

Lasso Regression: Regularization for feature selection

Emily Fox & Carlos Guestrin
Machine Learning Specialization
University of Washington

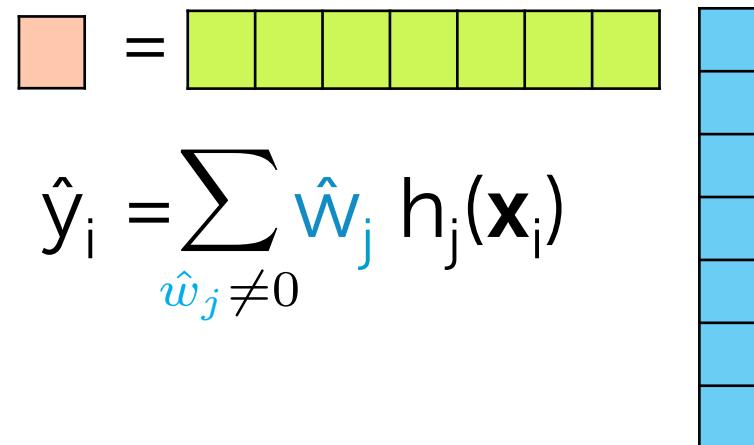
Feature selection task

Why might you want to perform feature selection?

Efficiency:

- If $\text{size}(\mathbf{w}) = 100B$, each prediction is expensive
- If $\hat{\mathbf{w}}$ sparse, computation only depends on # of non-zeros

many zeros

$$\hat{y}_i = \sum_{\hat{w}_j \neq 0} \hat{w}_j h_j(\mathbf{x}_i)$$


Interpretability:

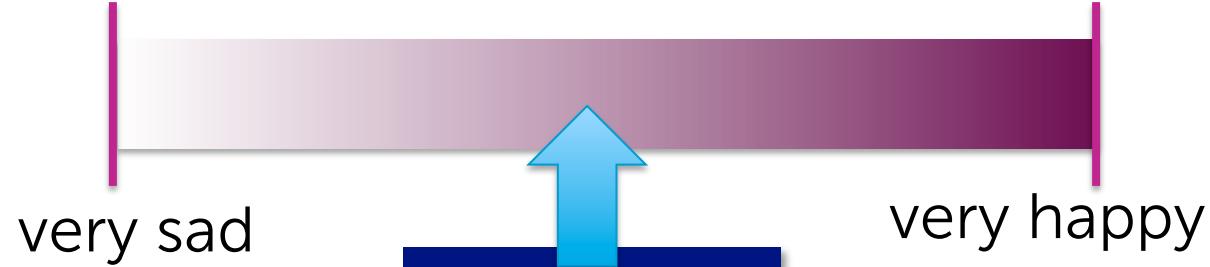
- Which features are relevant for prediction?

Sparsity: Housing application



Lot size	Dishwasher
Single Family	Garbage disposal
Year built	Microwave
Last sold price	Range / Oven
Last sale price/sqft	Refrigerator
Finished sqft	Washer
Unfinished sqft	Dryer
Finished basement sqft	Laundry location
# floors	Heating type
Flooring types	Jetted Tub
Parking type	Deck
Parking amount	Fenced Yard
Cooling	Lawn
Heating	Garden
Exterior materials	Sprinkler System
Roof type	:
Structure style	

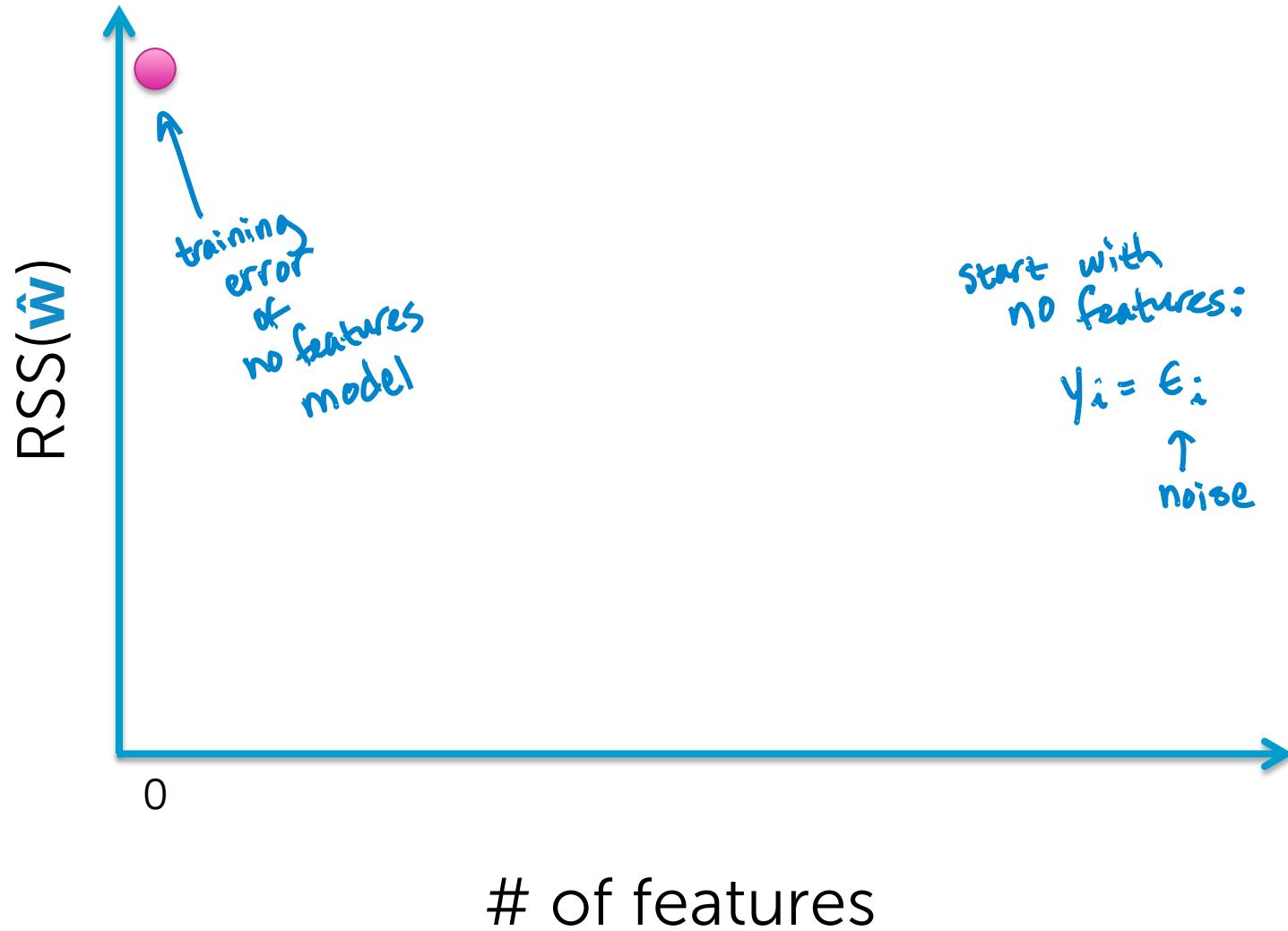
Sparsity: Reading your mind



Activity in which
brain regions
can predict
happiness?

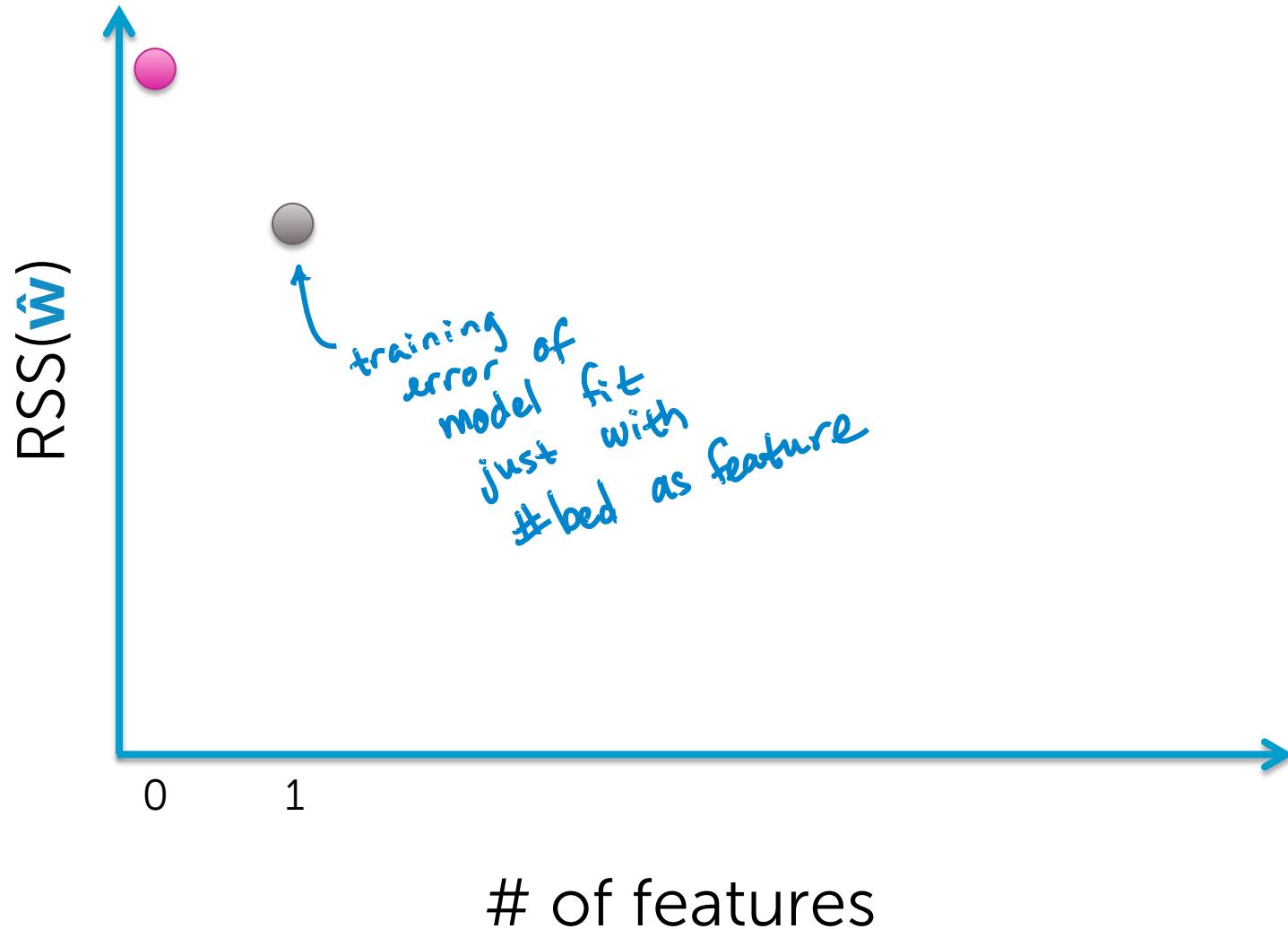
Option 1: All subsets

Find best model of size: 0



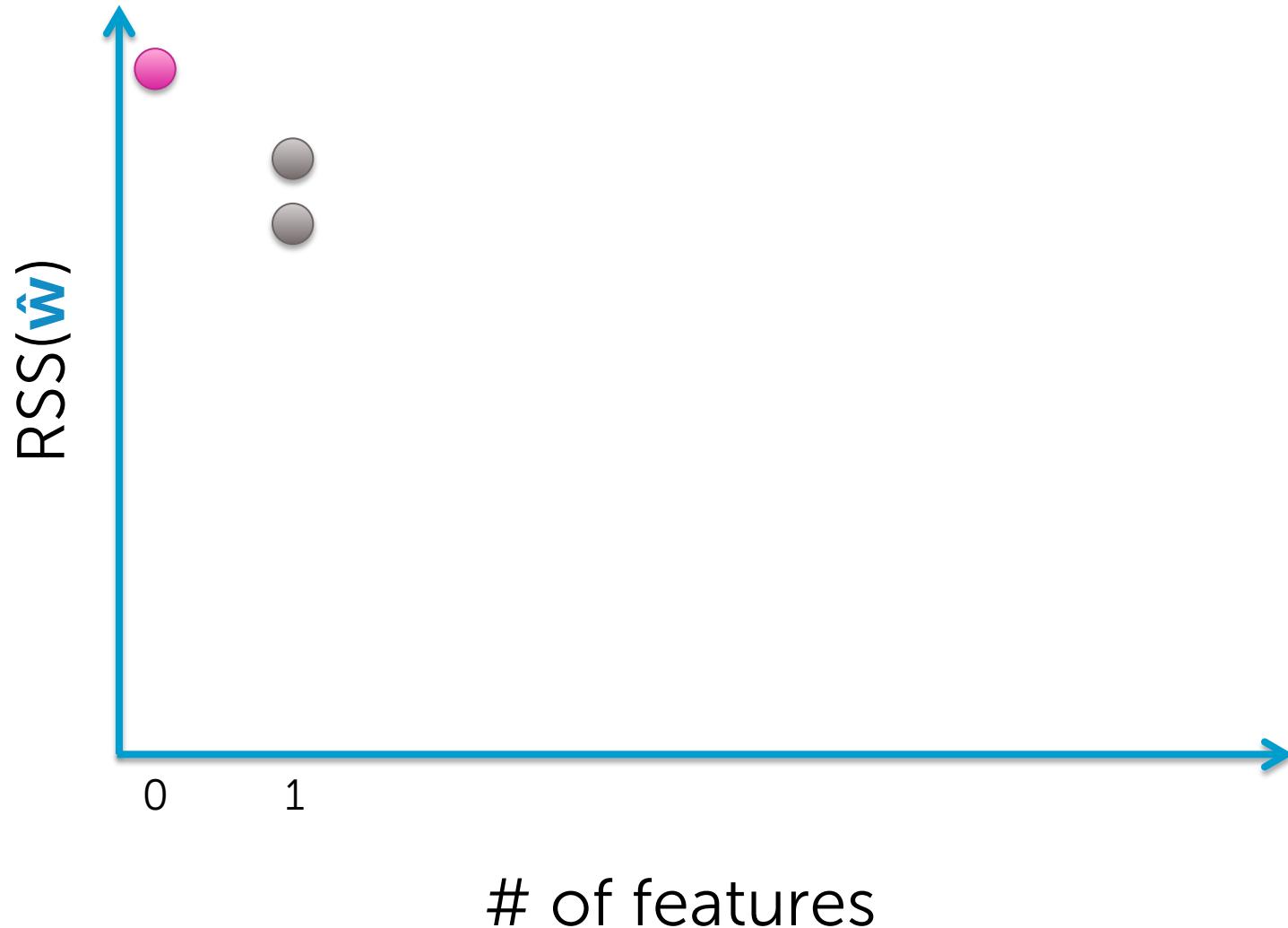
- ~~- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront~~

Find best model of size: 1



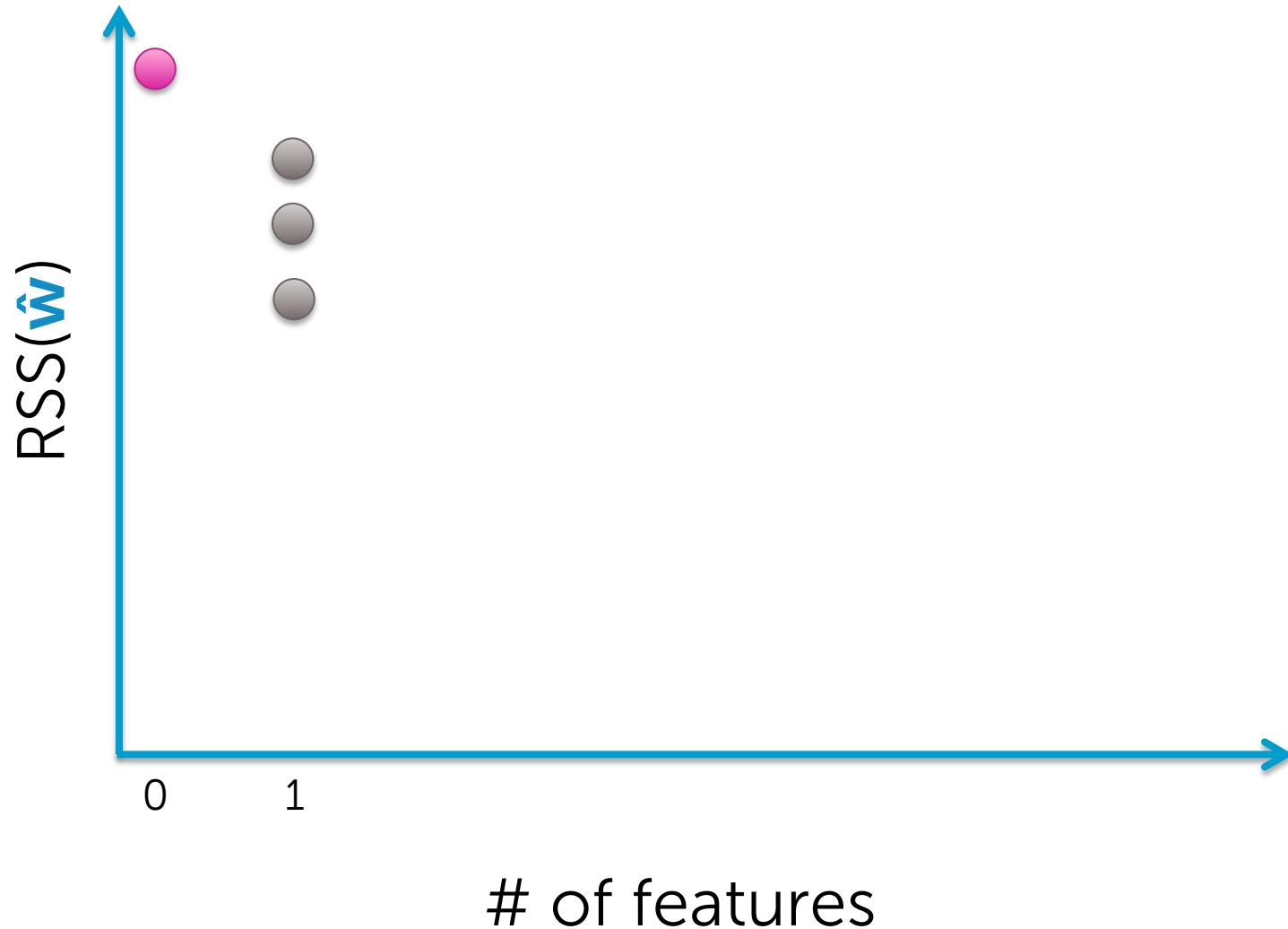
- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

