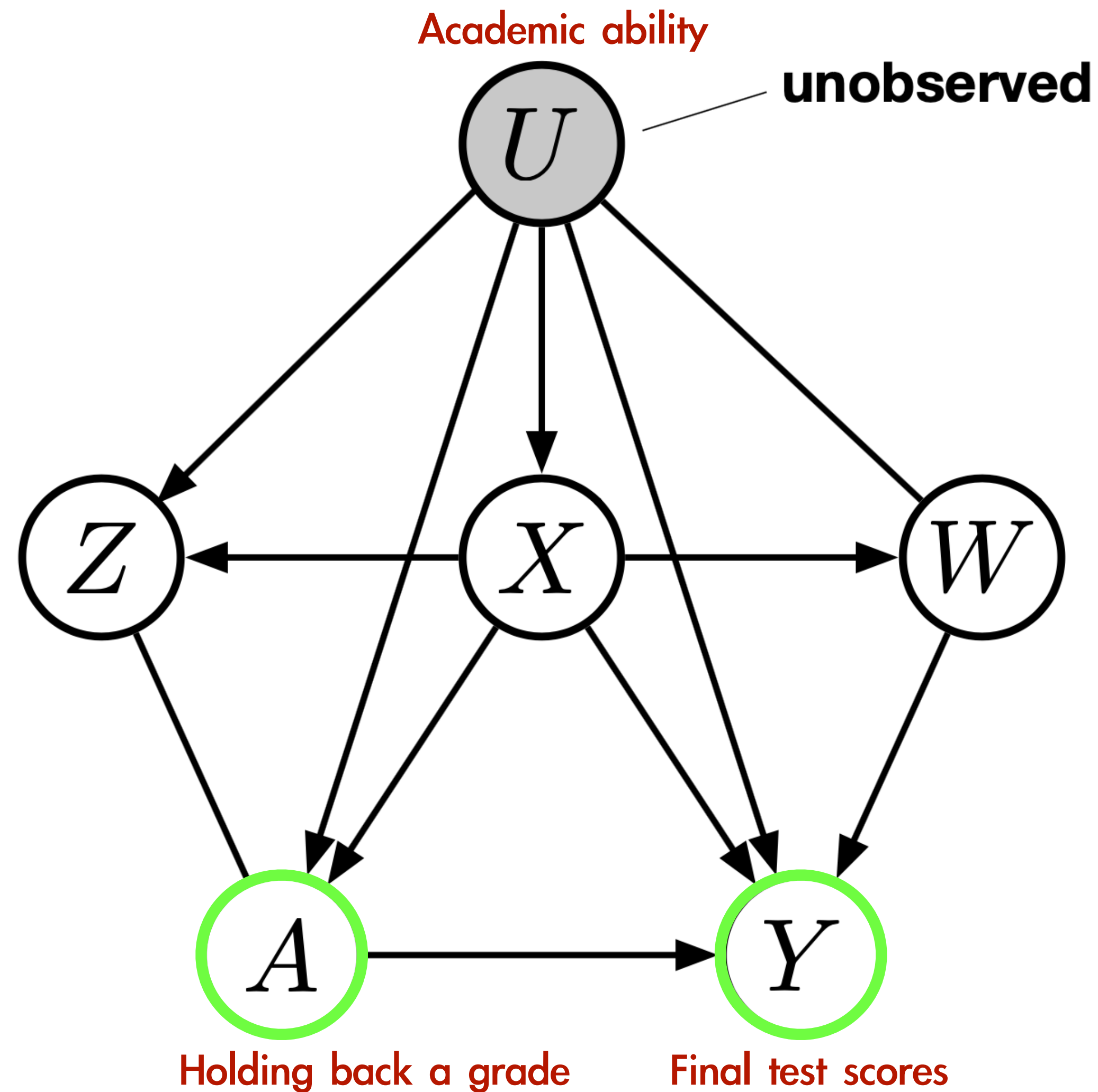
How to resolve **unobserved** confounding?



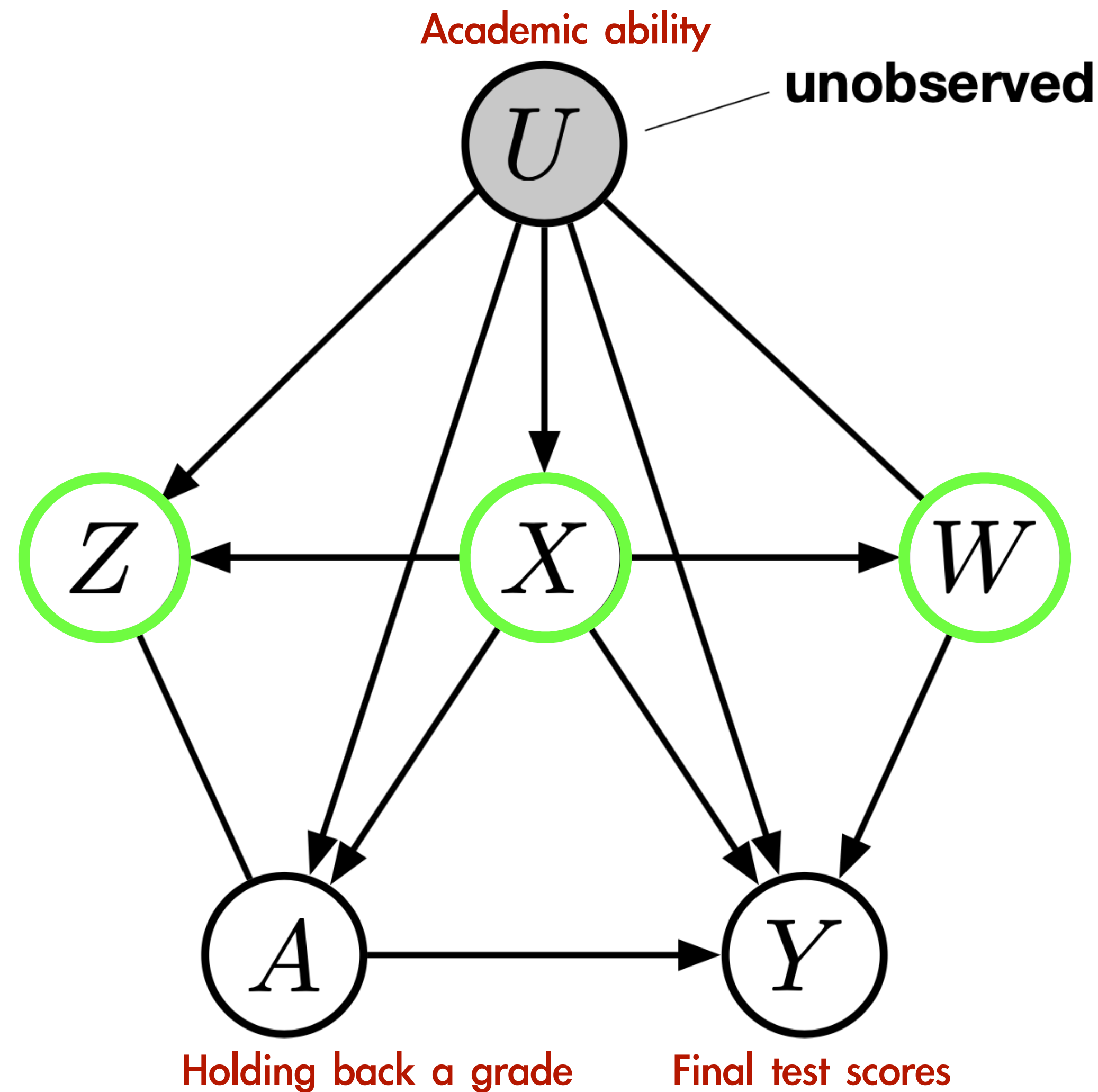
How to resolve **unobserved** confounding?



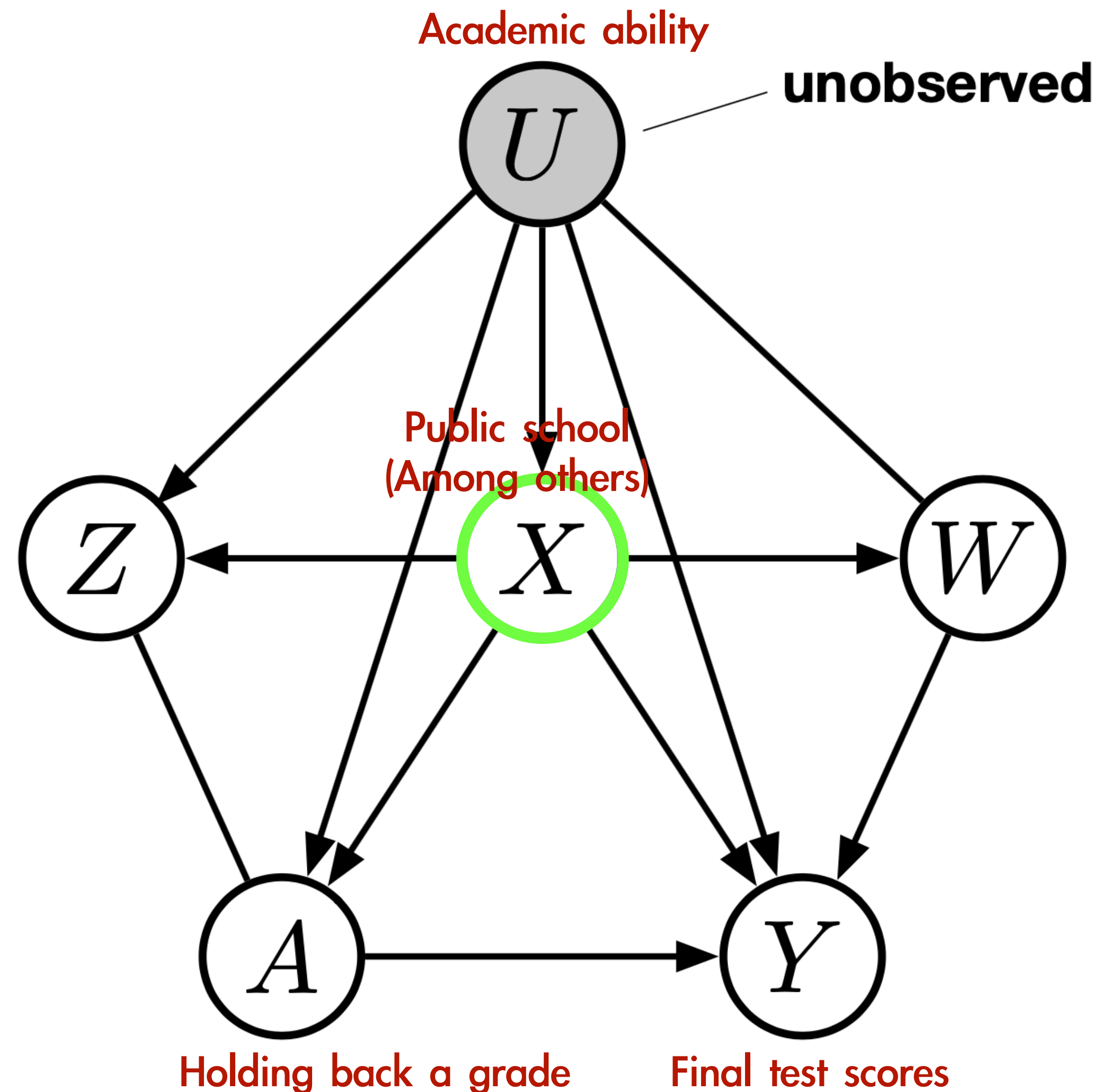
How to resolve **unobserved** confounding?