Find best model of size: 1



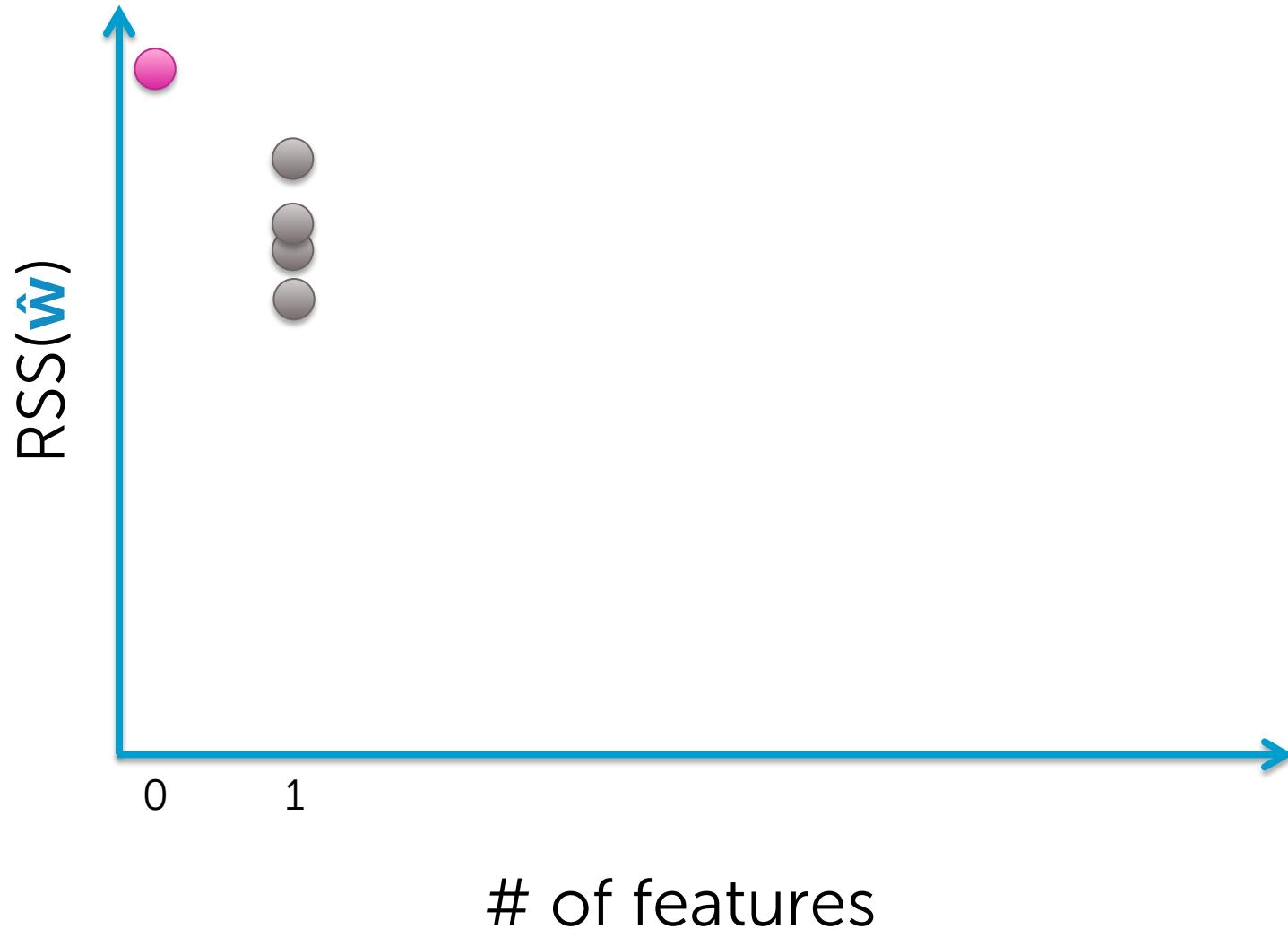
- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

Find best model of size: 1



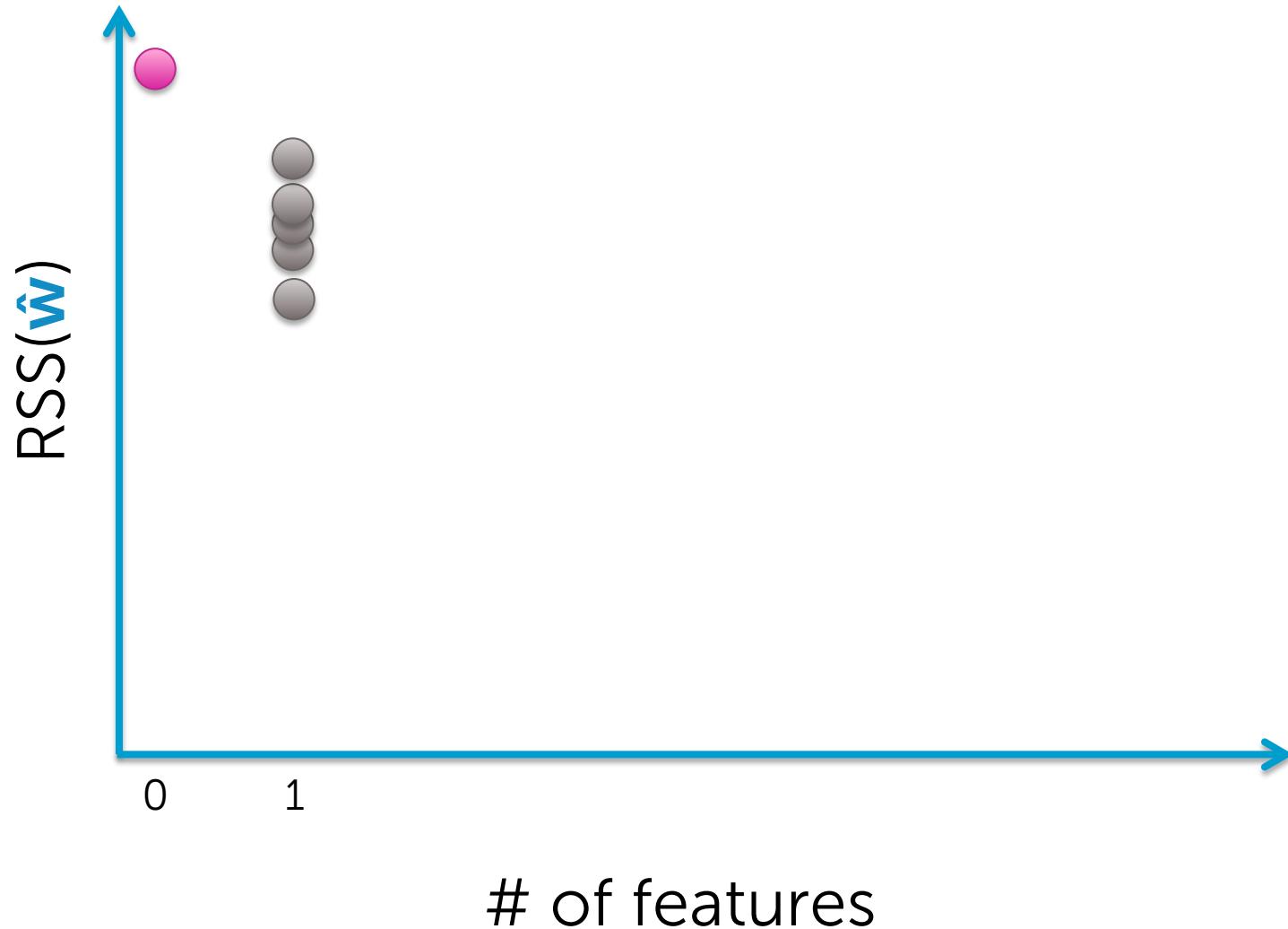
- # bedrooms
- # bathrooms
- *sq.ft. living*
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

Find best model of size: 1



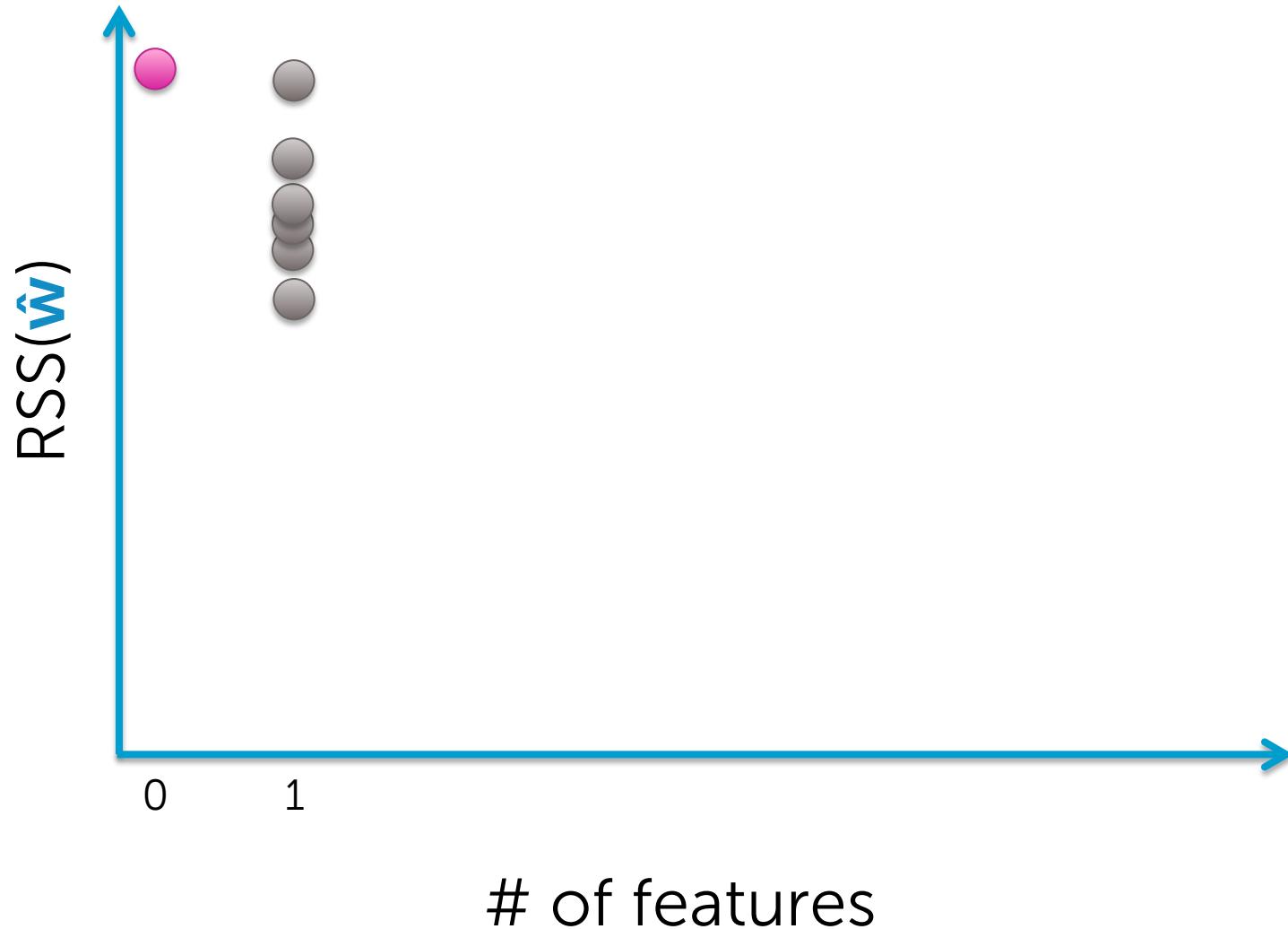
- # bedrooms
- # bathrooms
- sq.ft. living
- **sq.ft. lot**
- floors
- year built
- year renovated
- waterfront

Find best model of size: 1



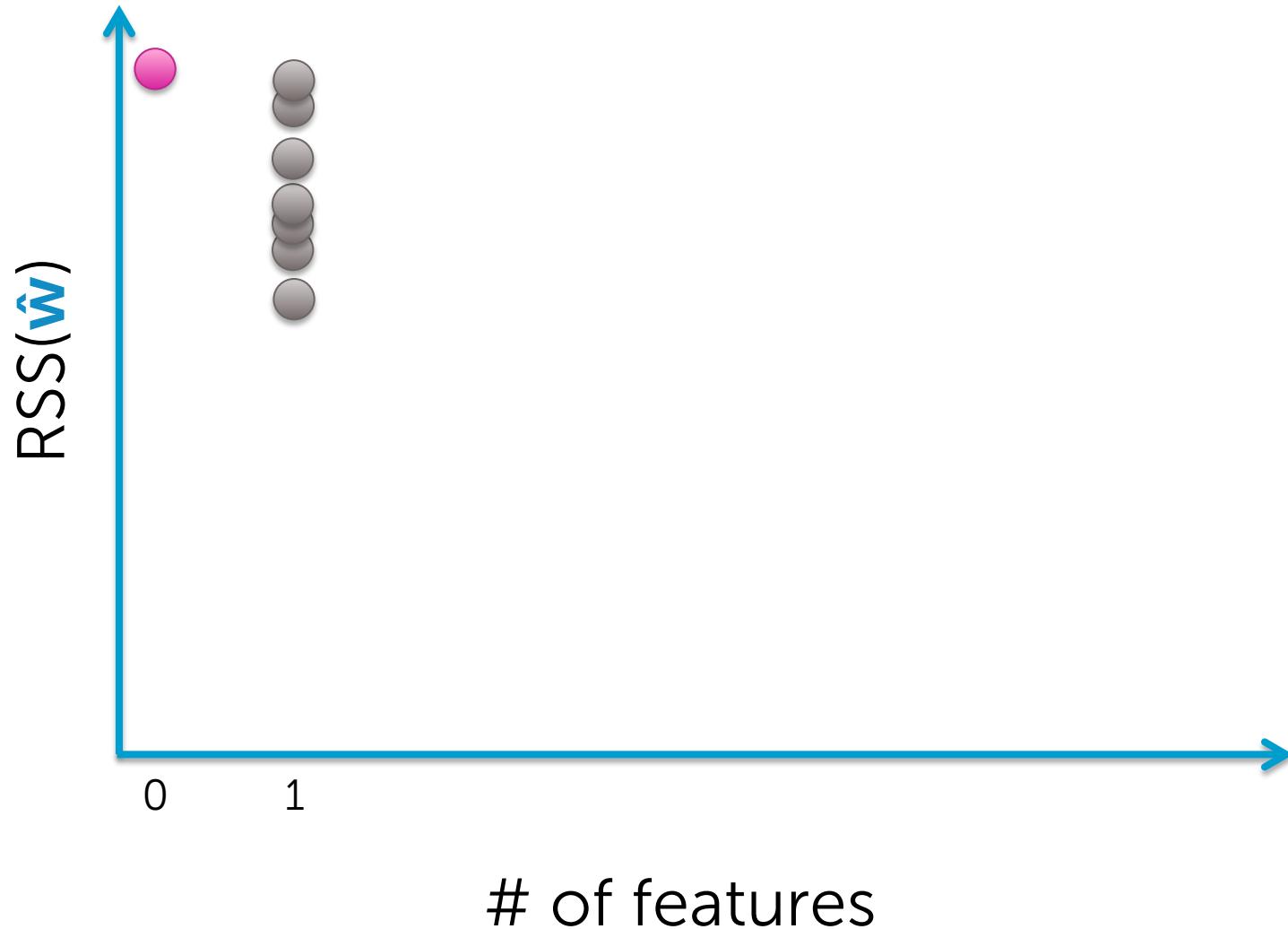
- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

Find best model of size: 1



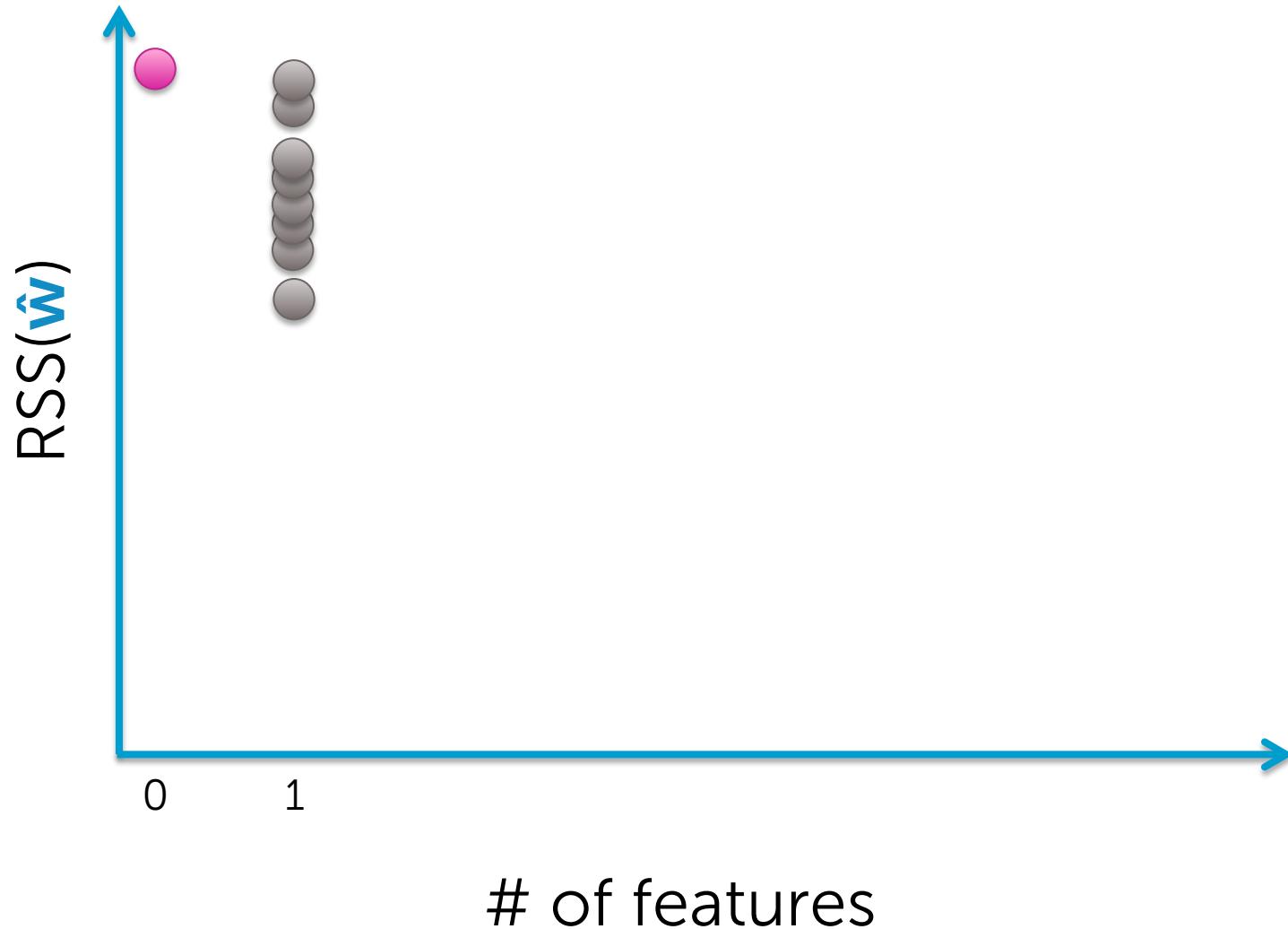
- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- **year built**
- year renovated
- waterfront