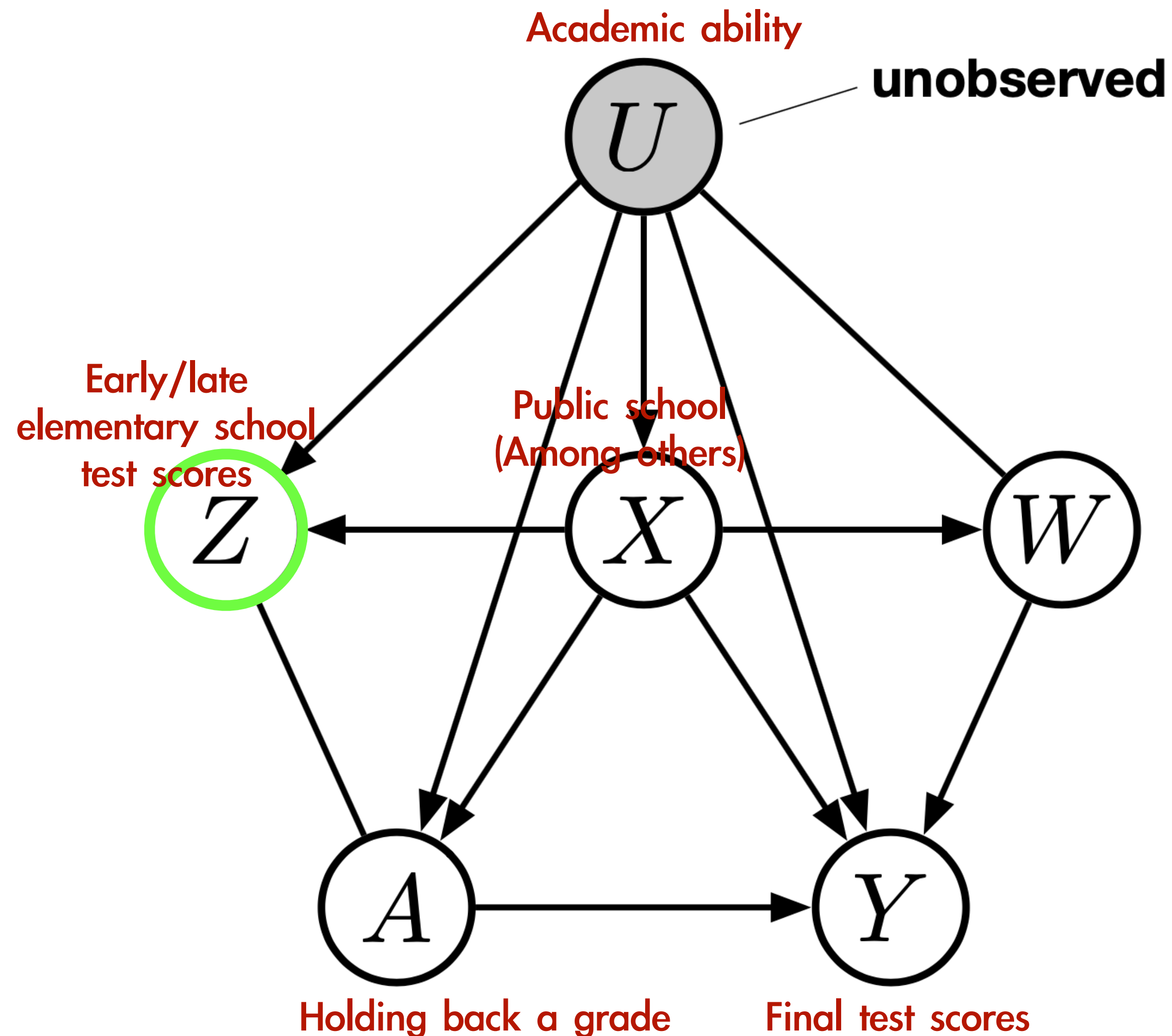
How to resolve **unobserved** confounding?



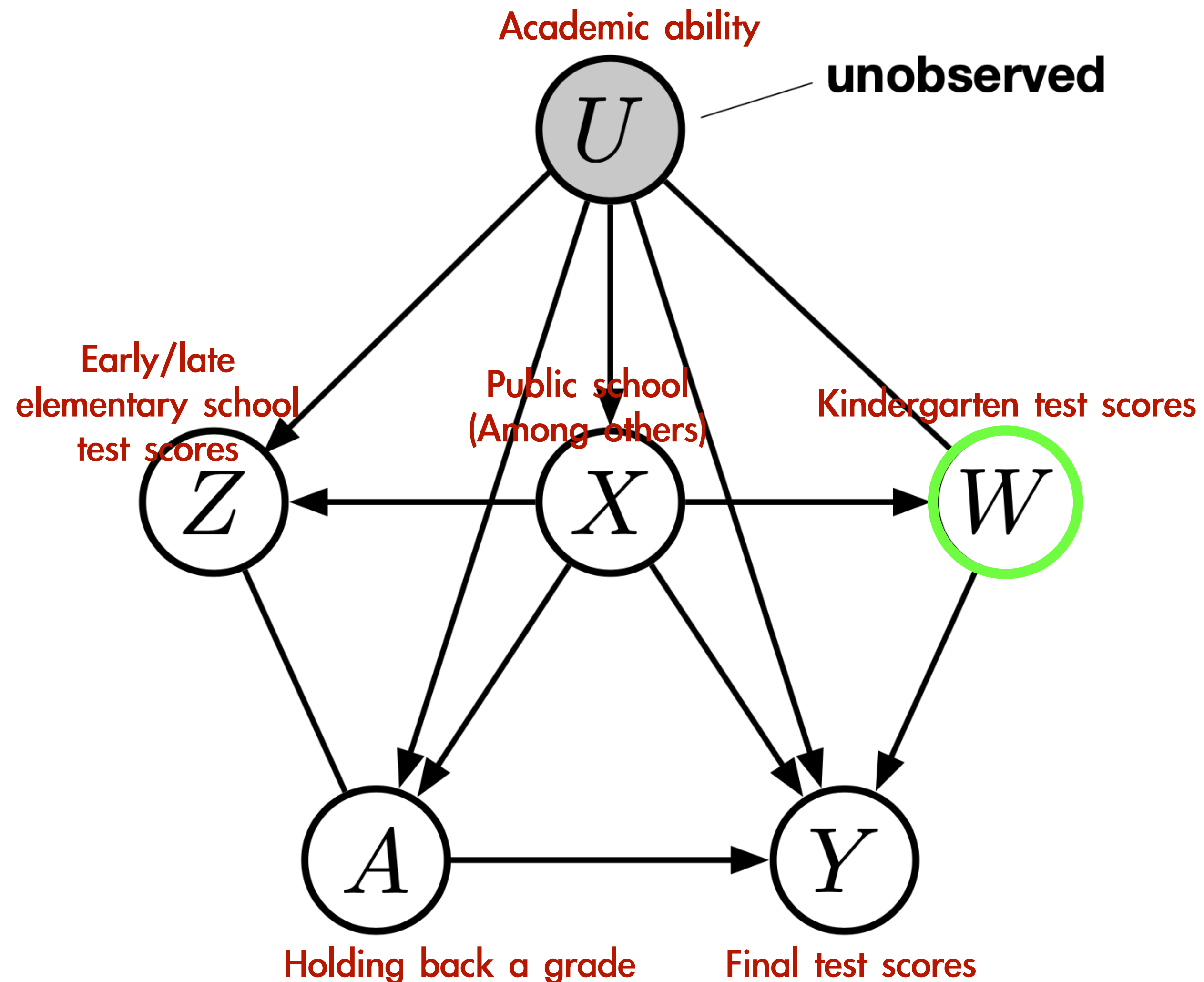
How to resolve **unobserved** confounding?



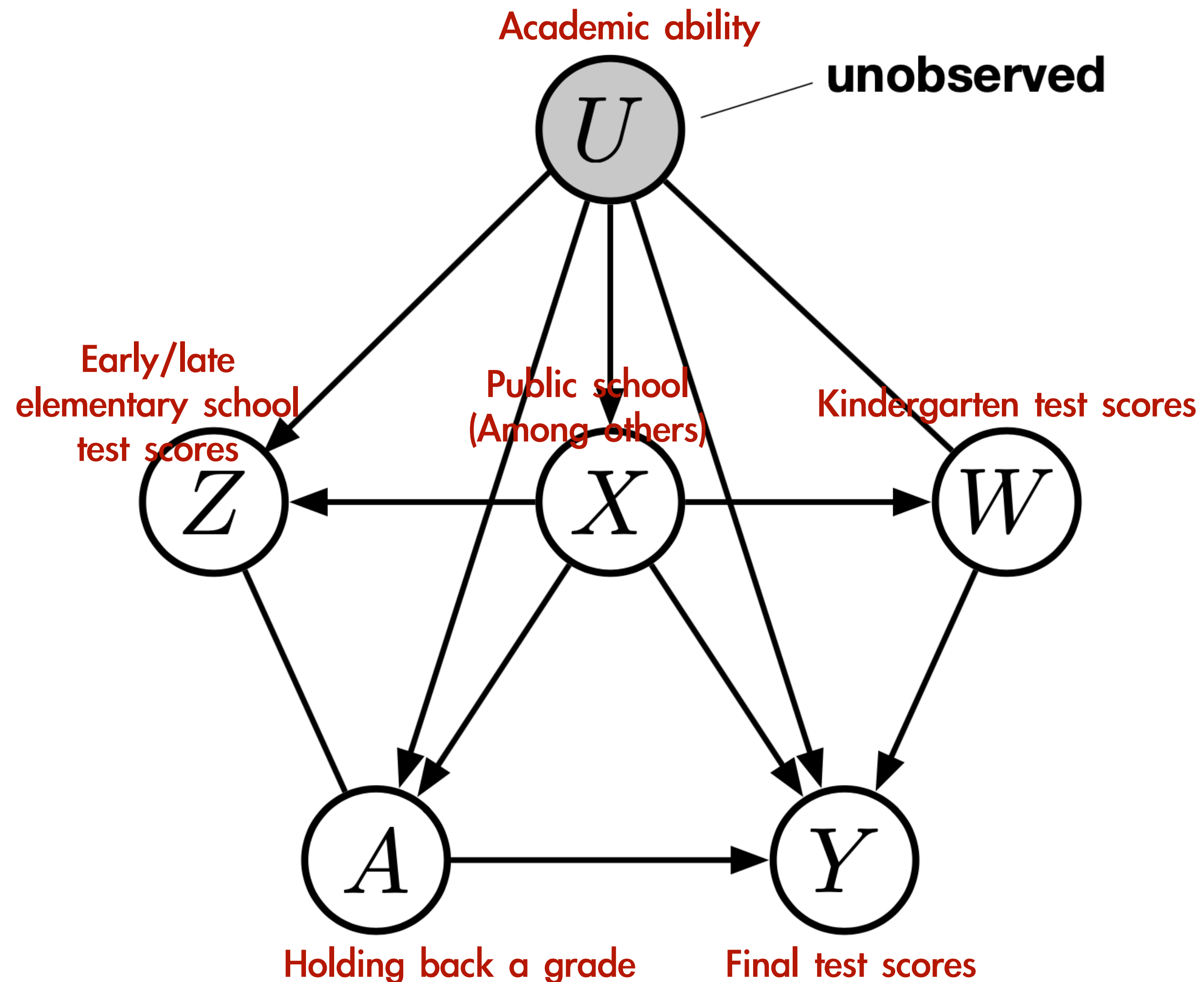
How to resolve **unobserved** confounding?



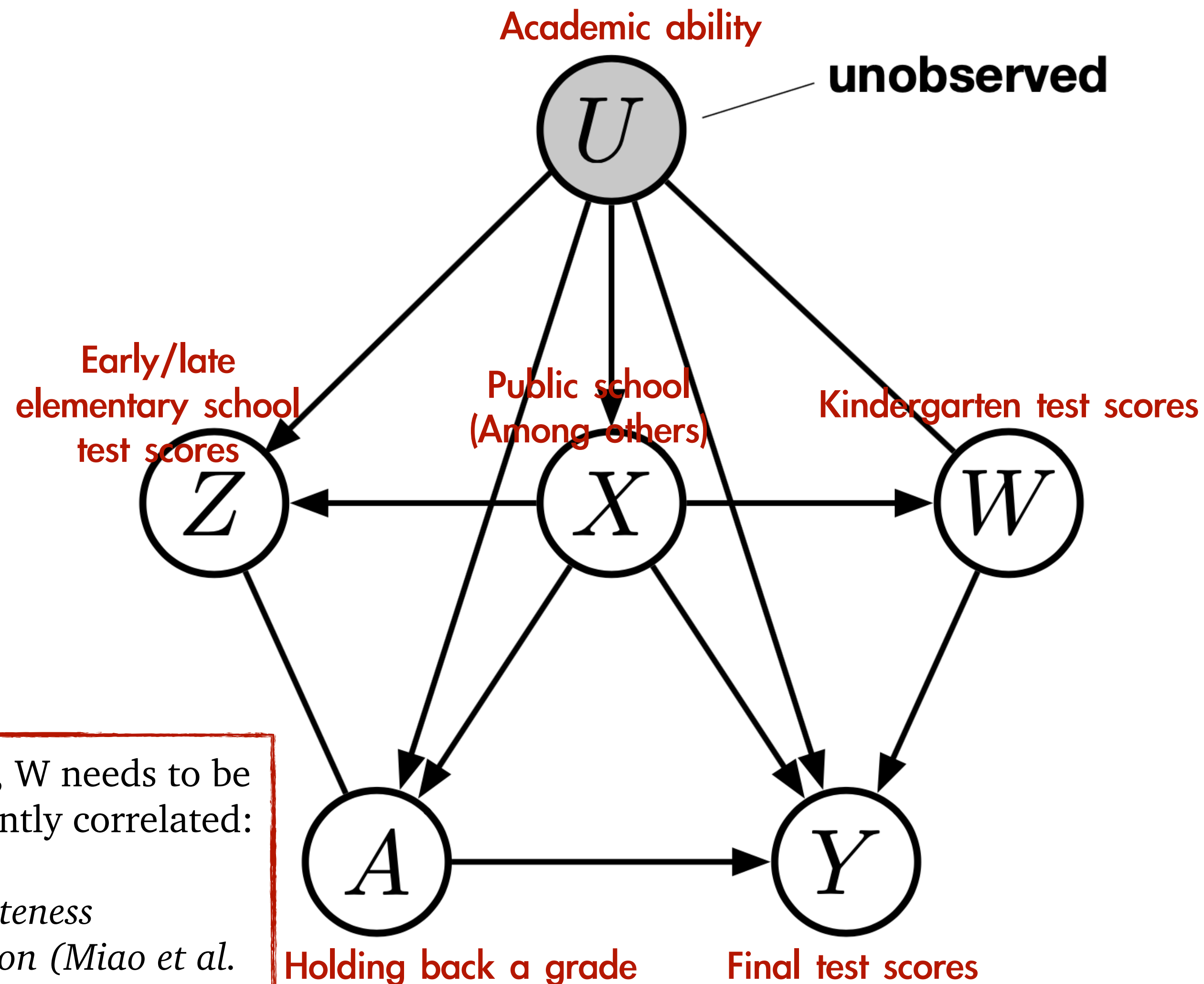
How to resolve **unobserved** confounding?