Find best model of size: 1



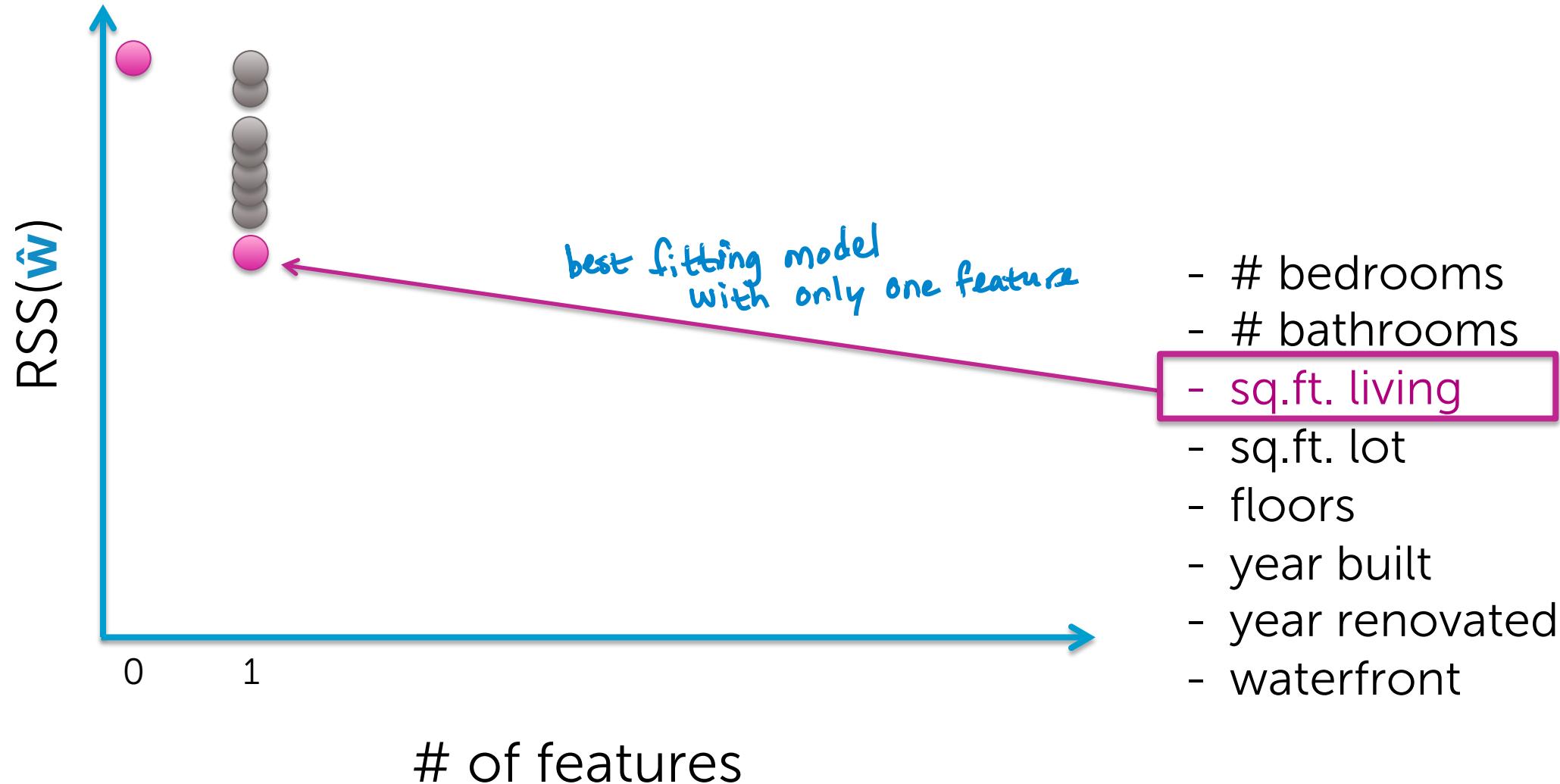
- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- **year renovated**
- waterfront

Find best model of size: 1

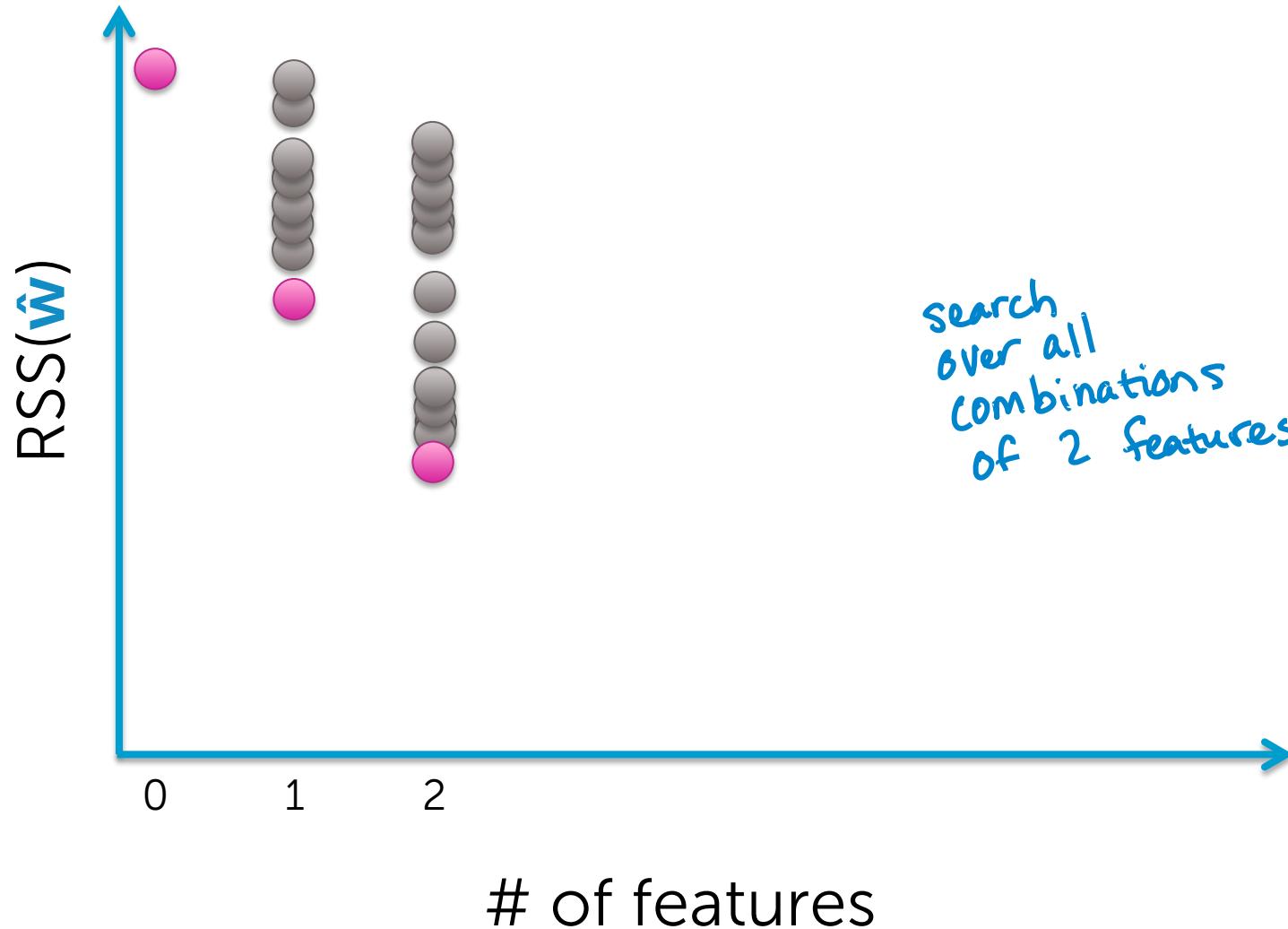


- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- **waterfront**

Find best model of size: 1

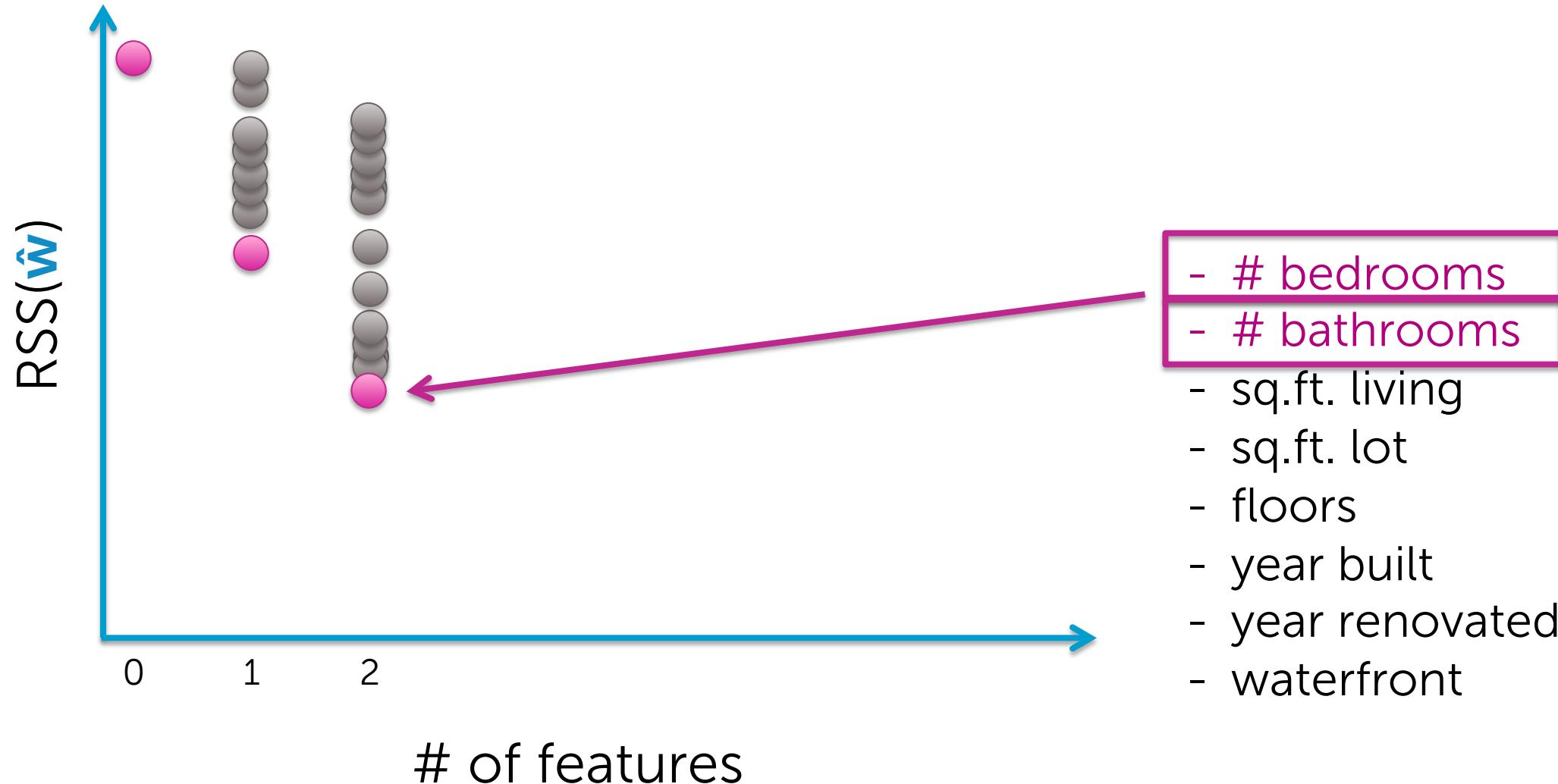


Find best model of size: 2

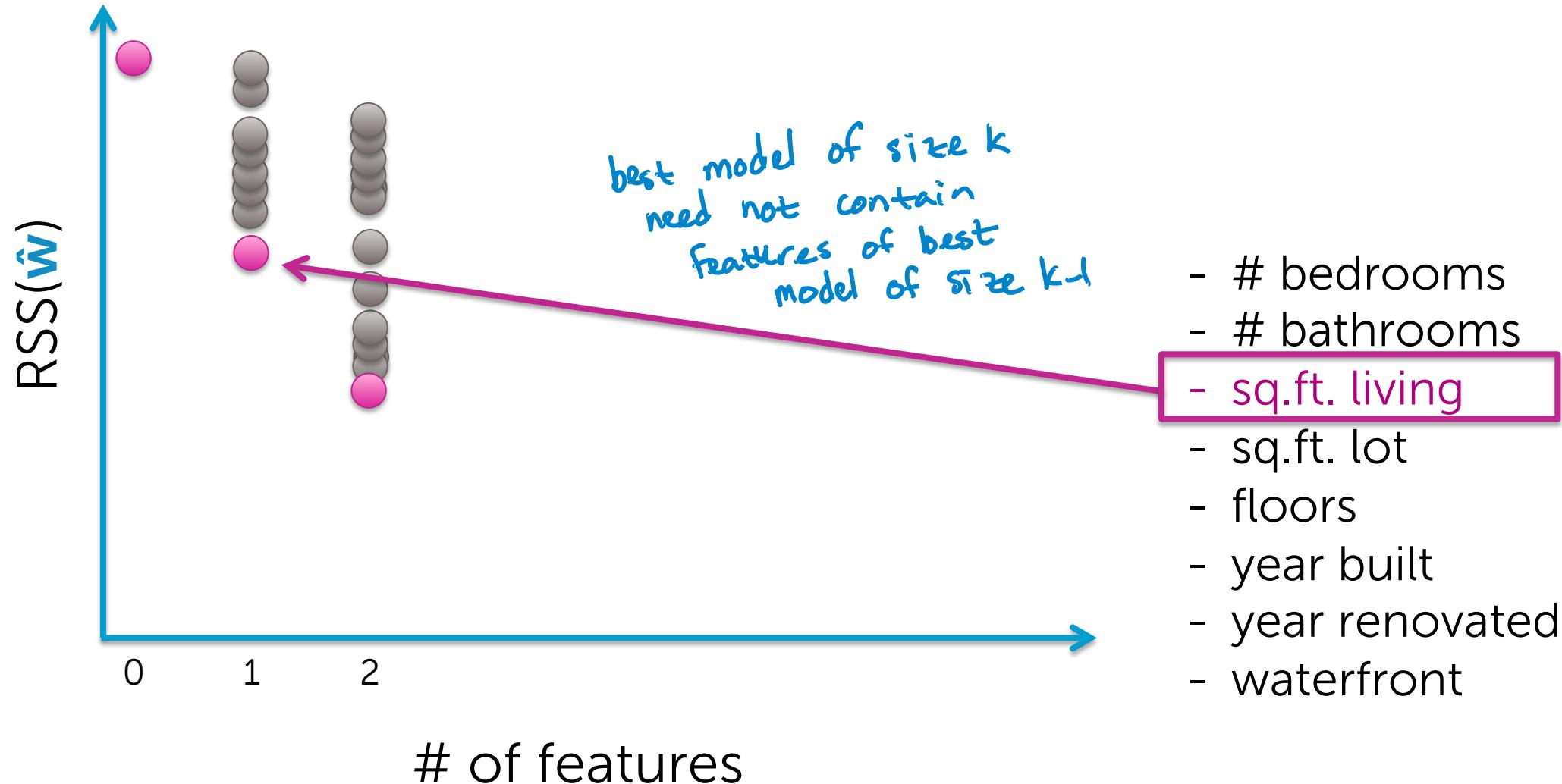


- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

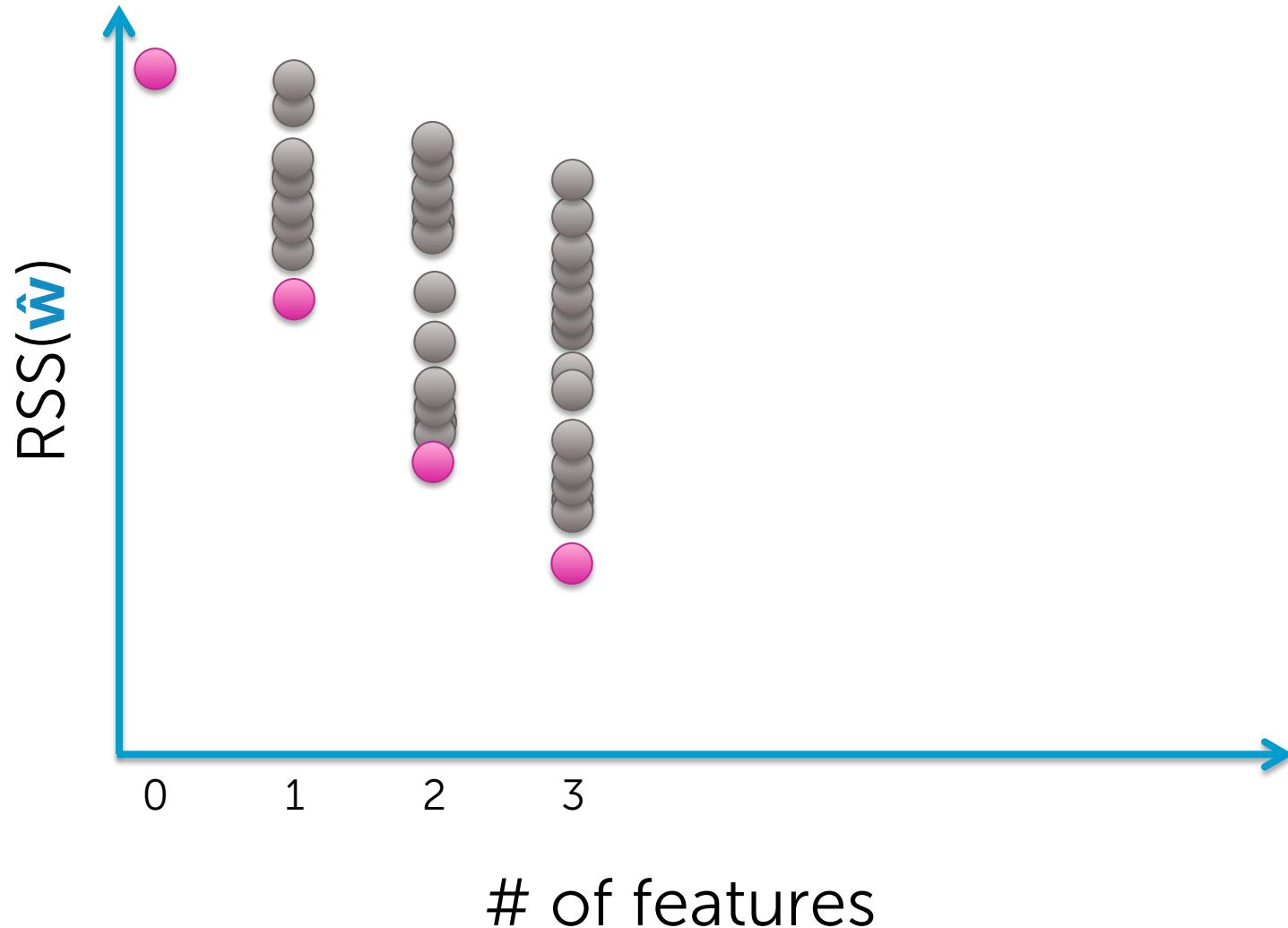
Note: Not necessarily nested!



Note: Not necessarily nested!