How to resolve **unobserved** confounding?



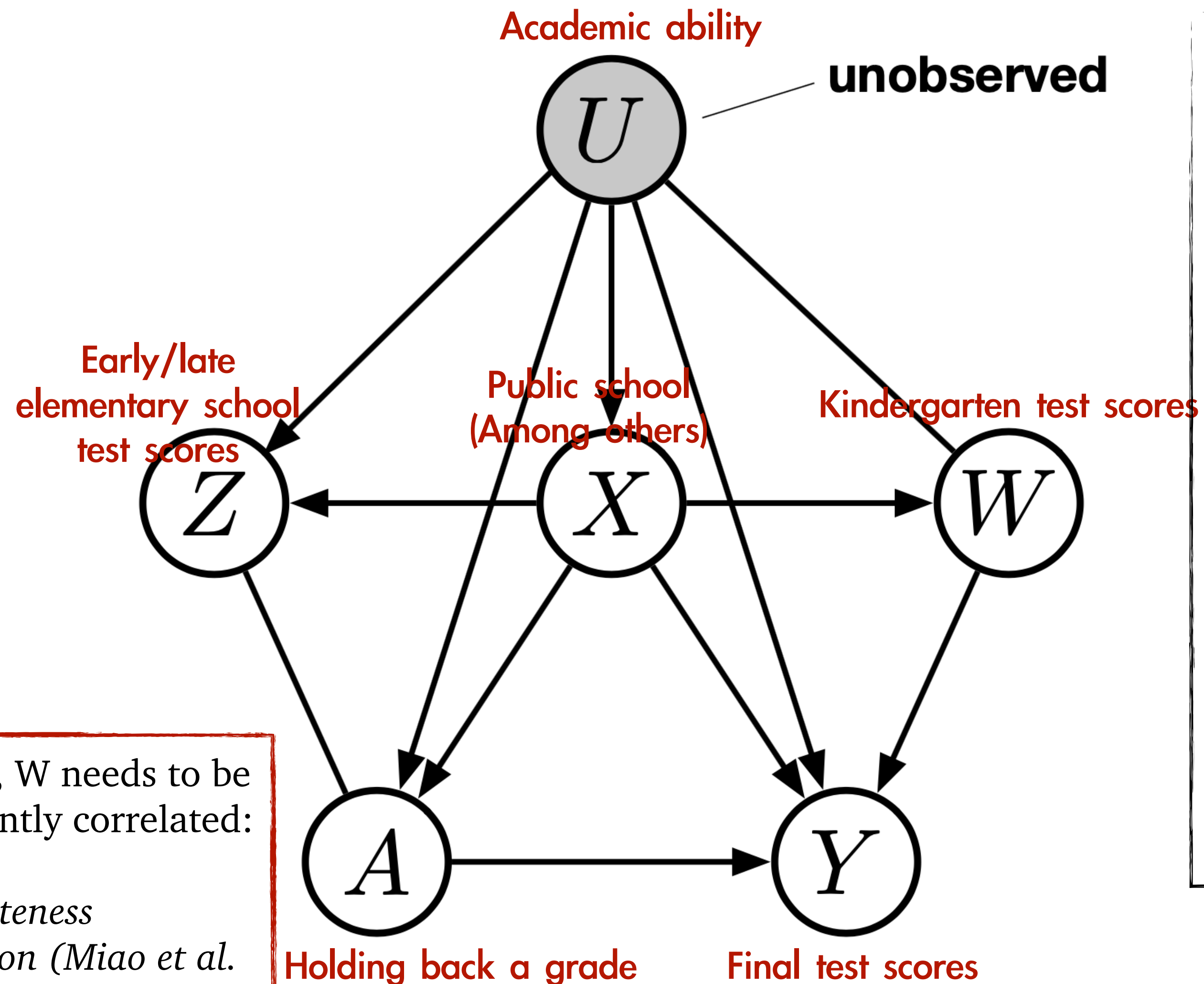
How to resolve **unobserved** confounding?



U, X, Z, W needs to be sufficiently correlated:

Completeness Condition (Miao et al. 2018)

How to resolve **unobserved** confounding?



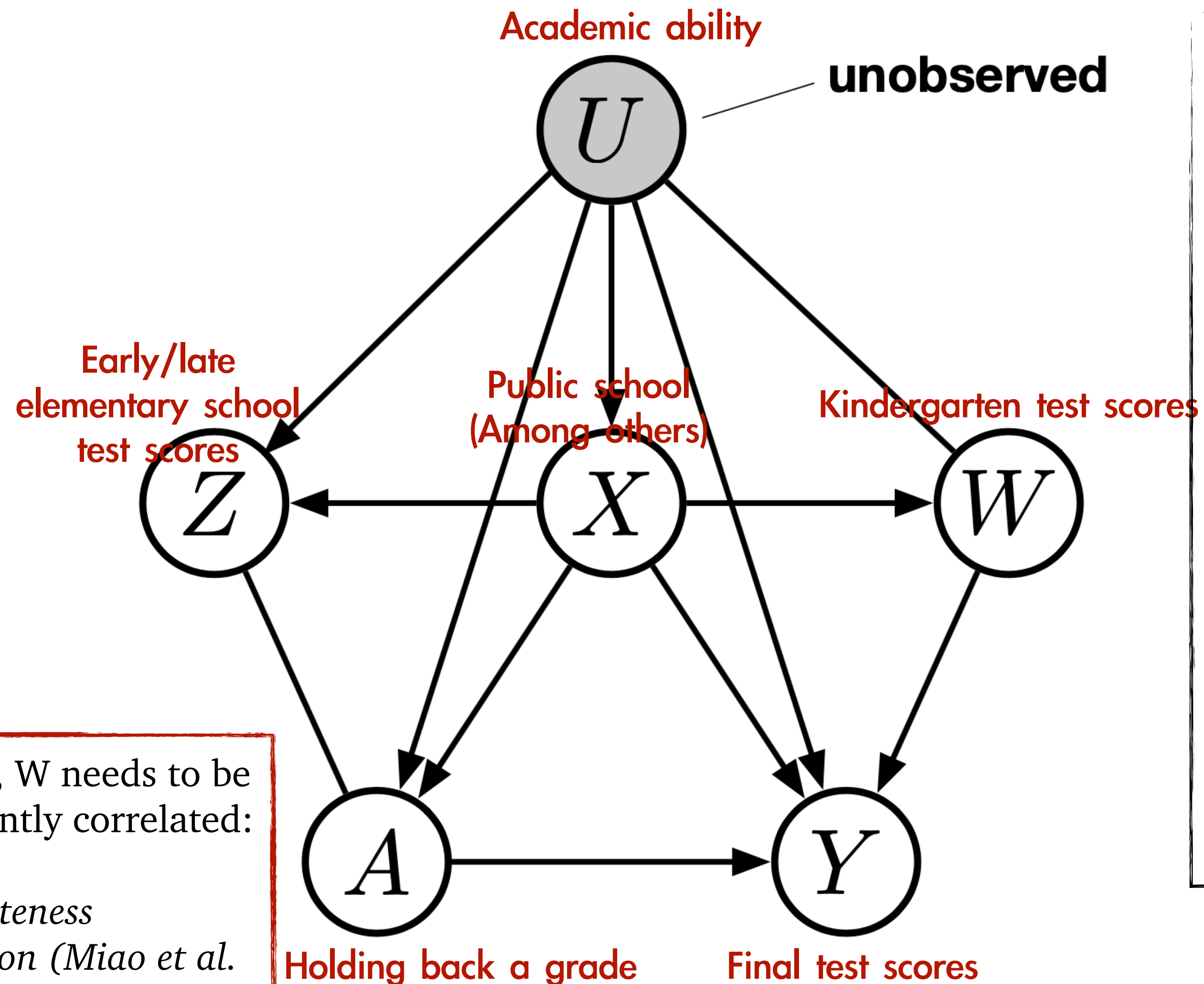
Average causal effect estimation:

$$\mathbb{E}[Y | do(A = a)] = \int_{XW} h(a, w, x) p(w, x) dx dw$$

U, X, Z, W needs to be sufficiently correlated:

Completeness
Condition (Miao et al.
2018)

How to resolve **unobserved** confounding?



Average causal effect estimation:

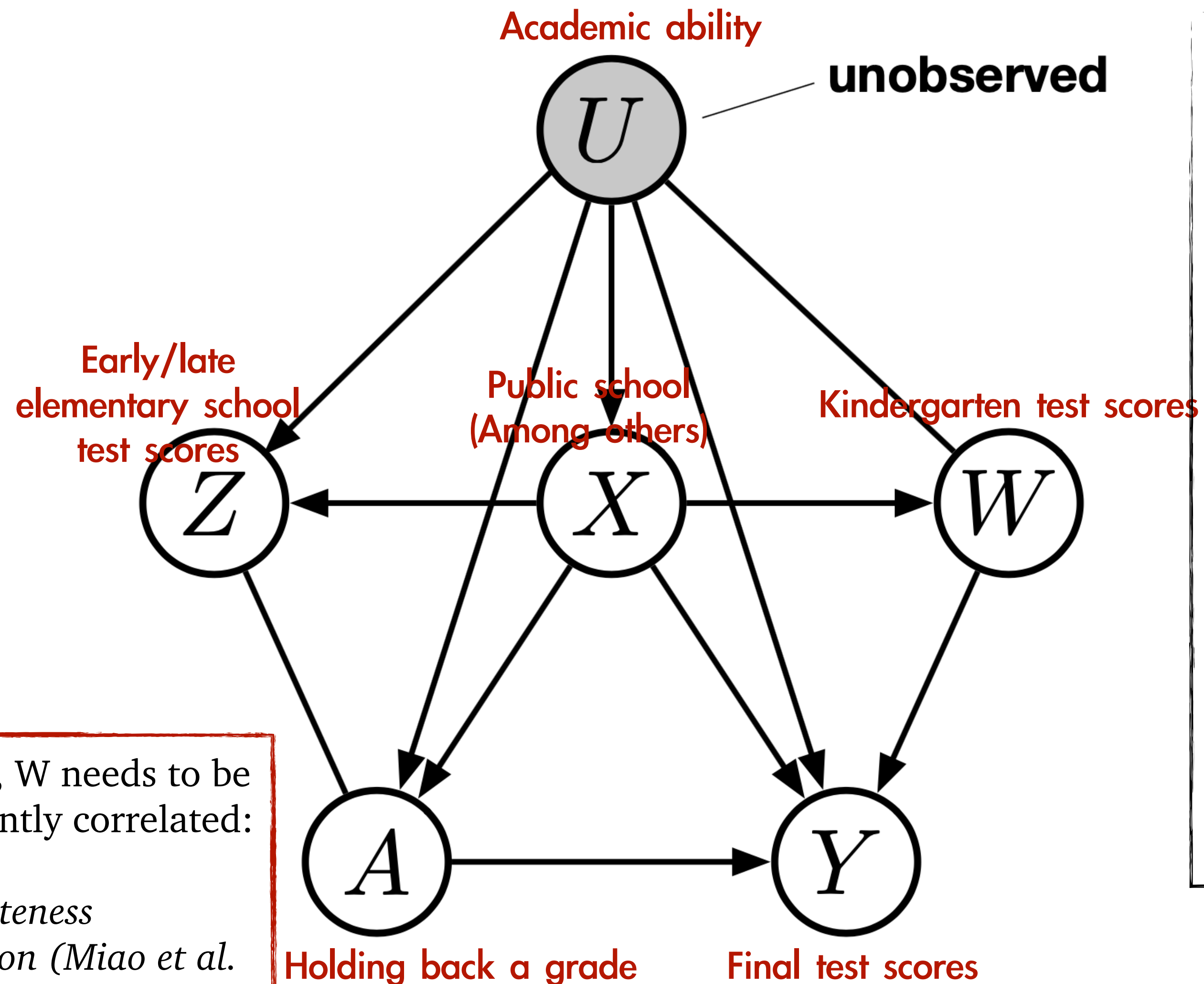
$$\mathbb{E}[Y | do(A = a)] = \int_{XW} h(a, w, x) p(w, x) dx dw$$

How to get h ?

U, X, Z, W needs to be sufficiently correlated:

Completeness Condition (Miao et al. 2018)

How to resolve **unobserved** confounding?