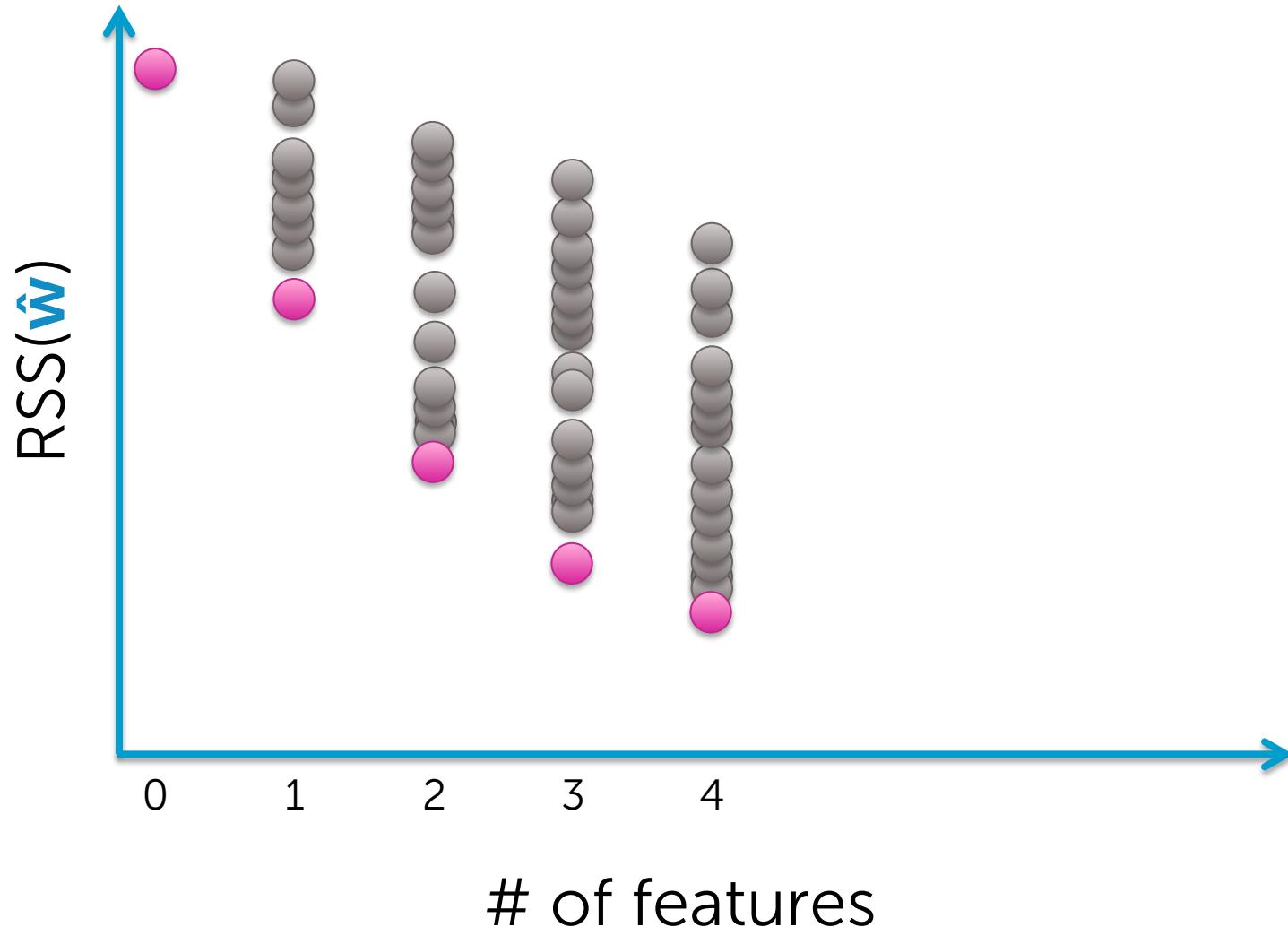


Find best model of size: 3



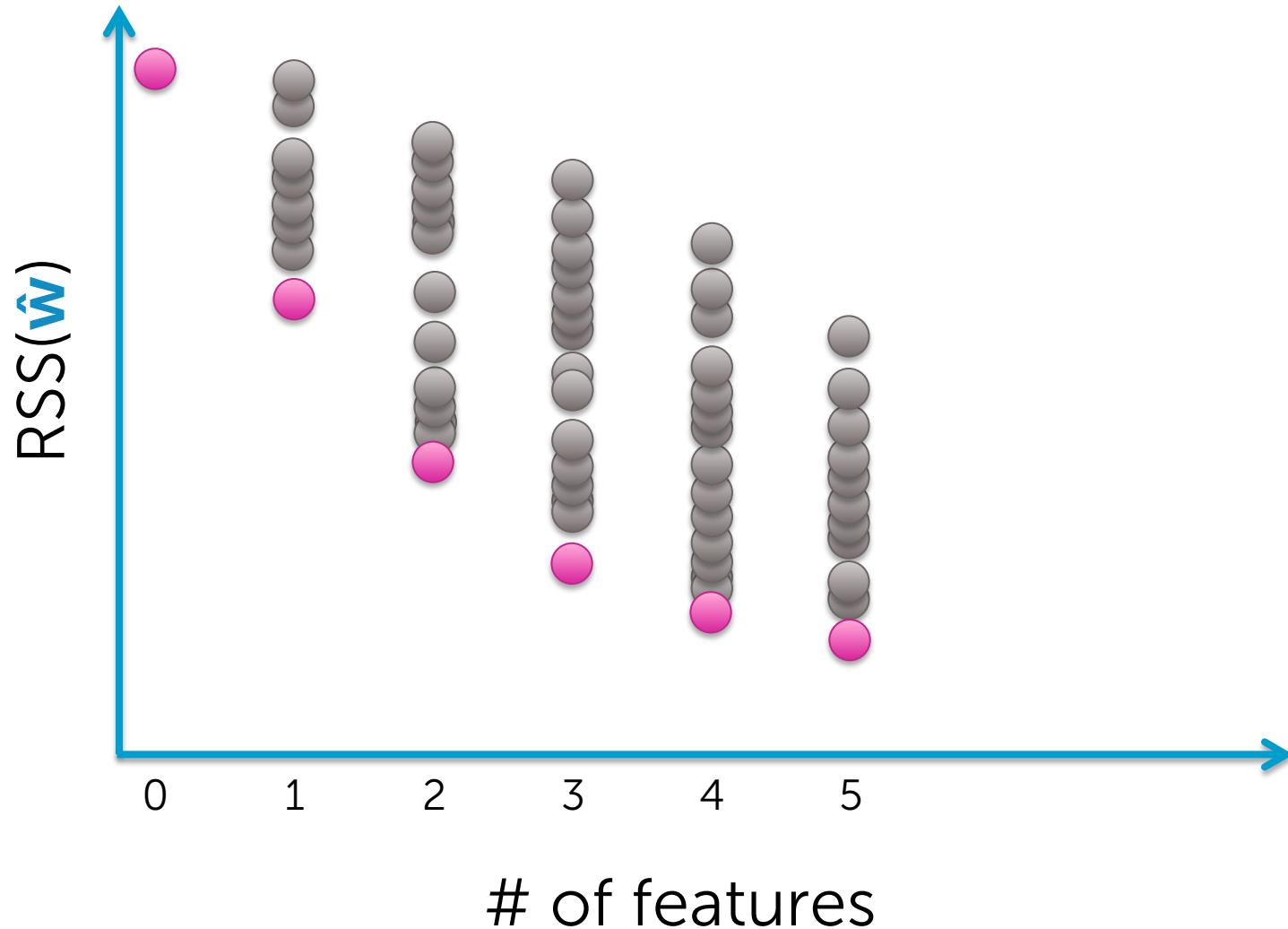
- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

Find best model of size: 4



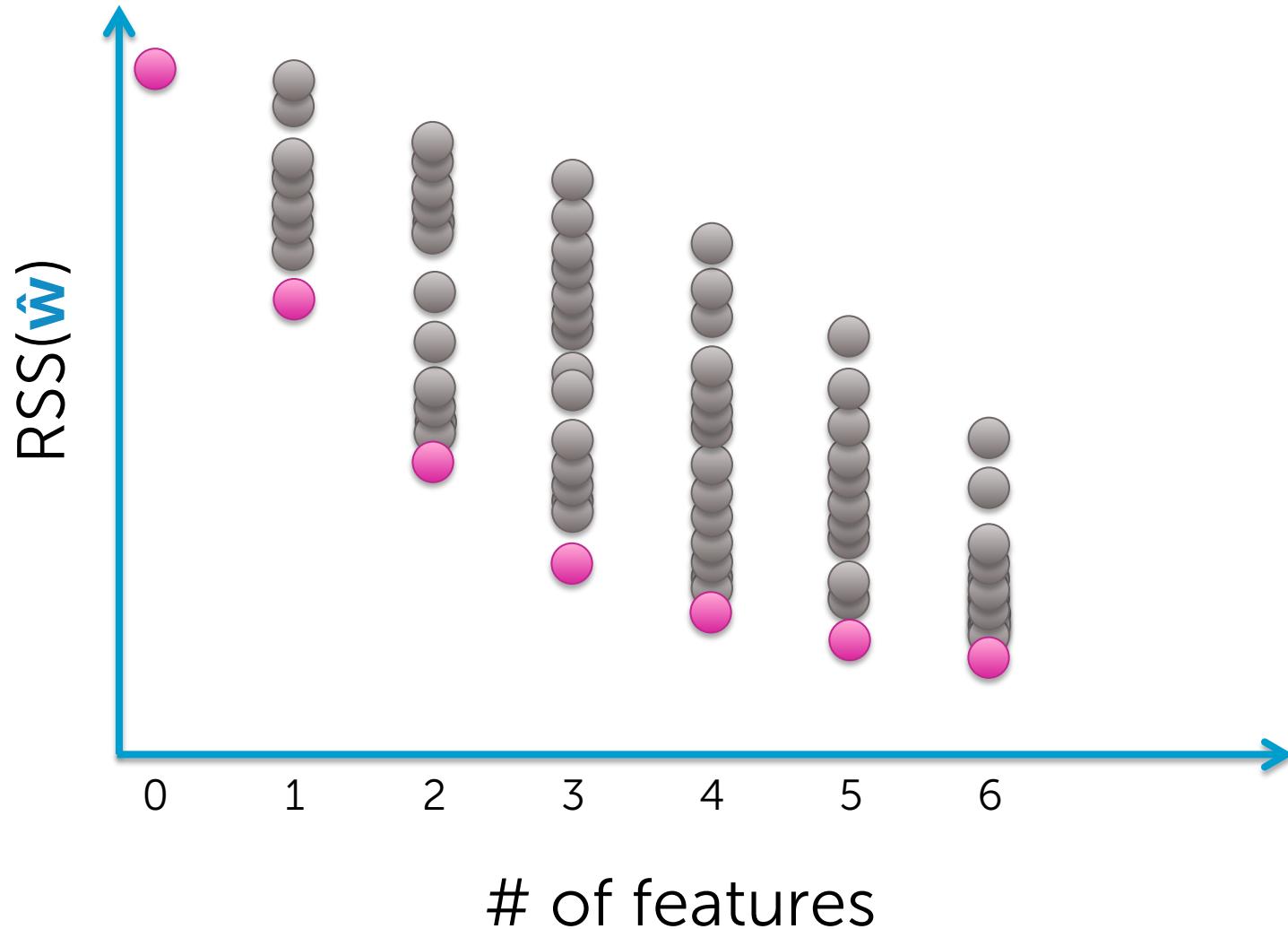
- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

Find best model of size: 5



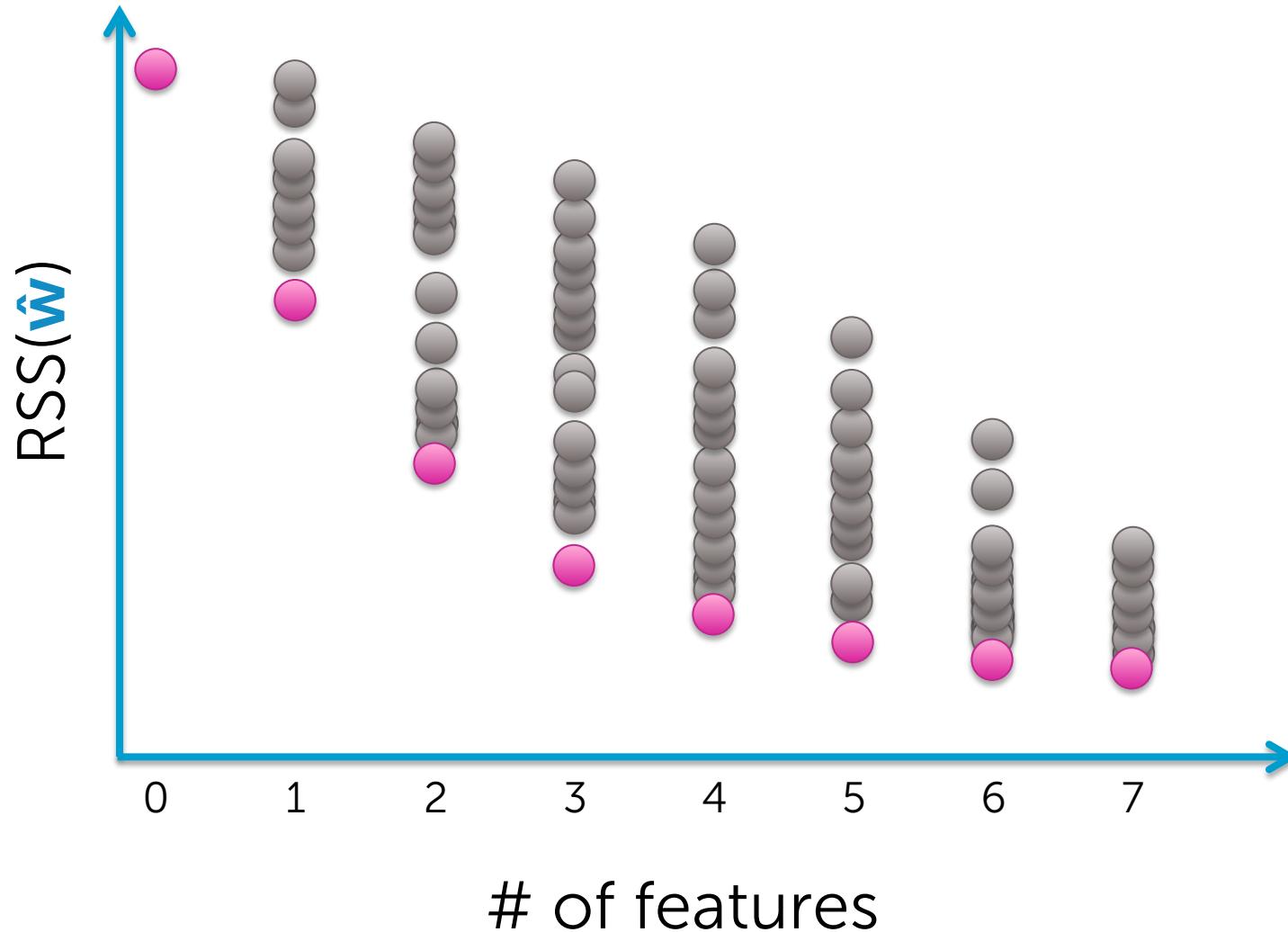
- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

Find best model of size: 6



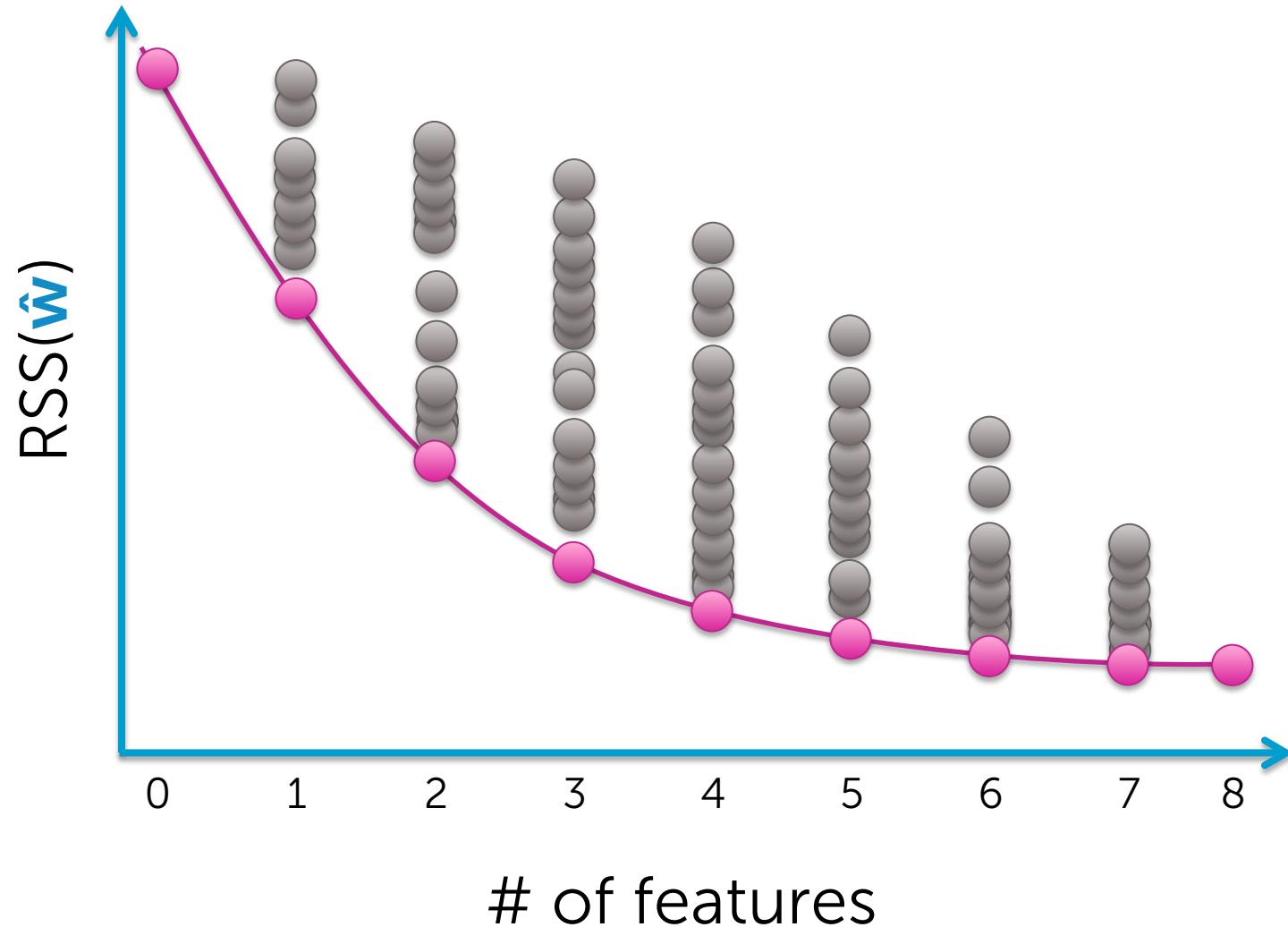
- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

Find best model of size: 7



- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

Find best model of size: 8



- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

Choosing model complexity?

Option 1: Assess on validation set

Option 2: Cross validation

Option 3+: Other metrics for penalizing
model complexity like BIC...

Complexity of “all subsets”

How many models were evaluated?