Average causal effect estimation:

$$\mathbb{E}[Y | do(A = a)] = \int_{XW} h(a, w, x) p(w, x) dx dw$$

How to get h ?



$$\mathbb{E}[Y - h(A, W, X) | A, Z, X] = 0 \quad \text{a.s. } P_{AZX}$$

U, X, Z, W needs to be sufficiently correlated:

Completeness
Condition (Miao et al.
2018)

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

**Proximal setting
characteristic equation**

$$\mathbb{E}[Y - h(A, X, W) | A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) | A, X, Z])^2]$$

$$\mathbb{E}[Y - h(A, X, W) | A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) | A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

$$\mathbb{E}[Y - h(A, X, W) | A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) | A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) \mid A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)} h(A, X, W))^2]$$

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) \mid A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)} h(A, X, W))^2]$$

$$R(h) \leq \tilde{R}(h)$$

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) \mid A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)} h(A, X, W))^2]$$

$$R(h) \leq \tilde{R}(h)$$

$$\text{Stage1} : (A, X, Z) \xrightarrow{f} \phi(W)$$

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) \mid A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)} h(A, X, W))^2]$$

$$R(h) \leq \tilde{R}(h)$$

$$\text{Stage1} : (A, X, Z) \xrightarrow{f} \phi(W)$$

$$\text{Stage2} : \mathbb{E}_{W|A,X,Z} h(A, X, W) = \gamma(A, X, Z)$$

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) \mid A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)} h(A, X, W))^2]$$

$$R(h) \leq \tilde{R}(h)$$

$$\text{Stage1} : (A, X, Z) \xrightarrow{f} \phi(W)$$

$$\text{Stage2} : \mathbb{E}_{W|A,X,Z} h(A, X, W) = \gamma(A, X, Z)$$

Proxy Maximum Moment Restriction(PMMR)

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

characteristic equation

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) \mid A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)} h(A, X, W))^2]$$

$$R(h) \leq \tilde{R}(h)$$

$$\text{Stage1} : (A, X, Z) \xrightarrow{f} \phi(W)$$

$$\text{Stage2} : \mathbb{E}_{W|A,X,Z} h(A, X, W) = \gamma(A, X, Z)$$

Proxy Maximum Moment Restriction(PMMR)

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

characteristic equation



$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) \mid A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)} h(A, X, W))^2]$$

$$R(h) \leq \tilde{R}(h)$$

$$\text{Stage1} : (A, X, Z) \xrightarrow{f} \phi(W)$$

$$\text{Stage2} : \mathbb{E}_{W|A,X,Z} h(A, X, W) = \gamma(A, X, Z)$$

Proxy Maximum Moment Restriction(PMMR)

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

characteristic equation



$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) \mid A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)} h(A, X, W))^2]$$

$$R(h) \leq \tilde{R}(h)$$

$$\text{Stage1} : (A, X, Z) \xrightarrow{f} \phi(W)$$

$$\text{Stage2} : \mathbb{E}_{W|A,X,Z} h(A, X, W) = \gamma(A, X, Z)$$

Proxy Maximum Moment Restriction(PMMR)

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

characteristic equation



CMR

$$\mathbb{E}[(Y - h(A, X, W))k((A, X, Z), \cdot)] = 0 \quad \text{a.s. } P_{AXZ}$$

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) \mid A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)} h(A, X, W))^2]$$

$$R(h) \leq \tilde{R}(h)$$

$$\text{Stage1} : (A, X, Z) \xrightarrow{f} \phi(W)$$

$$\text{Stage2} : \mathbb{E}_{W|A,X,Z} h(A, X, W) = \gamma(A, X, Z)$$

Proxy Maximum Moment Restriction(PMMR)

$$\mathbb{E}[Y - h(A, X, W) \mid A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

characteristic equation



CMR

$$\mathbb{E}[(Y - h(A, X, W))k((A, X, Z), \cdot)] = 0 \quad \text{a.s. } P_{AXZ}$$

$$\mathbb{E}[Y - h(A, X, W) | A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) | A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)}h(A, X, W))^2]$$

$$R(h) \leq \tilde{R}(h)$$

$$\text{Stage1} : (A, X, Z) \xrightarrow{f} \phi(W)$$

$$\text{Stage2} : \mathbb{E}_{W|A,X,Z}h(A, X, W) = \gamma(A, X, Z)$$

Proxy Maximum Moment Restriction(PMMR)

$$\mathbb{E}[Y - h(A, X, W) | A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

characteristic equation



CMR

$$\mathbb{E}[(Y - h(A, X, W))k((A, X, Z), \cdot)] = 0 \quad \text{a.s. } P_{AXZ}$$

PMMR surrogate loss $R_k(h)$

$$R_k(h) = \| \mathbb{E}[(Y - h(A, W, X))k((A, Z, X), \cdot)] \|_{\mathcal{H}_{AXZ}}^2$$

$$\arg \min R(h) = \arg \min R_k(h)$$

$$\mathbb{E}[Y - h(A, X, W) | A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

Proximal setting
characteristic equation

True Loss

$$\min_h R(h) := \mathbb{E}_{AXZ}[(\mathbb{E}[Y - h(A, X, W) | A, X, Z])^2]$$

Kernel Proxy Variable (KPV)

KPV surrogate loss

$$\tilde{R}(h) := \mathbb{E}_{AXYZ}[(Y - \mathbb{E}_{W|(A,X,Z)} h(A, X, W))^2]$$

$$R(h) \leq \tilde{R}(h)$$

$$\text{Stage1} : (A, X, Z) \xrightarrow{f} \phi(W)$$

$$\text{Stage2} : \mathbb{E}_{W|A,X,Z} h(A, X, W) = \gamma(A, X, Z)$$

Proxy Maximum Moment Restriction(PMMR)