- each indexed by features included

$$y_i = \varepsilon_i$$

$$y_i = w_0 h_0(\mathbf{x}_i) + \varepsilon_i$$

$$y_i = w_1 h_1(\mathbf{x}_i) + \varepsilon_i$$

:

$$y_i = w_0 h_0(\mathbf{x}_i) + w_1 h_1(\mathbf{x}_i) + \varepsilon_i$$

:

$$y_i = w_0 h_0(\mathbf{x}_i) + w_1 h_1(\mathbf{x}_i) + \dots + w_D h_D(\mathbf{x}_i) + \varepsilon_i$$

feature 0 feature 1 ... feature D	0 if "no" 0 if "yes"
	[0 0 0 ... 0 0 0]
	[1 0 0 ... 0 0 0]
	[0 1 0 ... 0 0 0]
	⋮
	[1 1 0 ... 0 0 0]
	⋮
	[1 1 1 ... 1 1 1]

2^{D+1}

Typically,
computationally
infeasible

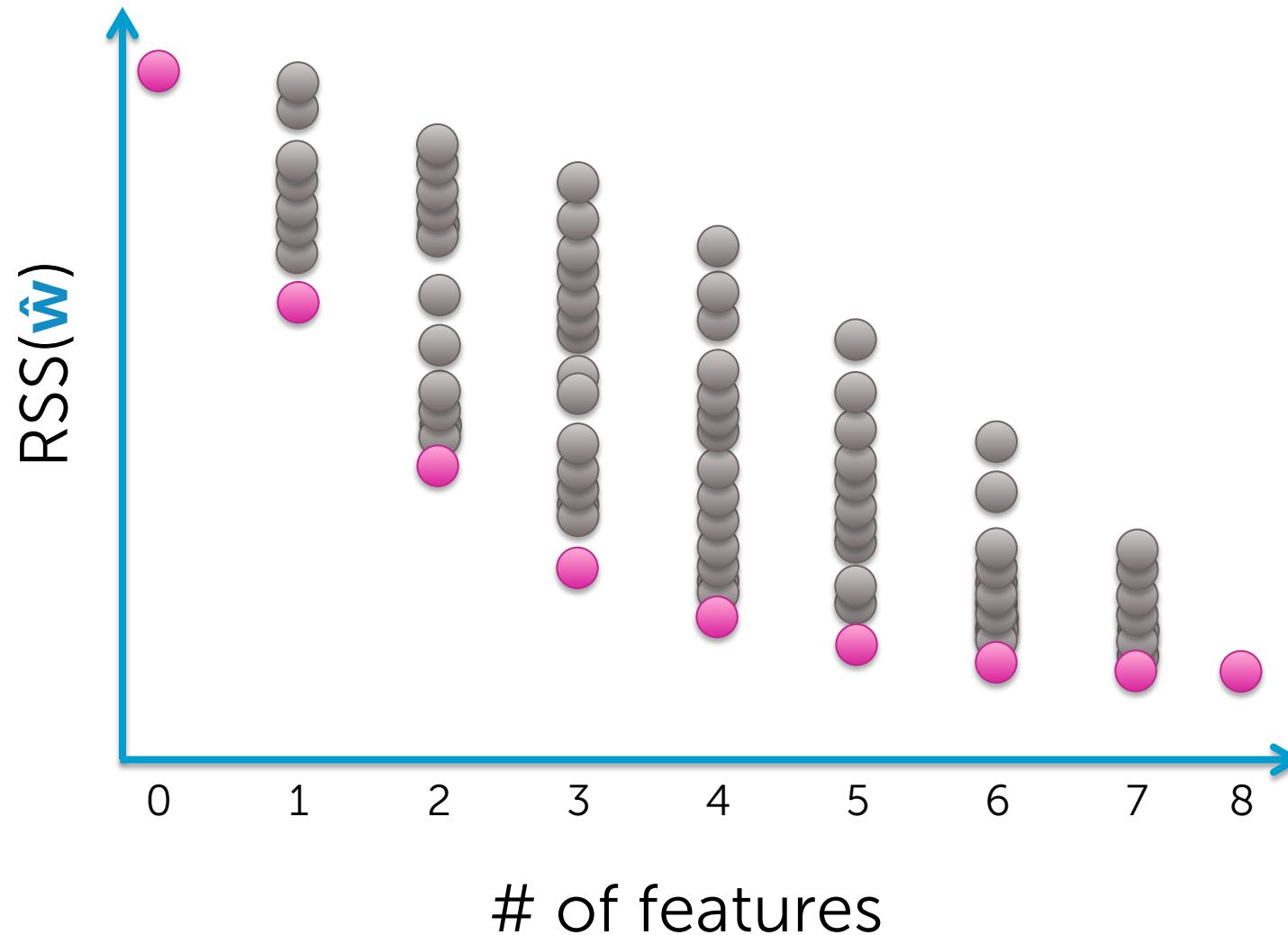
$$\begin{aligned}2^8 &= 256 \\2^{30} &= 1,073,741,824 \\2^{1000} &= 1.071509 \times 10^{301} \\2^{100B} &= \text{HUGE!!!!!!}\end{aligned}$$

Option 2: Greedy algorithms

Forward stepwise algorithm

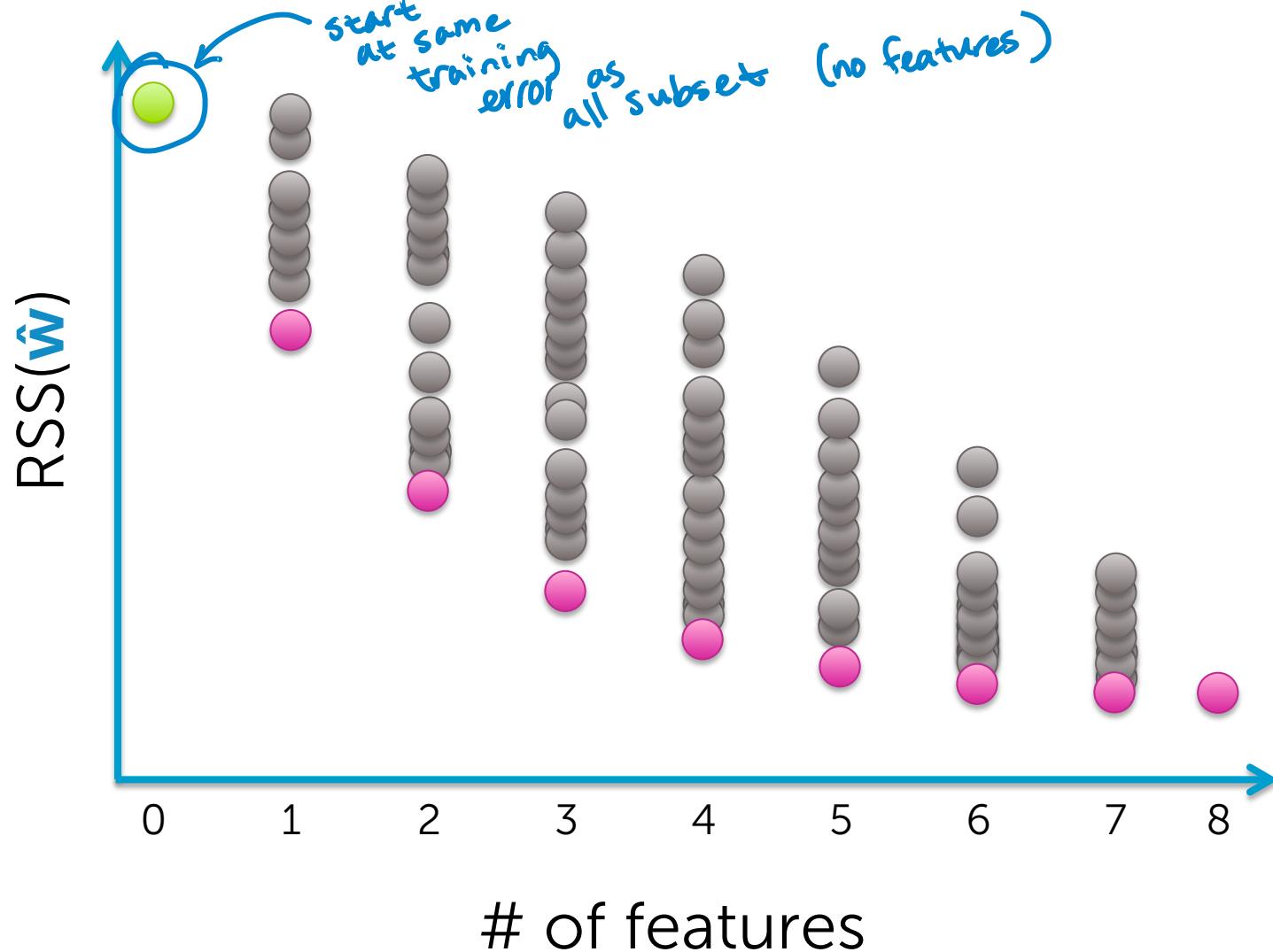
1. Pick a dictionary of features $\{h_0(\mathbf{x}), \dots, h_D(\mathbf{x})\}$
 - e.g., polynomials for linear regression
2. Greedy heuristic:
 - i. Start with empty set of features $F_0 = \emptyset$
(or simple set, like just $h_0(\mathbf{x})=1 \rightarrow y_i = w_0 + \varepsilon_i$)
 - ii. Fit model using current feature set F_t to get $\hat{\mathbf{w}}^{(t)}$
 - iii. Select next best feature $h_{j^*}(\mathbf{x})$
 - e.g., $h_j(\mathbf{x})$ resulting in lowest training error
when learning with $F_t + \{h_j(\mathbf{x})\}$
 - iv. Set $F_{t+1} \leftarrow F_t + \{h_{j^*}(\mathbf{x})\}$
 - v. Recurse

Visualizing greedy procedure

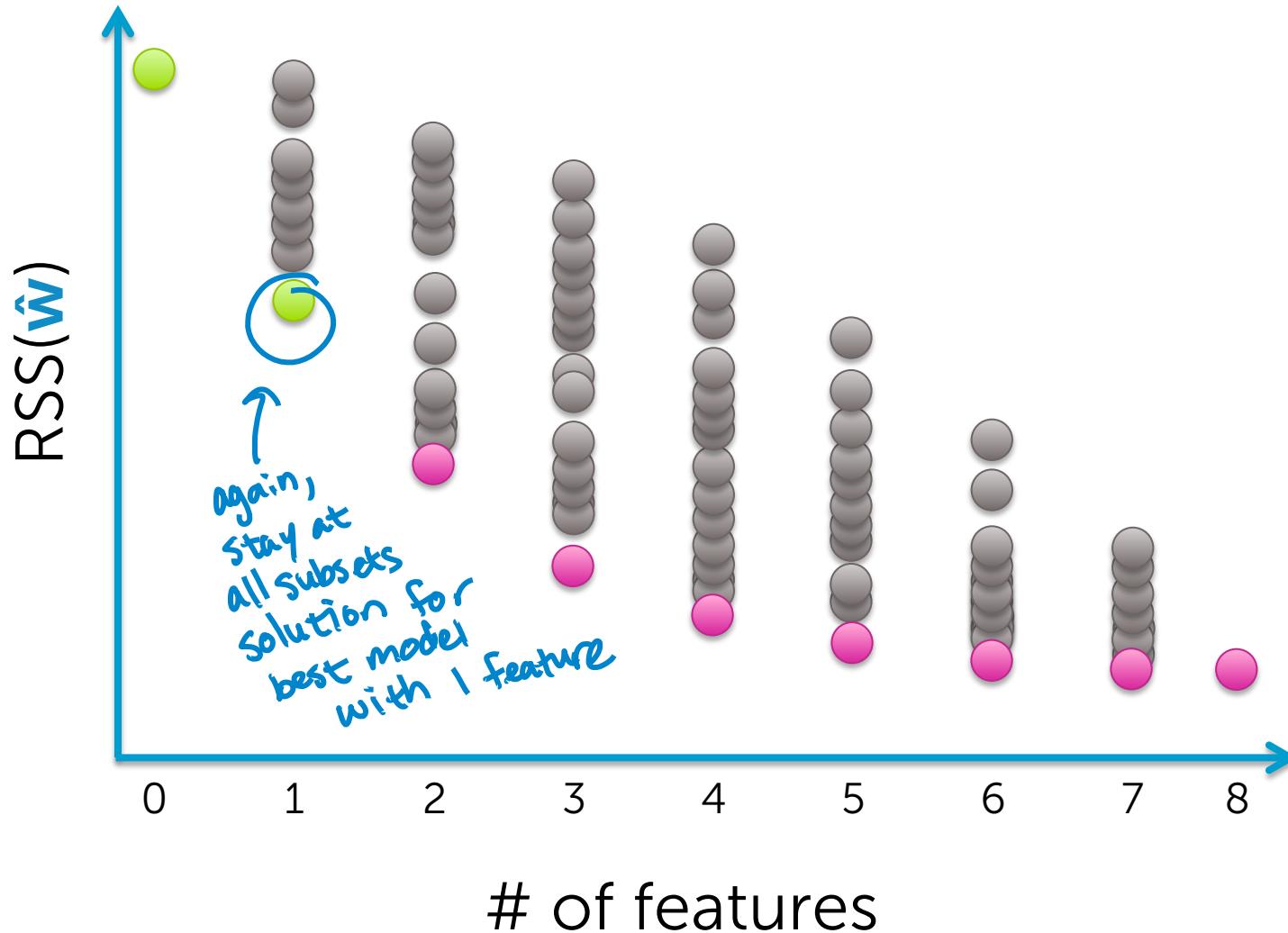


- # bedrooms
- # bathrooms
- sq.ft. living
- sq.ft. lot
- floors
- year built
- year renovated
- waterfront

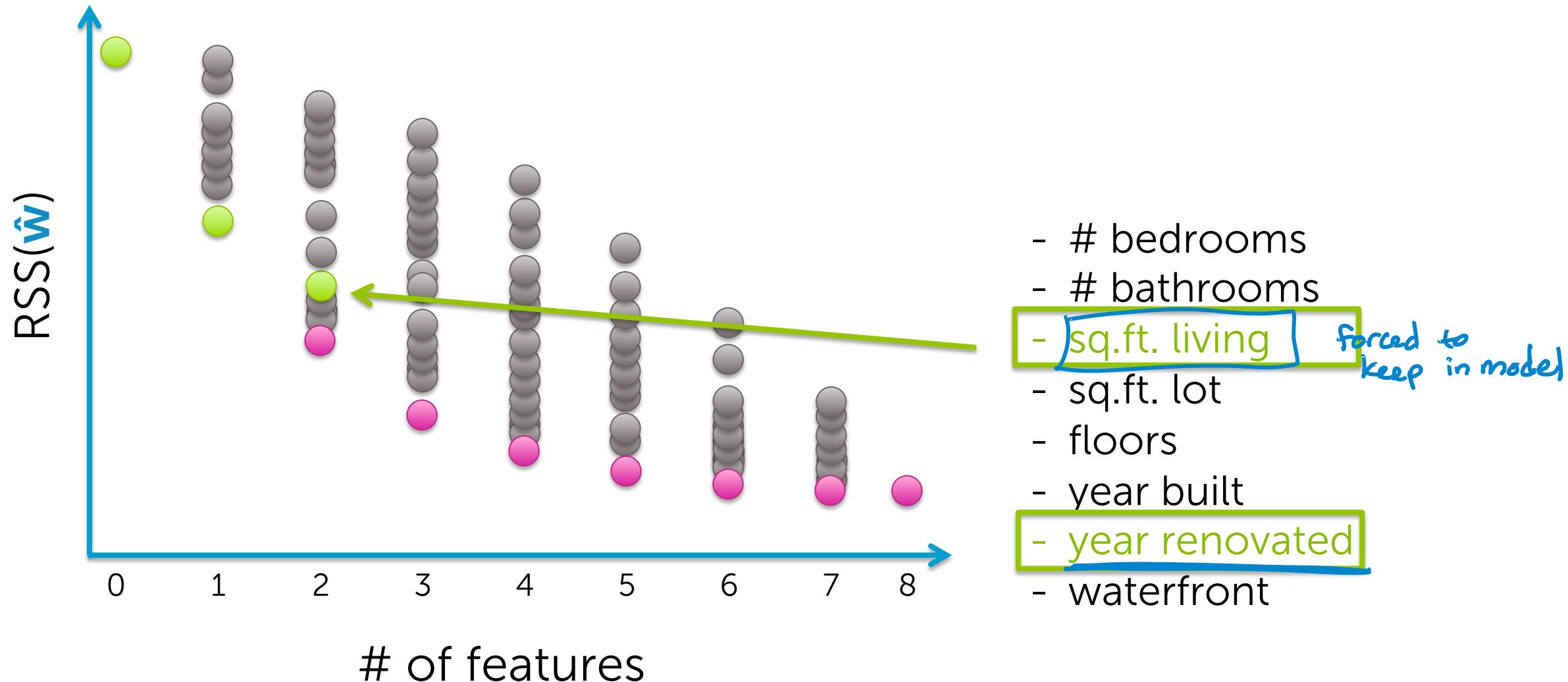
Visualizing greedy procedure



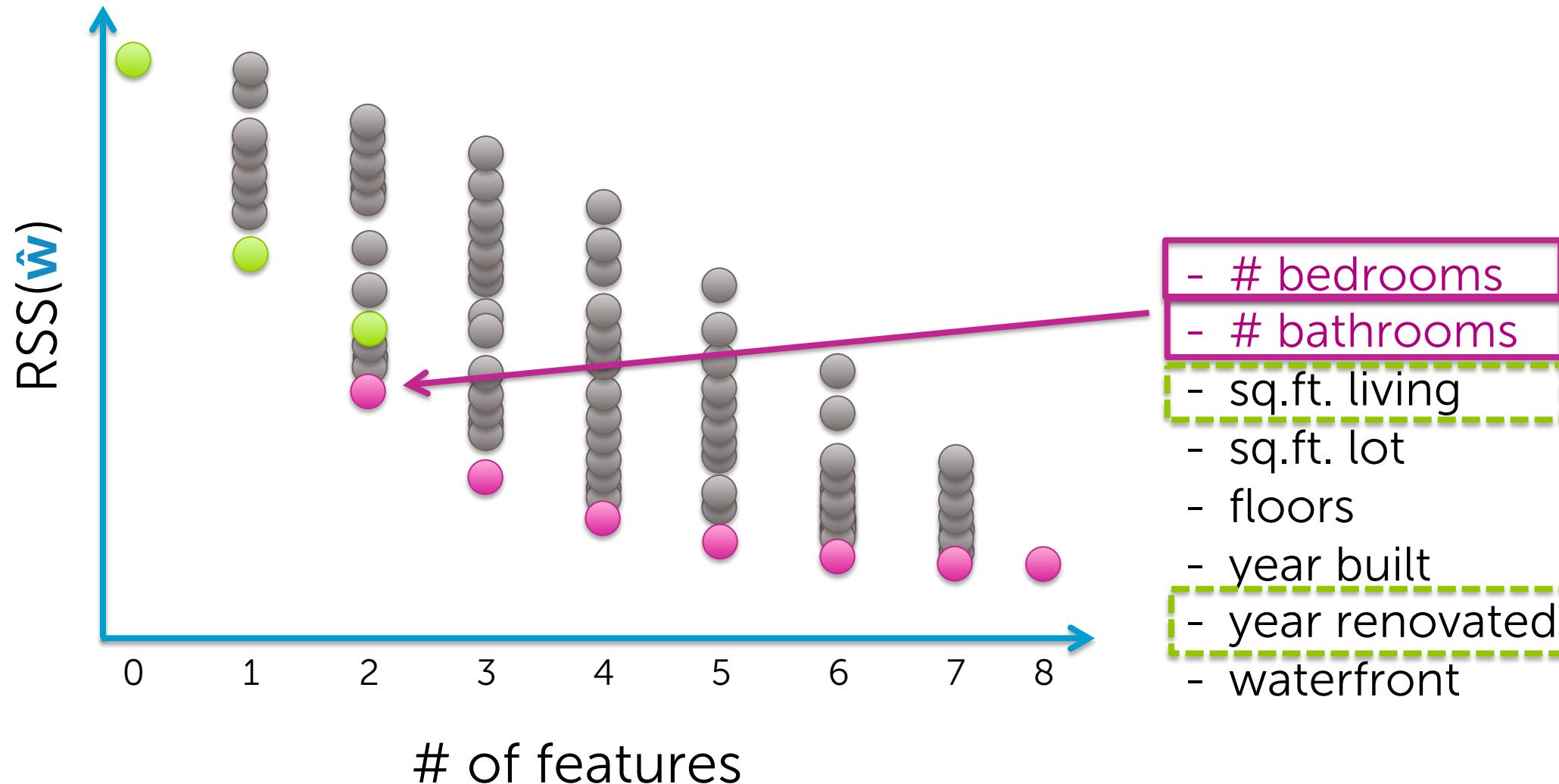
Visualizing greedy procedure



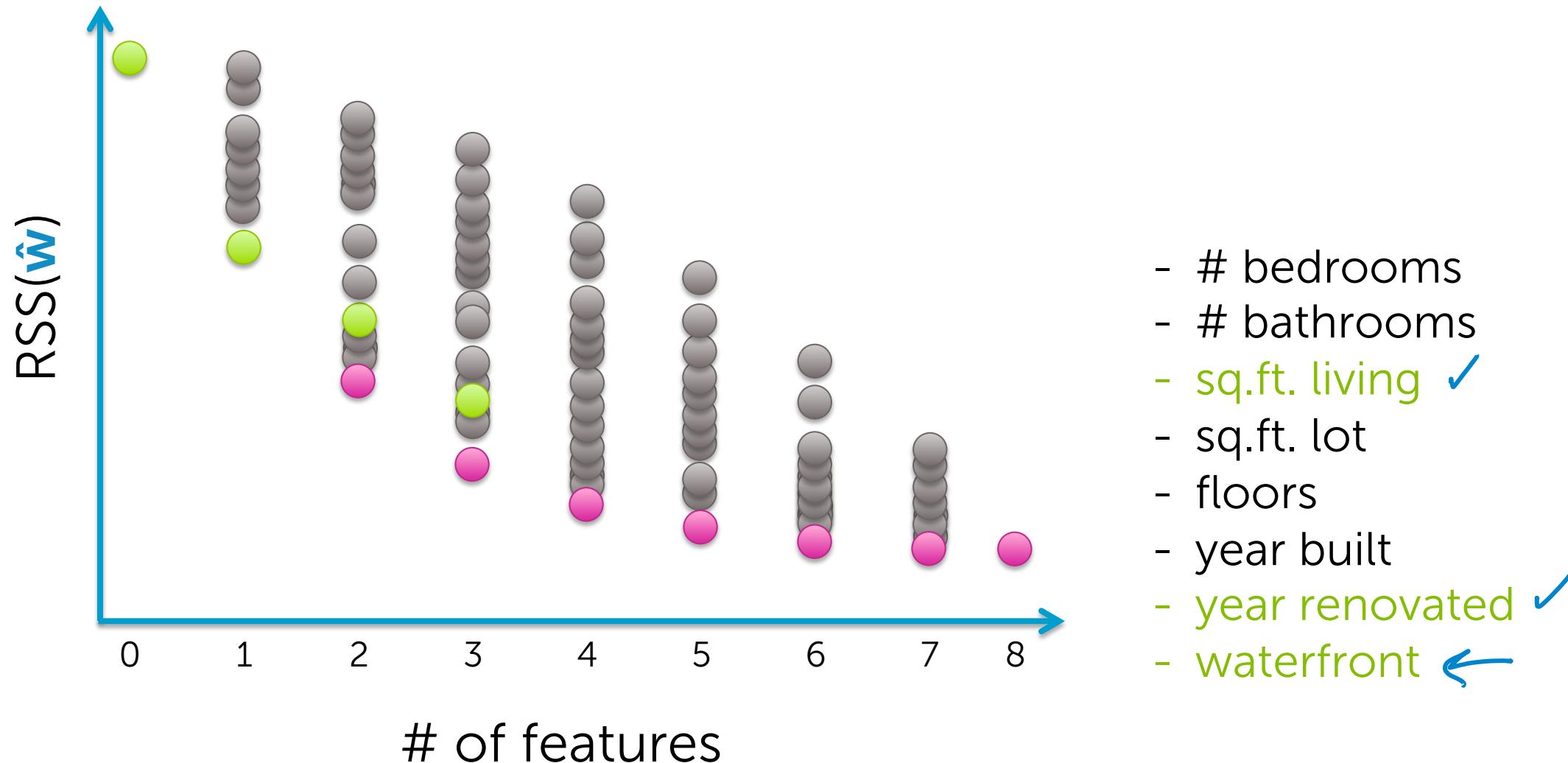
Visualizing greedy procedure



Visualizing greedy procedure



Visualizing greedy procedure



Visualizing greedy procedure



When do we stop?

When **training error** is low enough?

No!

When **test error** is low enough?

No!

Use *validation set* or *cross validation*!

Complexity of forward stepwise

How many models were evaluated?

- 1st step, **D models**
- 2nd step, **D-1 models** (add 1 feature out of D-1 possible)
- 3rd step, **D-2 models** (add 1 feature out of D-2 possible)
- ...

How many steps?

- Depends
- At most **D steps** (to full model)

$$O(D^2) \ll 2^D$$

for large D

Other greedy algorithms

Instead of starting from simple model
and always growing...

Backward stepwise:

Start with full model and iteratively remove
features least useful to fit

Combining forward and backward steps:

In forward algorithm, insert steps to remove
features no longer as important

Lots of other variants, too.

Option 3: Regularize

Ridge regression: L_2 regularized regression

Total cost =

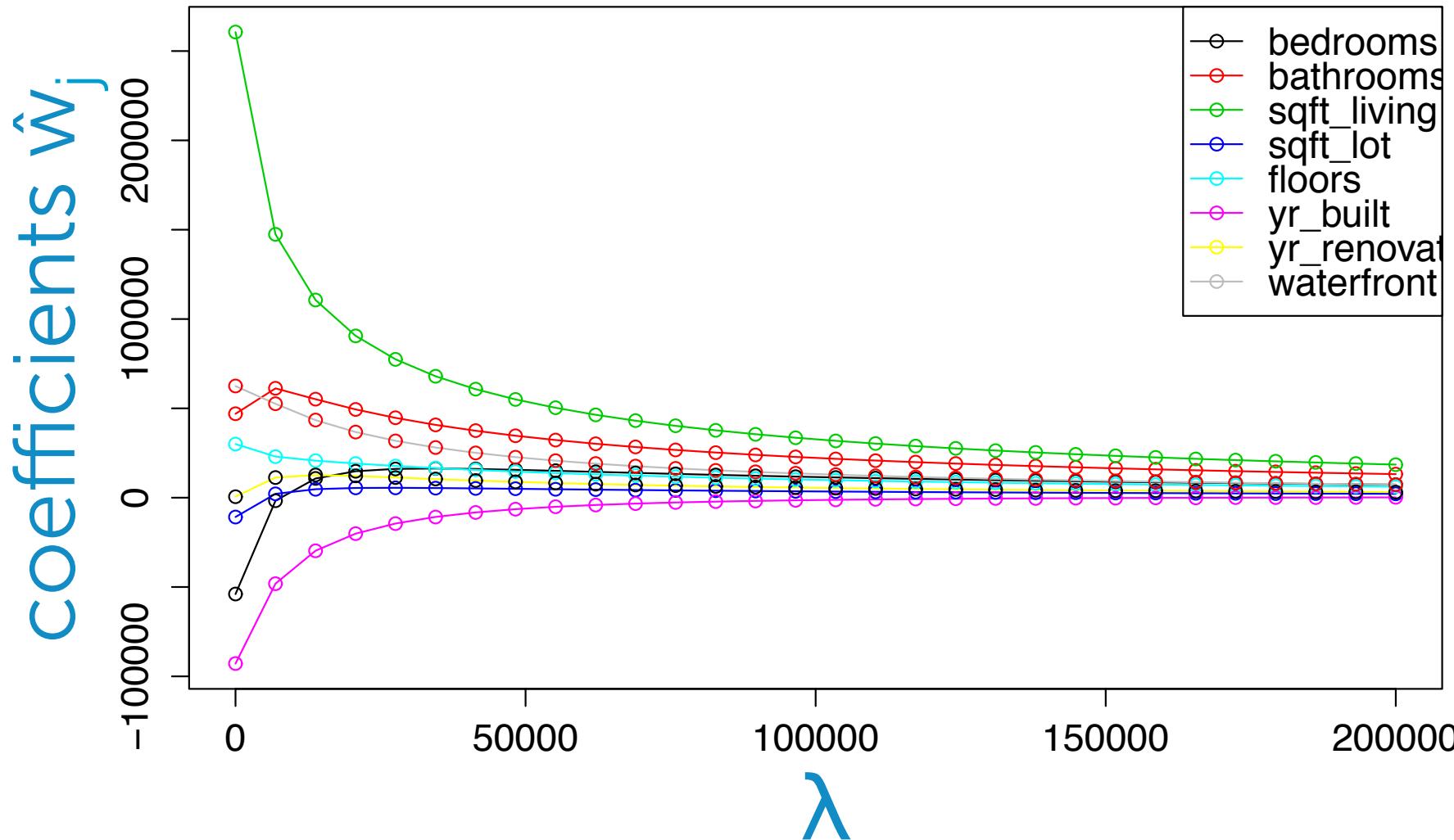
$$\text{measure of fit} + \lambda \text{ measure of magnitude}$$



$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_2^2 = w_0^2 + \dots + w_D^2$$

Encourages small weights
but not exactly 0

Coefficient path – ridge

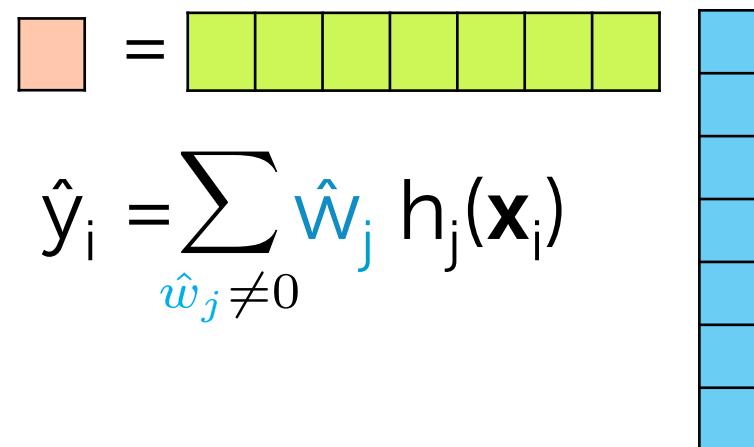


Recall **sparsity** (many $\hat{w}_j=0$) gives efficiency and interpretability

Efficiency:

- If $\text{size}(\mathbf{w}) = 100B$, each prediction is expensive
- If $\hat{\mathbf{w}}$ sparse, computation only depends on # of non-zeros

many zeros

$$\hat{y}_i = \sum_{\hat{w}_j \neq 0} \hat{w}_j h_j(\mathbf{x}_i)$$


Interpretability:

- Which features are relevant for prediction?

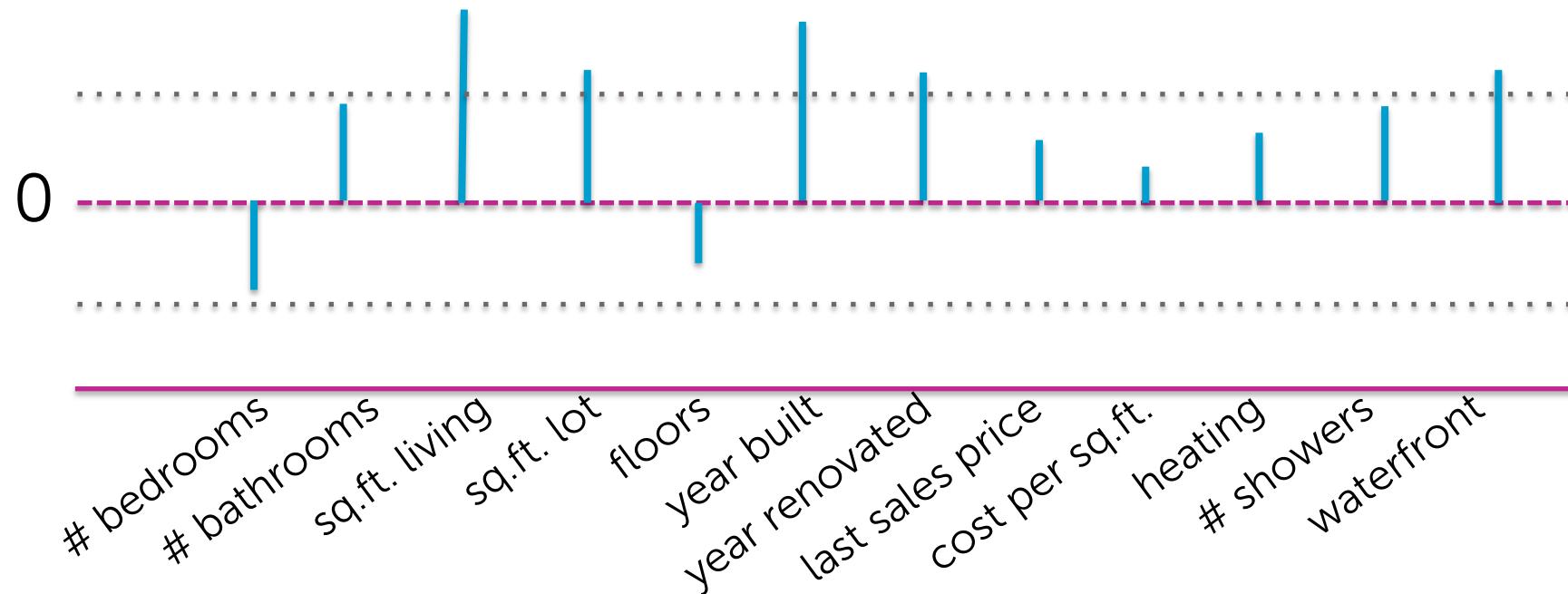
Using regularization for feature selection

Instead of searching over a discrete set of solutions, can we use **regularization**?

- Start with full model (all possible features)
- “Shrink” some coefficients *exactly to 0*
 - i.e., knock out certain features
- Non-zero coefficients indicate “selected” features

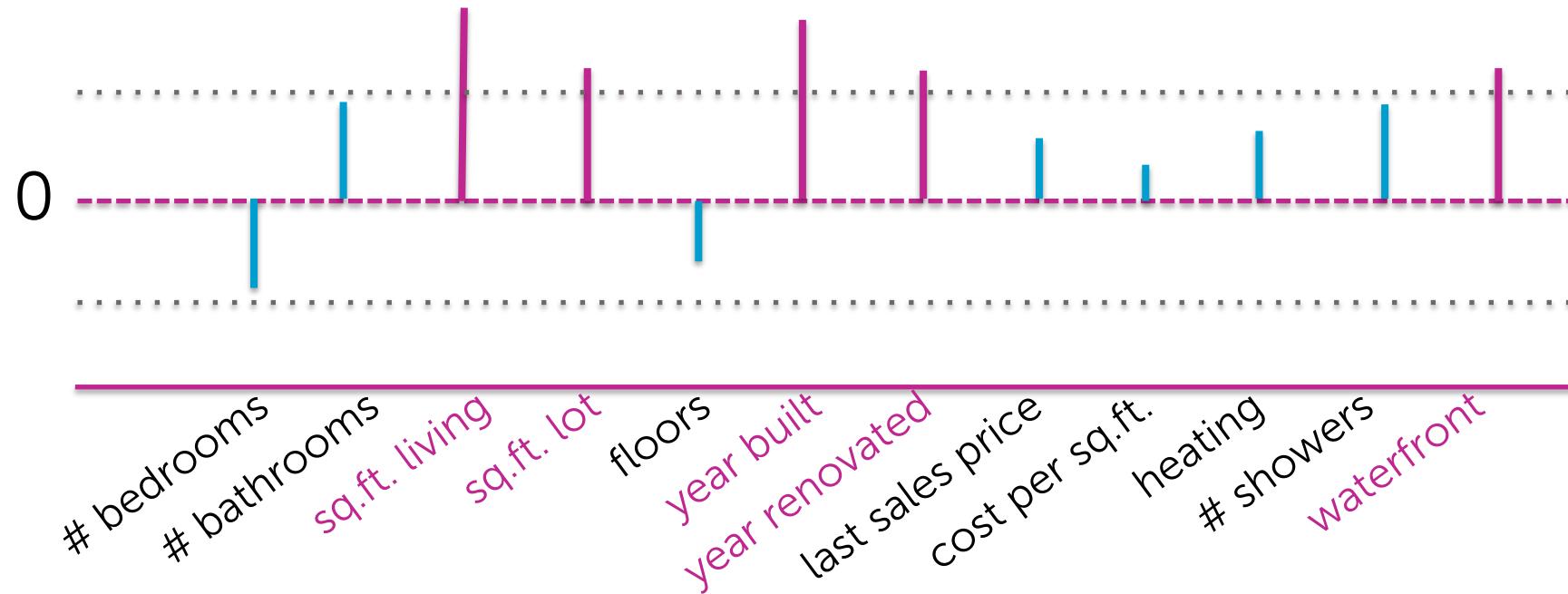
Thresholding ridge coefficients?

Why don't we just set small ridge coefficients to 0?



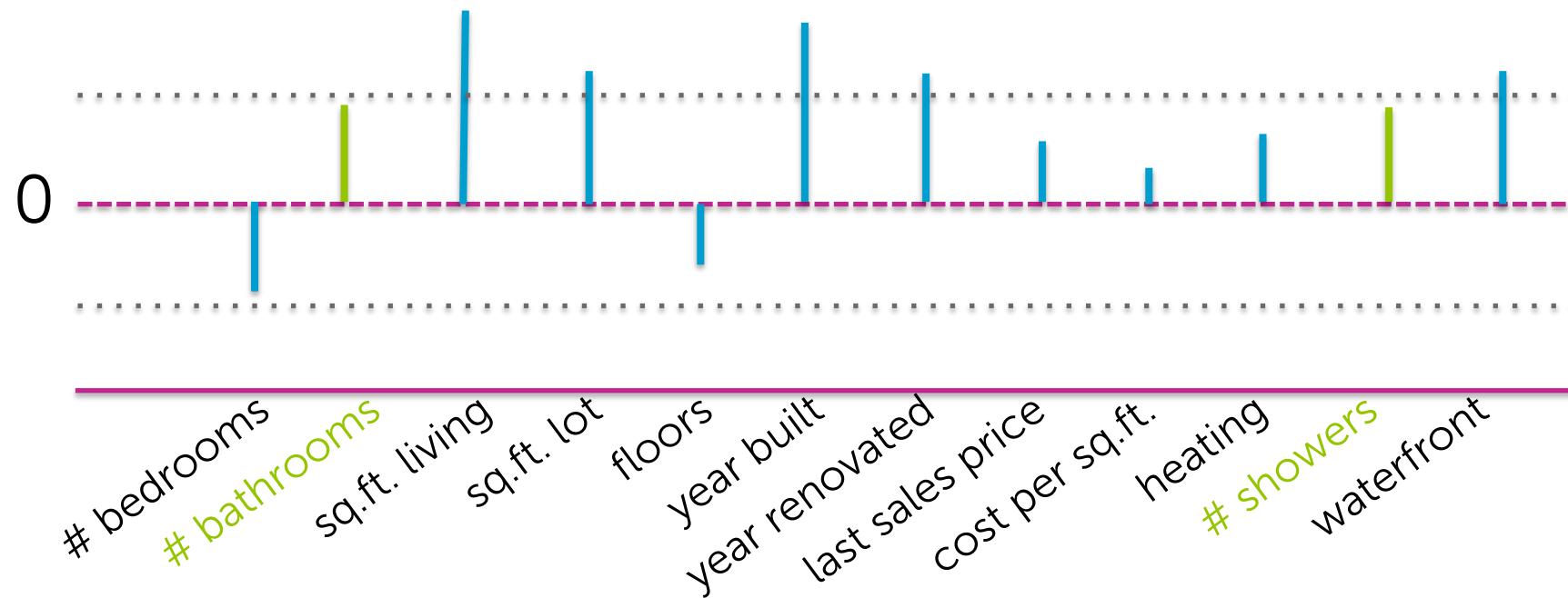
Thresholding ridge coefficients?

Selected features for a given threshold value



Thresholding ridge coefficients?

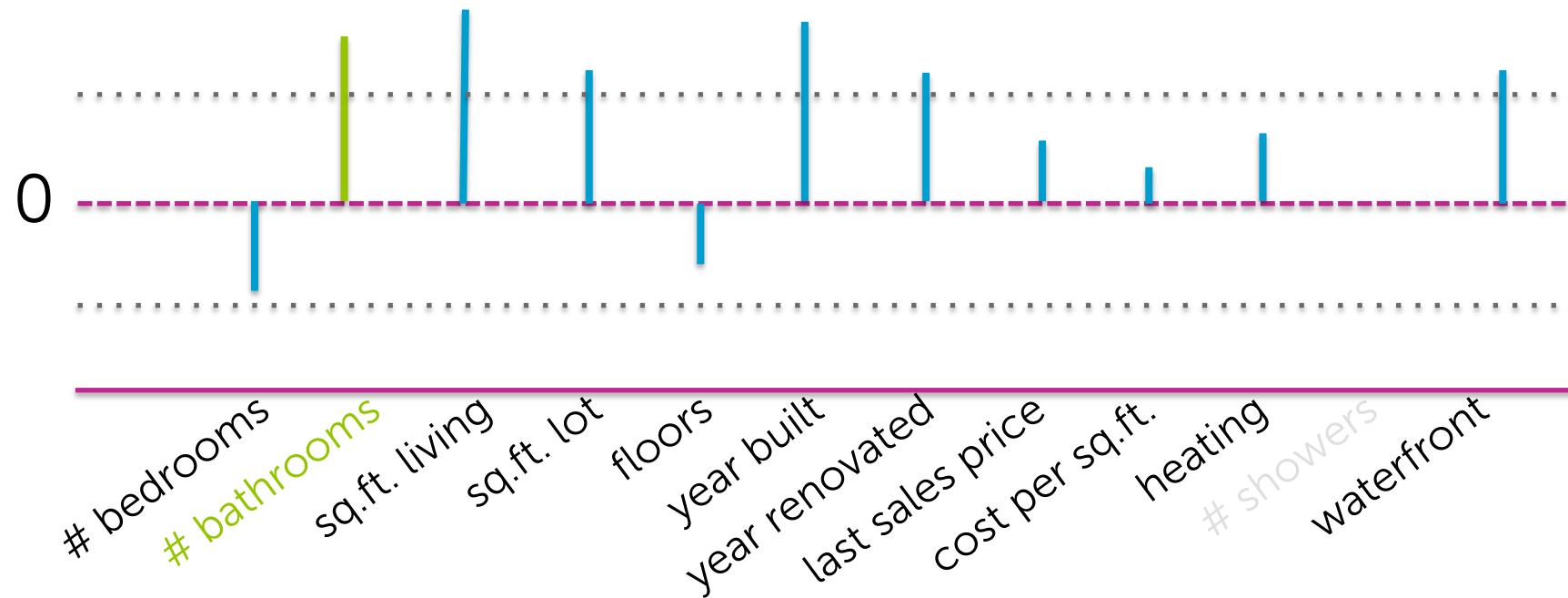
Let's look at two related features...