$$\mathbb{E}[Y - h(A, X, W) | A, X, Z] = 0 \quad \text{a.s. } P_{AXZ}$$

characteristic equation



CMR

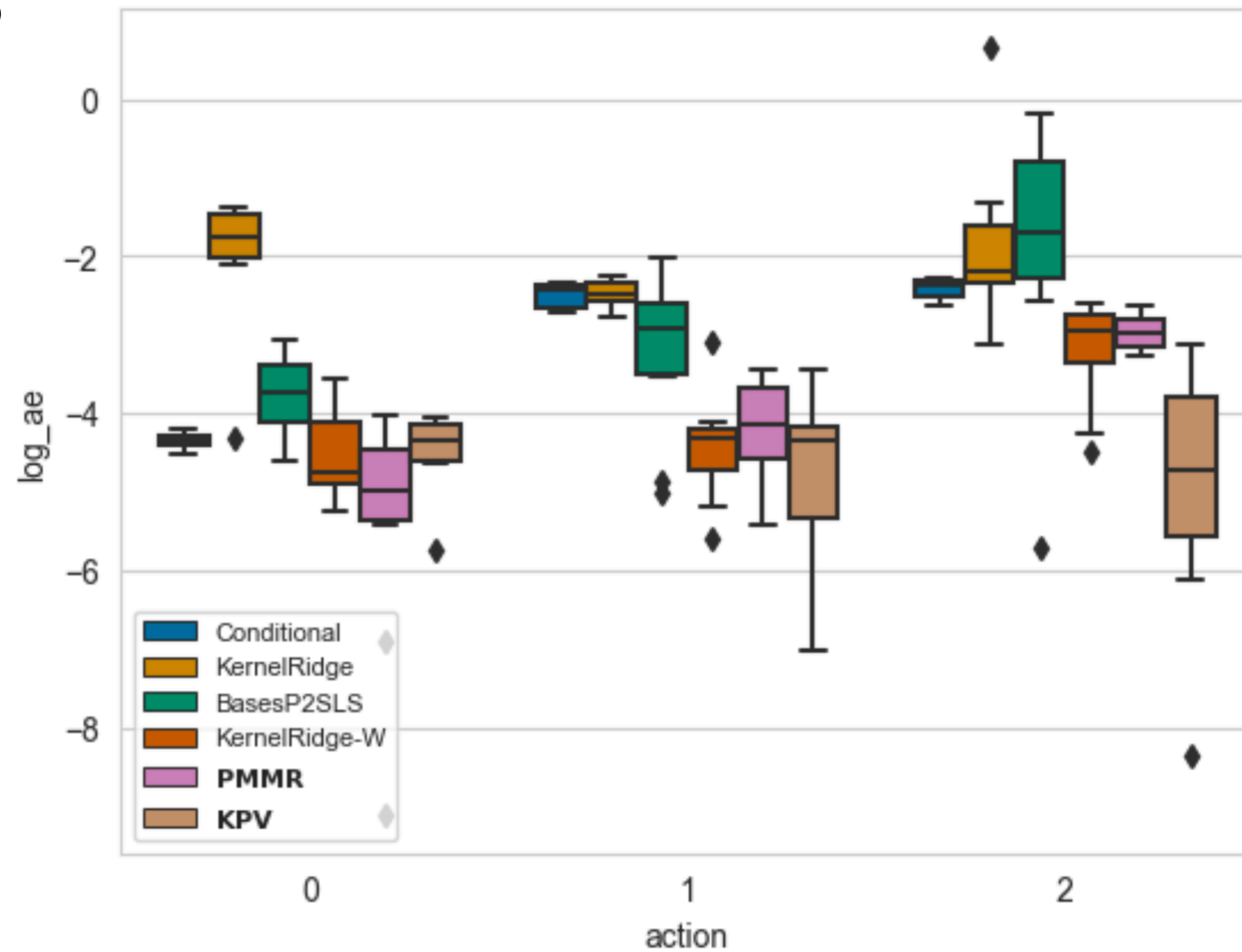
$$\mathbb{E}[(Y - h(A, X, W))k((A, X, Z), \cdot)] = 0 \quad \text{a.s. } P_{AXZ}$$

PMMR surrogate loss $R_k(h)$

$$R_k(h) = \| \mathbb{E}[(Y - h(A, W, X))k((A, Z, X), \cdot)] \|_{\mathcal{H}_{AXZ}}^2$$

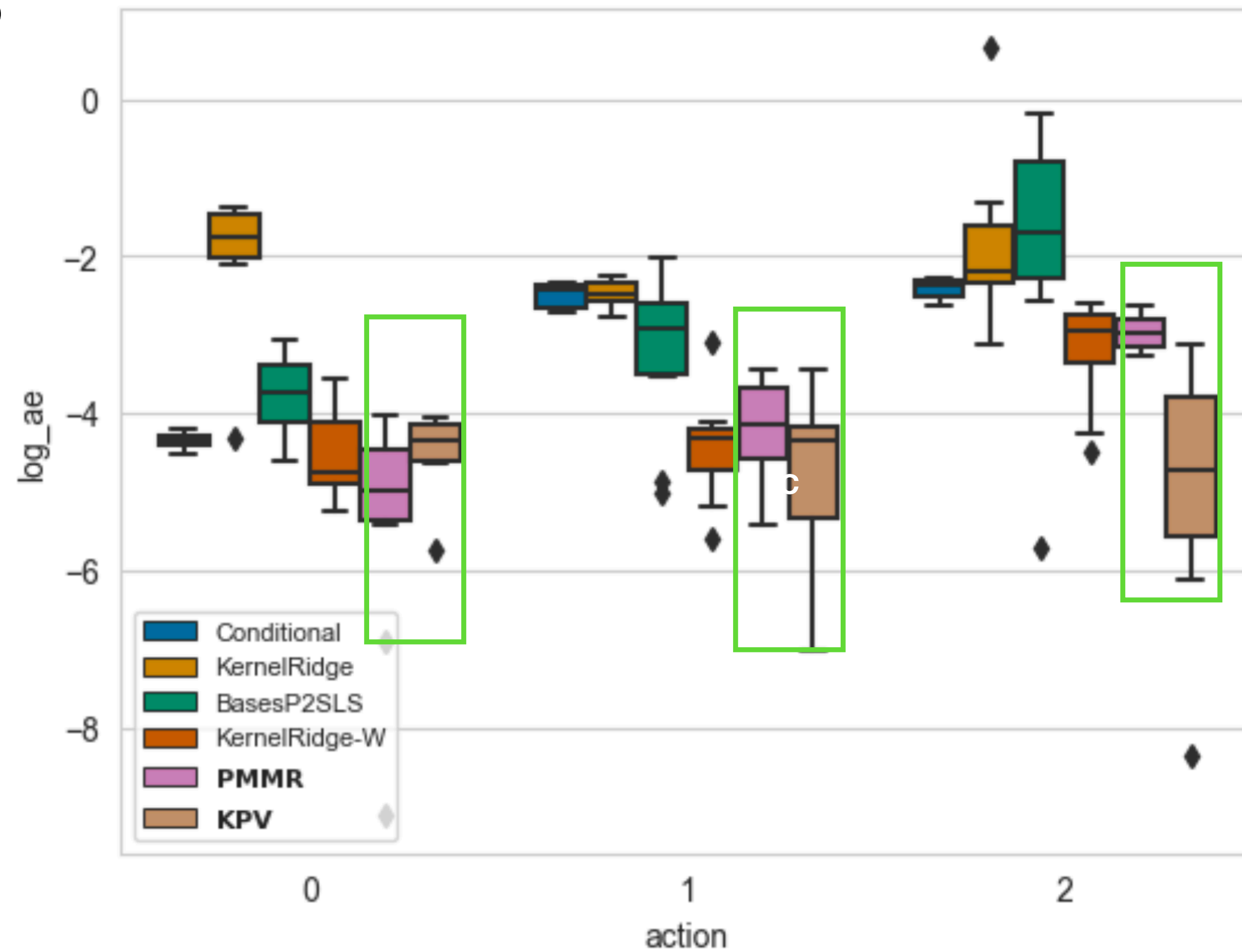
$$\arg \min R(h) = \arg \min R_k(h)$$

Results



Y: maths score

Results



Y: maths score