Nothing measuring bathrooms was included!

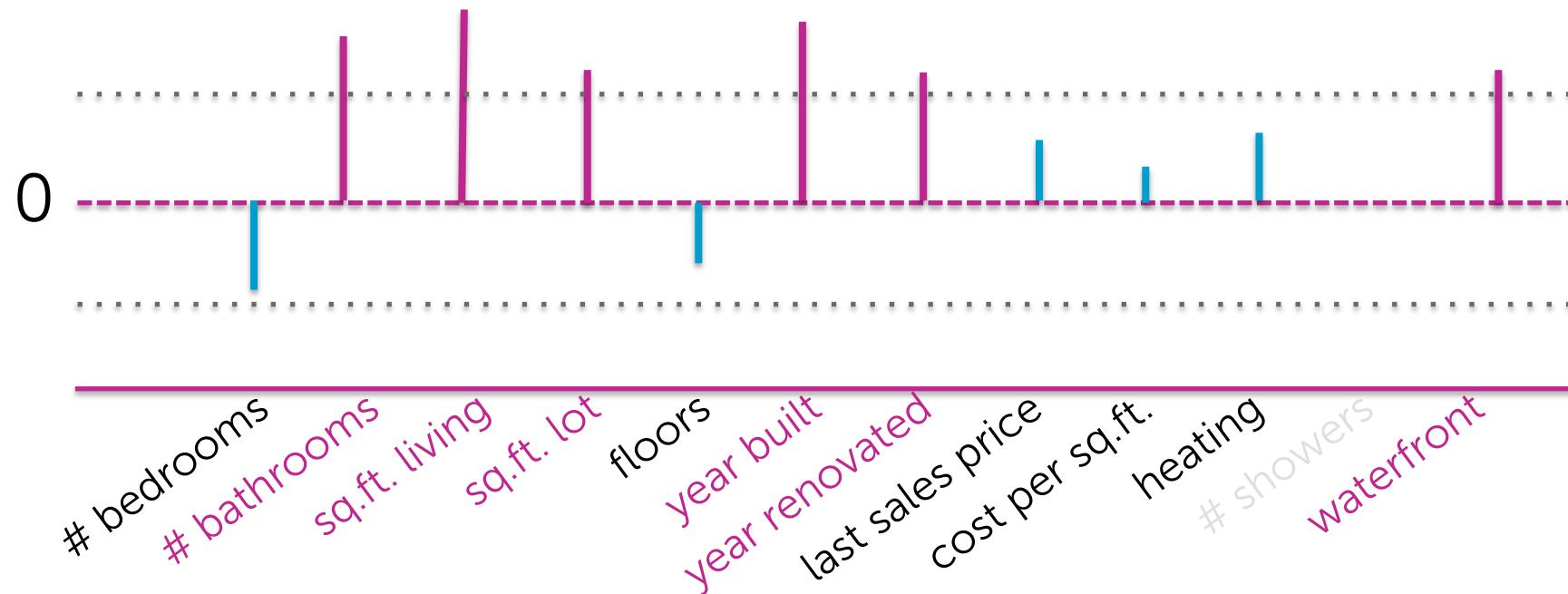
Thresholding ridge coefficients?

If only one of the features had been included...



Thresholding ridge coefficients?

Would have included bathrooms in selected model



Can regularization lead directly to sparsity?

Try this cost instead of ridge...

Total cost =

measure of fit + λ measure of magnitude
of coefficients

RSS(w)

$$\|w\|_1 = |w_0| + \dots + |w_D|$$

Lasso regression
(a.k.a. L_1 regularized regression)

Leads to
sparse
solutions!

Lasso regression: L_1 regularized regression

Just like ridge regression, solution is governed by a continuous parameter λ

$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1$$

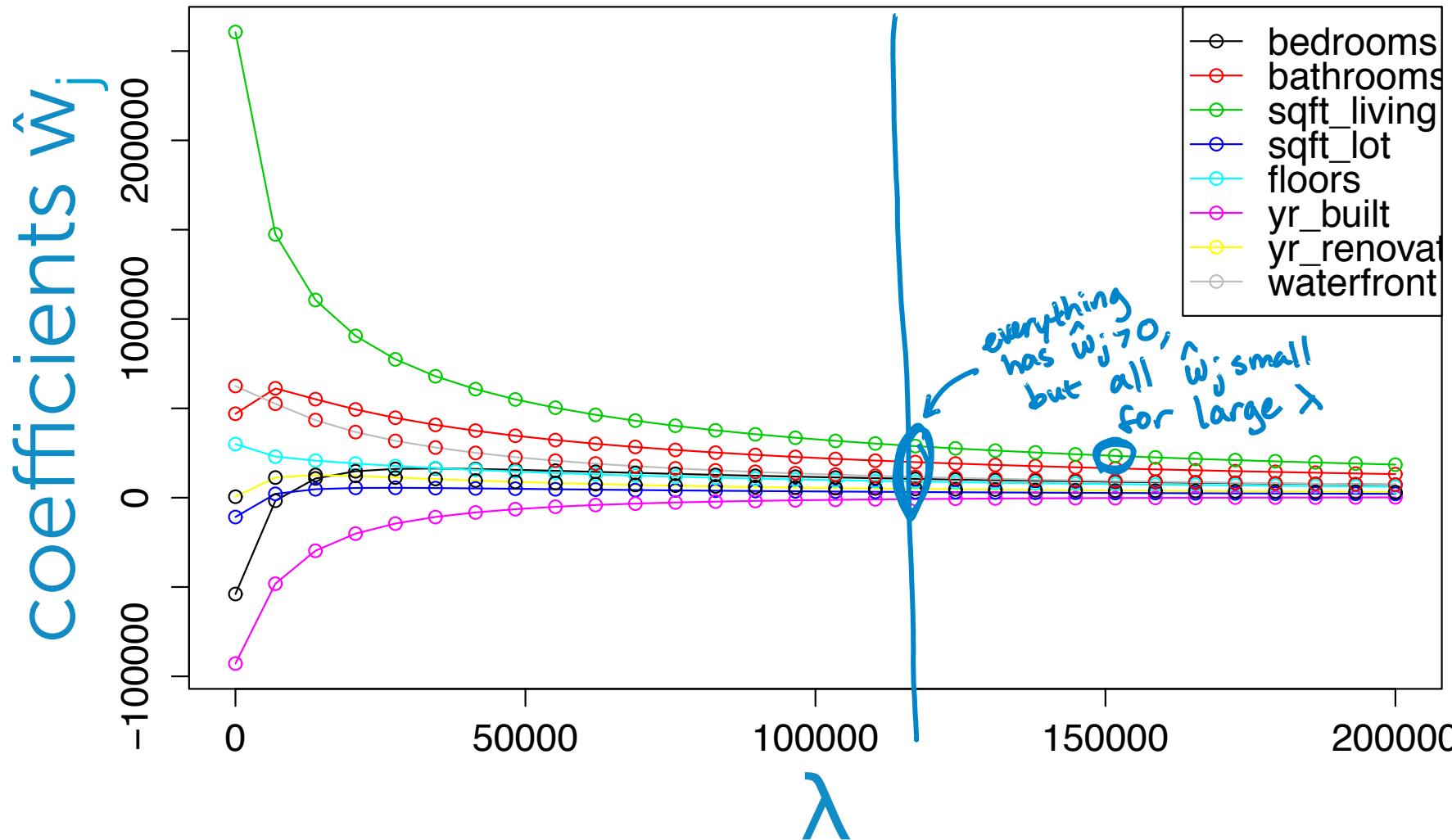
tuning parameter = balance of fit and sparsity

If $\lambda=0$: $\hat{\mathbf{w}}^{\text{lasso}} = \hat{\mathbf{w}}^{\text{LS}}$ (unregularized solution)

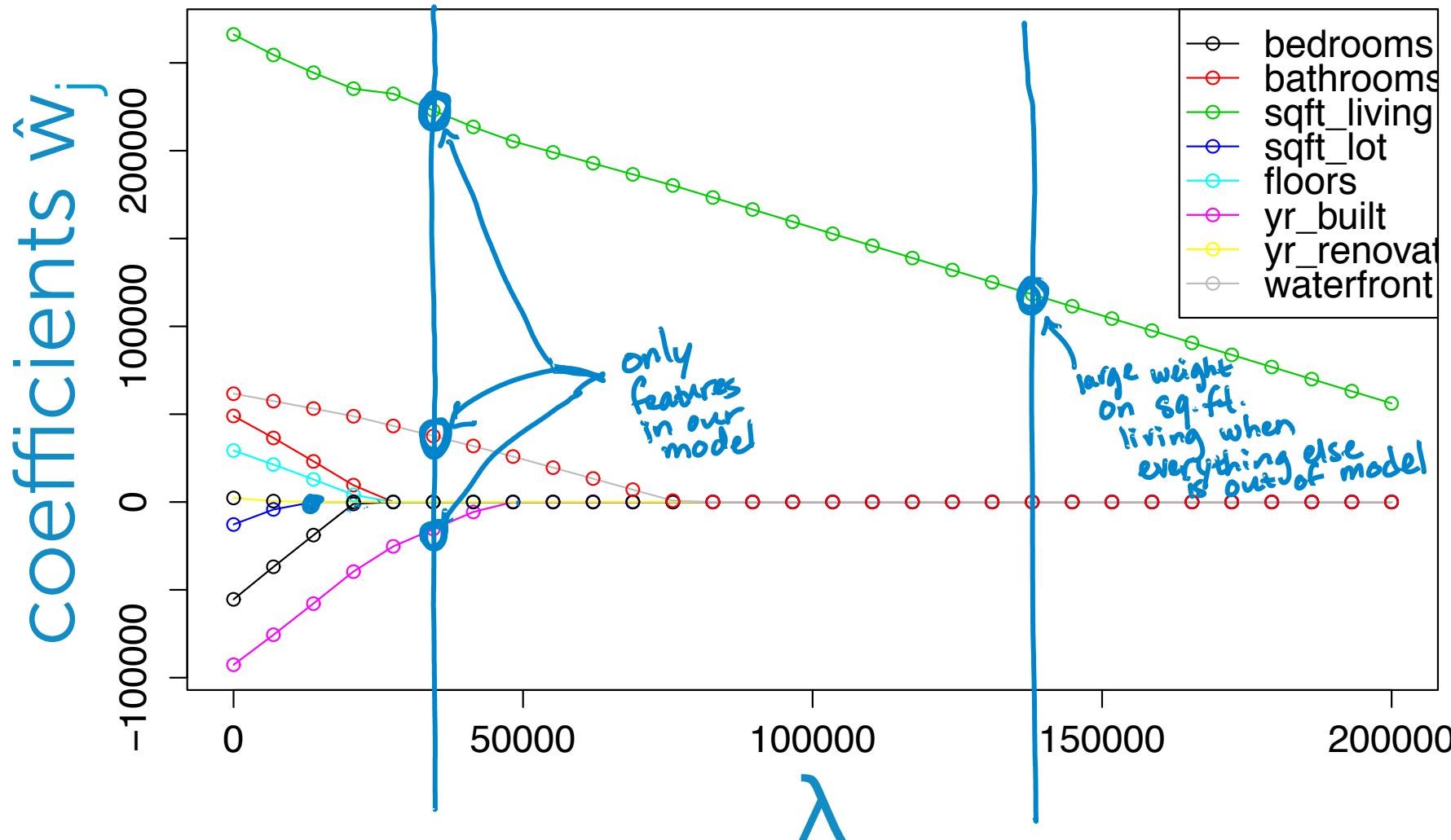
If $\lambda=\infty$: $\hat{\mathbf{w}}^{\text{lasso}} = \mathbf{0}$

If λ in between: $0 \leq \|\hat{\mathbf{w}}^{\text{lasso}}\|_1 \leq \|\hat{\mathbf{w}}^{\text{LS}}\|_1$

Coefficient path – ridge



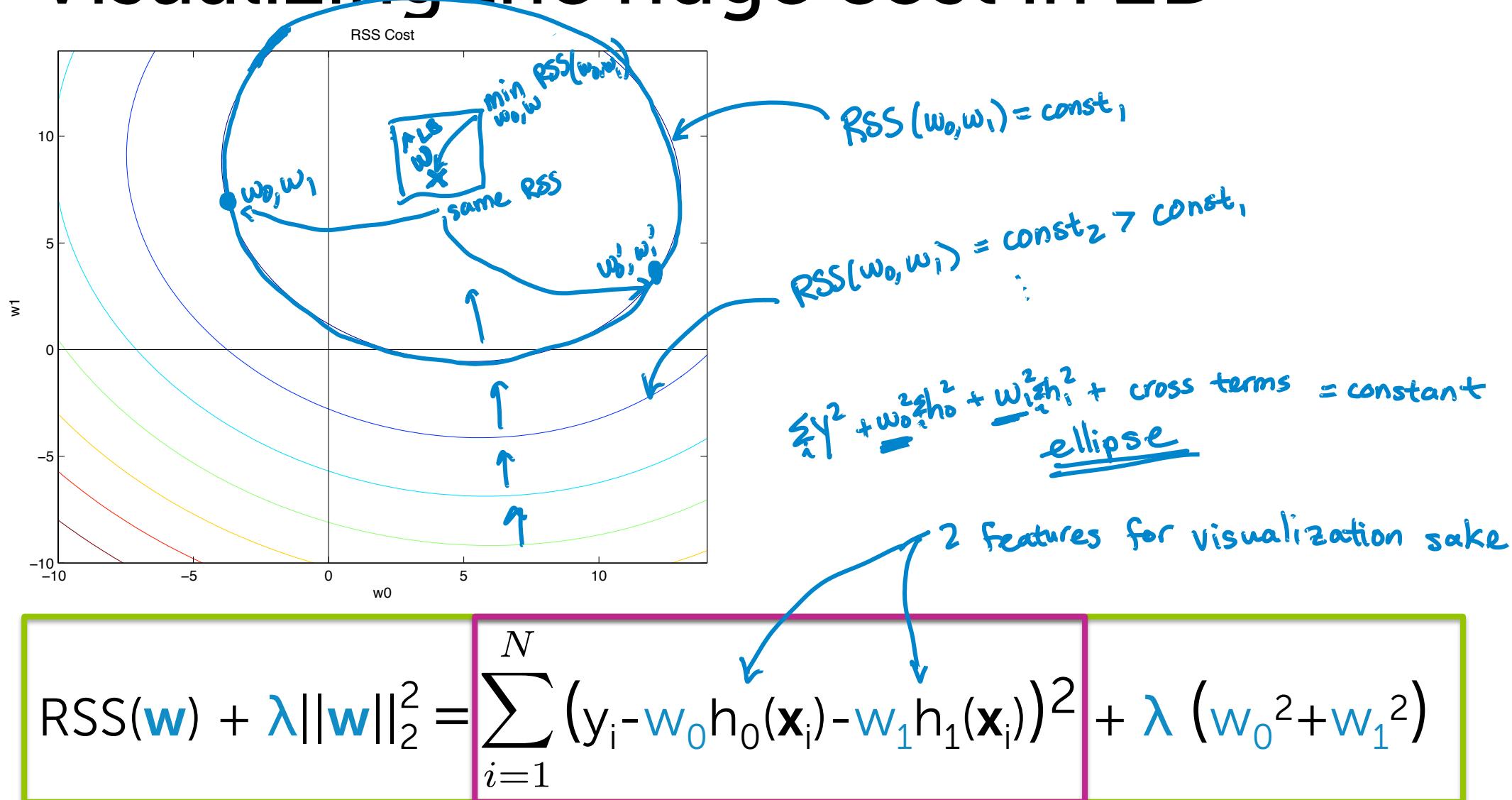
Coefficient path – lasso



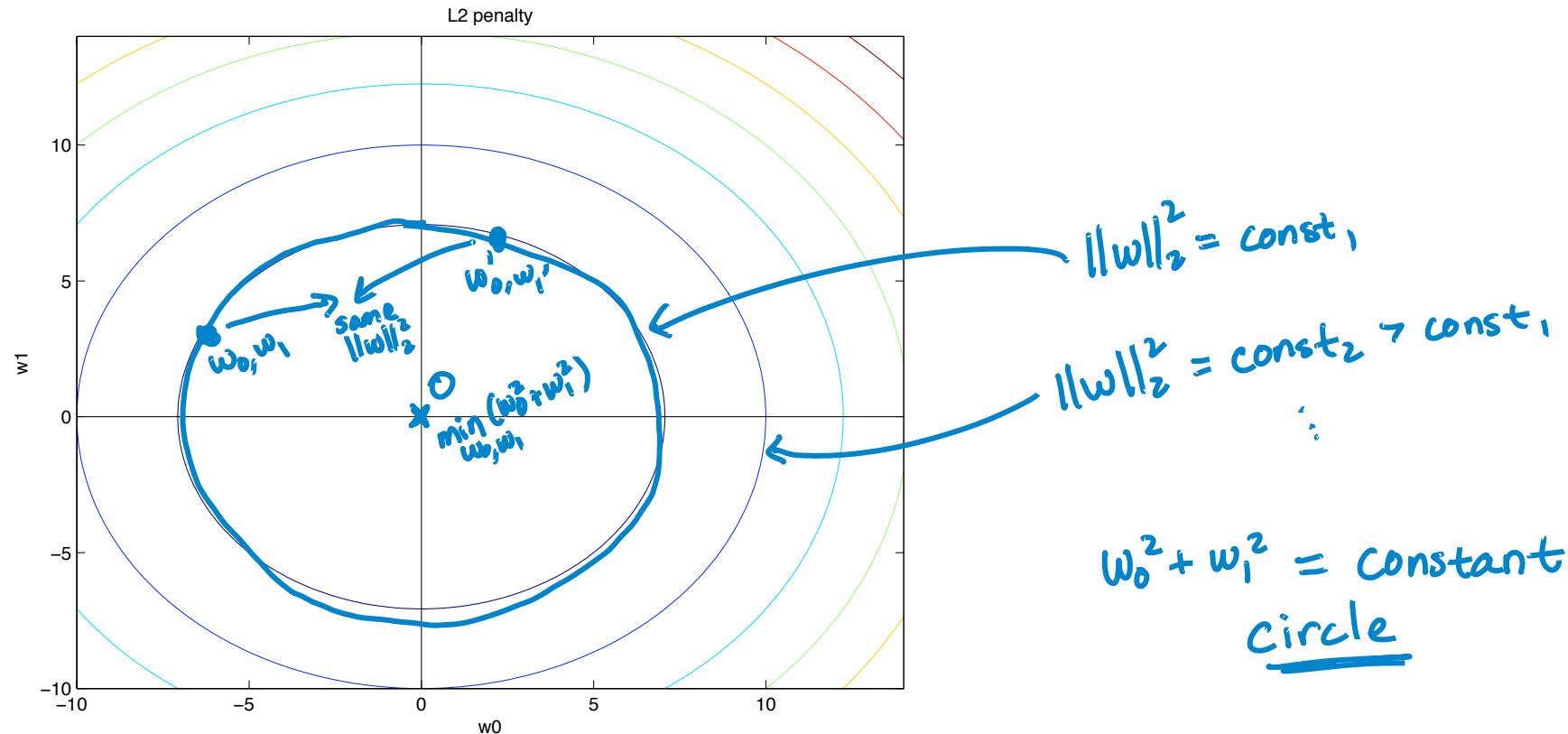
Geometric intuition for sparsity of lasso solution

Geometric intuition for ridge regression

Visualizing the ridge cost in 2D

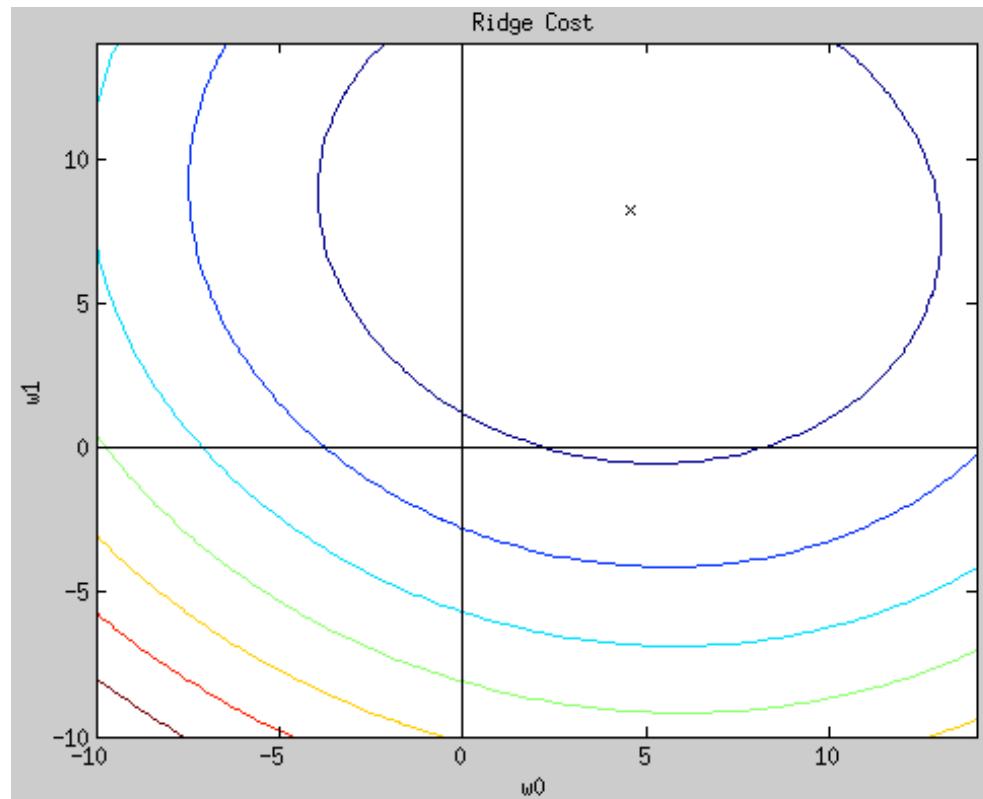


Visualizing the ridge cost in 2D



$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_2^2 = \sum_{i=1}^N (y_i - w_0 h_0(\mathbf{x}_i) - w_1 h_1(\mathbf{x}_i))^2 + \underline{\lambda} (w_0^2 + w_1^2)$$

Visualizing the ridge cost in 2D



Add contour plots together

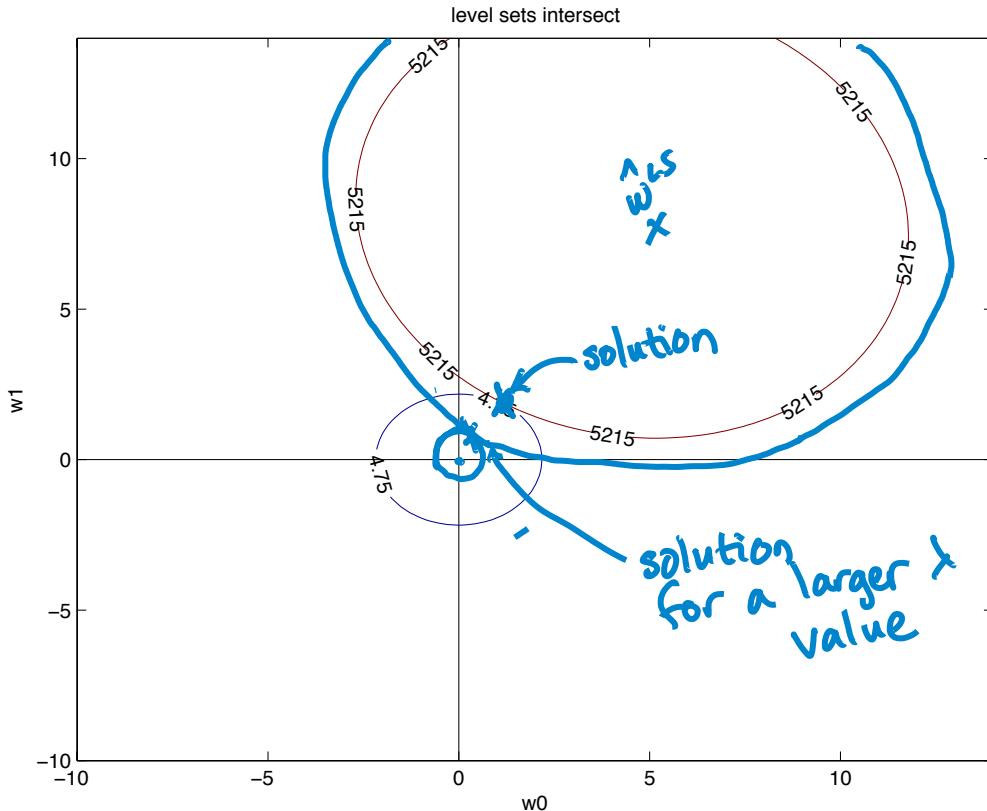
$RSS(w) + \lambda ||w||_2^2$
ellipses ↑ circles
weighting

Movie: function of increasing λ

X mark optimal solution for a specific λ

$$RSS(\mathbf{w}) + \lambda ||\mathbf{w}||_2^2 = \sum_{i=1}^N (y_i - w_0 h_0(\mathbf{x}_i) - w_1 h_1(\mathbf{x}_i))^2 + \lambda (w_0^2 + w_1^2)$$

Visualizing the ridge solution

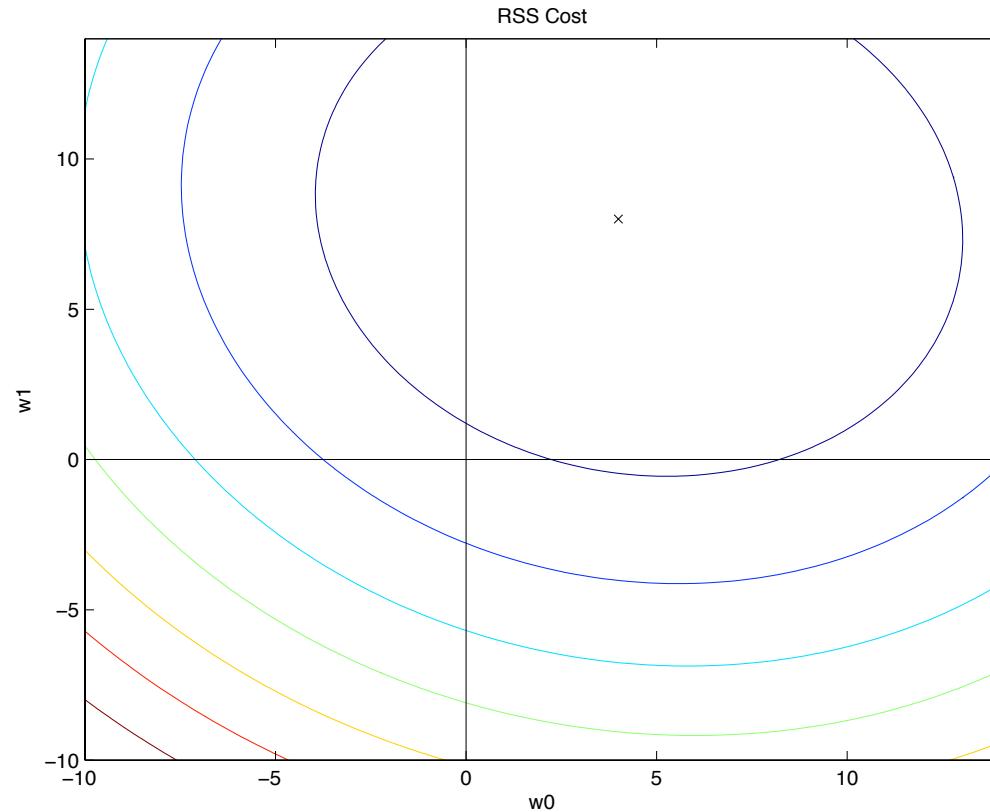


For a specific λ value,
some balance between
RSS and $\|w\|_2^2$

$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_2^2 = \sum_{i=1}^N (y_i - w_0 h_0(\mathbf{x}_i) - w_1 h_1(\mathbf{x}_i))^2 + \lambda (w_0^2 + w_1^2)$$

Geometric intuition for lasso

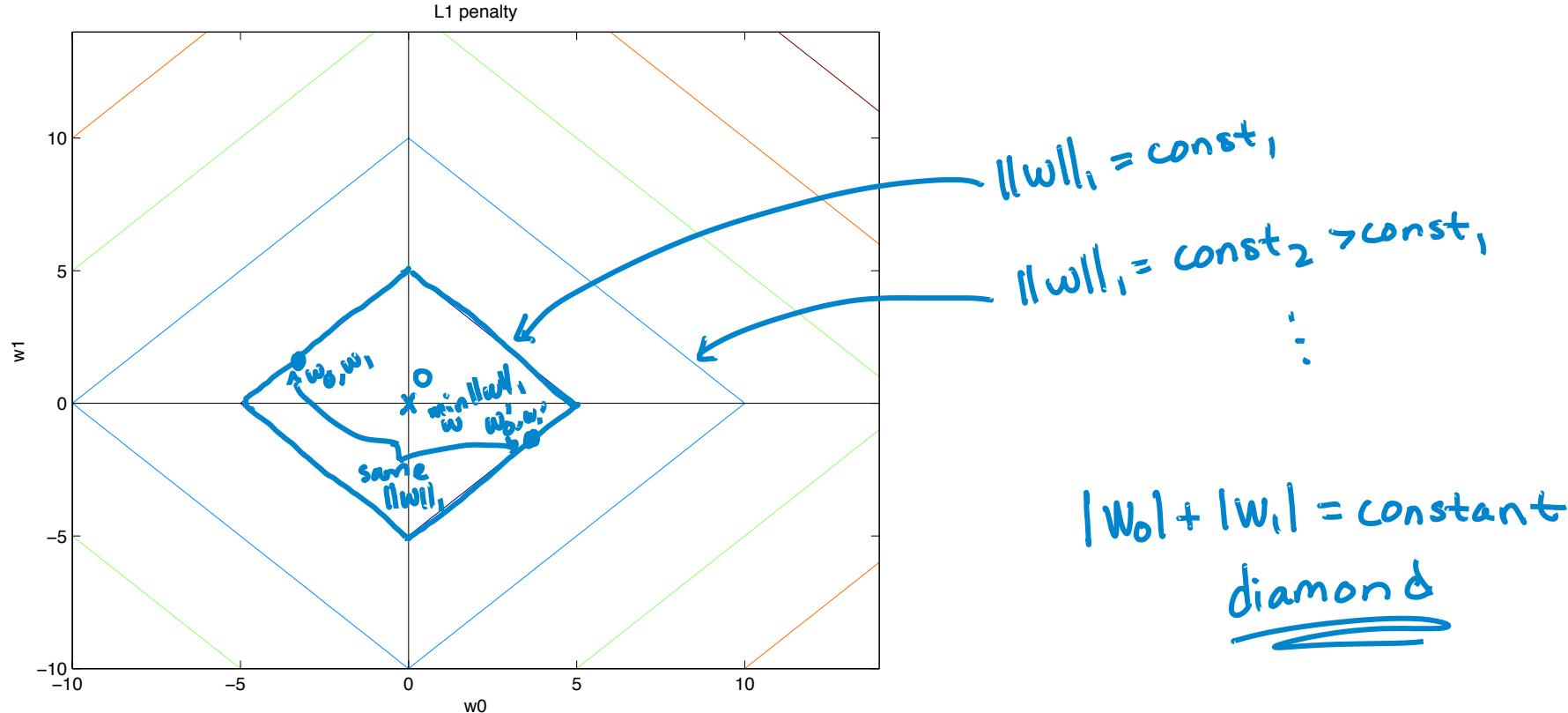
Visualizing the lasso cost in 2D



RSS contours for
lasso are exactly
the same as
those for ridge!

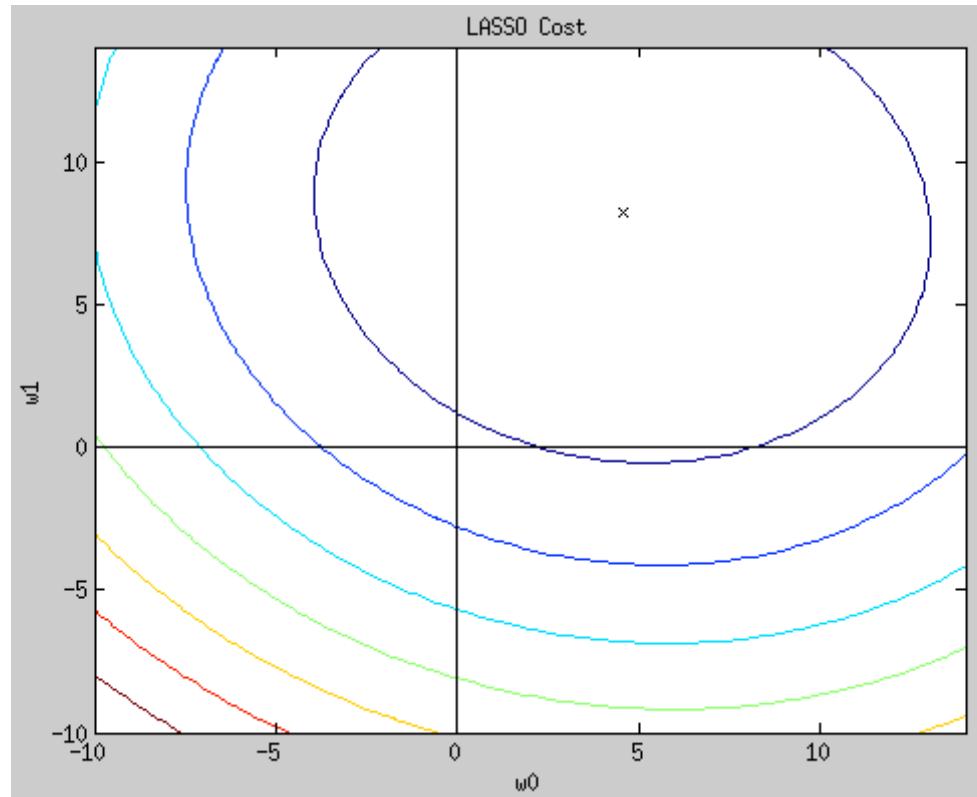
$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1 = \sum_{i=1}^N (y_i - w_0 h_0(\mathbf{x}_i) - w_1 h_1(\mathbf{x}_i))^2 + \lambda (|w_0| + |w_1|)$$

Visualizing the lasso cost in 2D



$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1 = \sum_{i=1}^N (y_i - w_0 h_0(\mathbf{x}_i) - w_1 h_1(\mathbf{x}_i))^2 + \lambda (|w_0| + |w_1|)$$

Visualizing the lasso cost in 2D

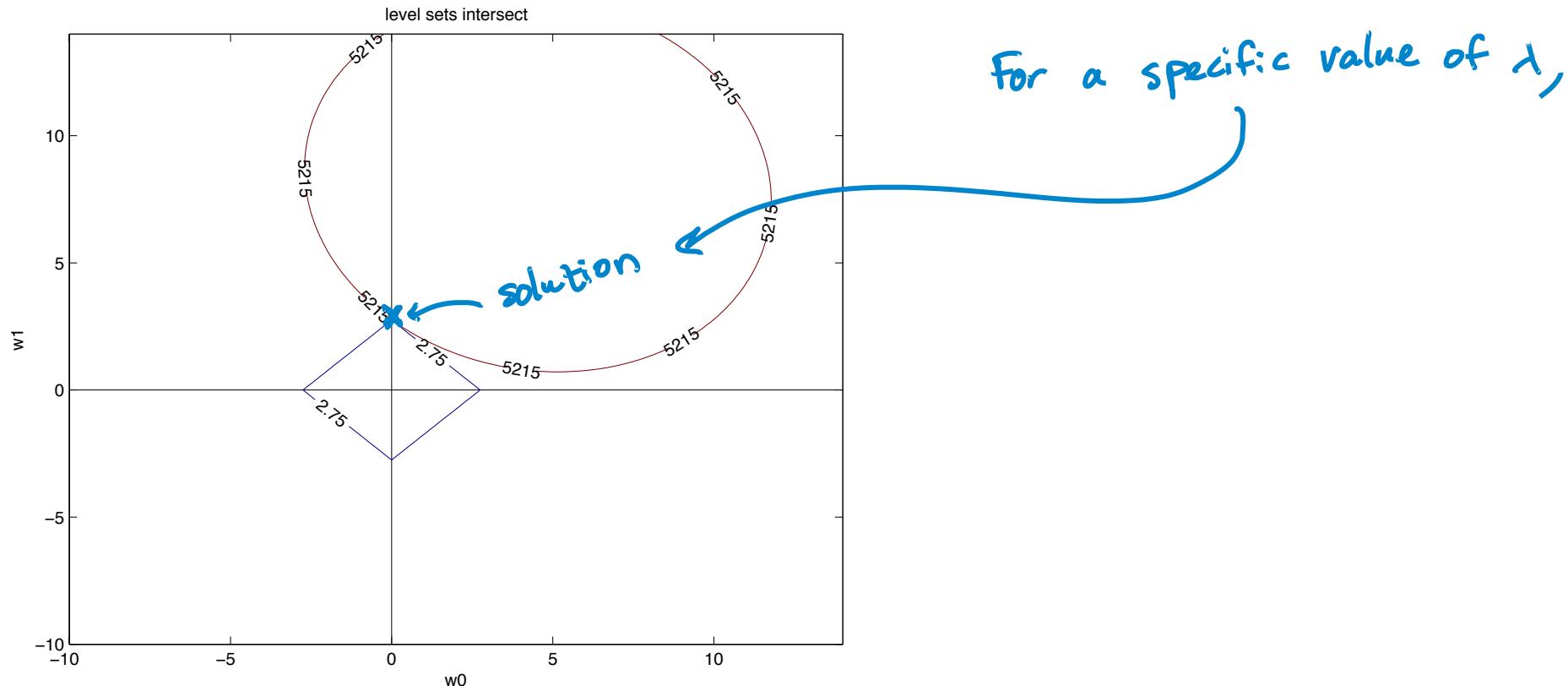


Adding
RSS + $\lambda \|\mathbf{w}\|_1$
ellipses diamonds

$x = \text{optimal } \hat{\mathbf{w}} \text{ for a specific } \lambda$

$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1 = \sum_{i=1}^N (y_i - w_0 h_0(\mathbf{x}_i) - w_1 h_1(\mathbf{x}_i))^2 + \lambda (|w_0| + |w_1|)$$

Visualizing the lasso solution



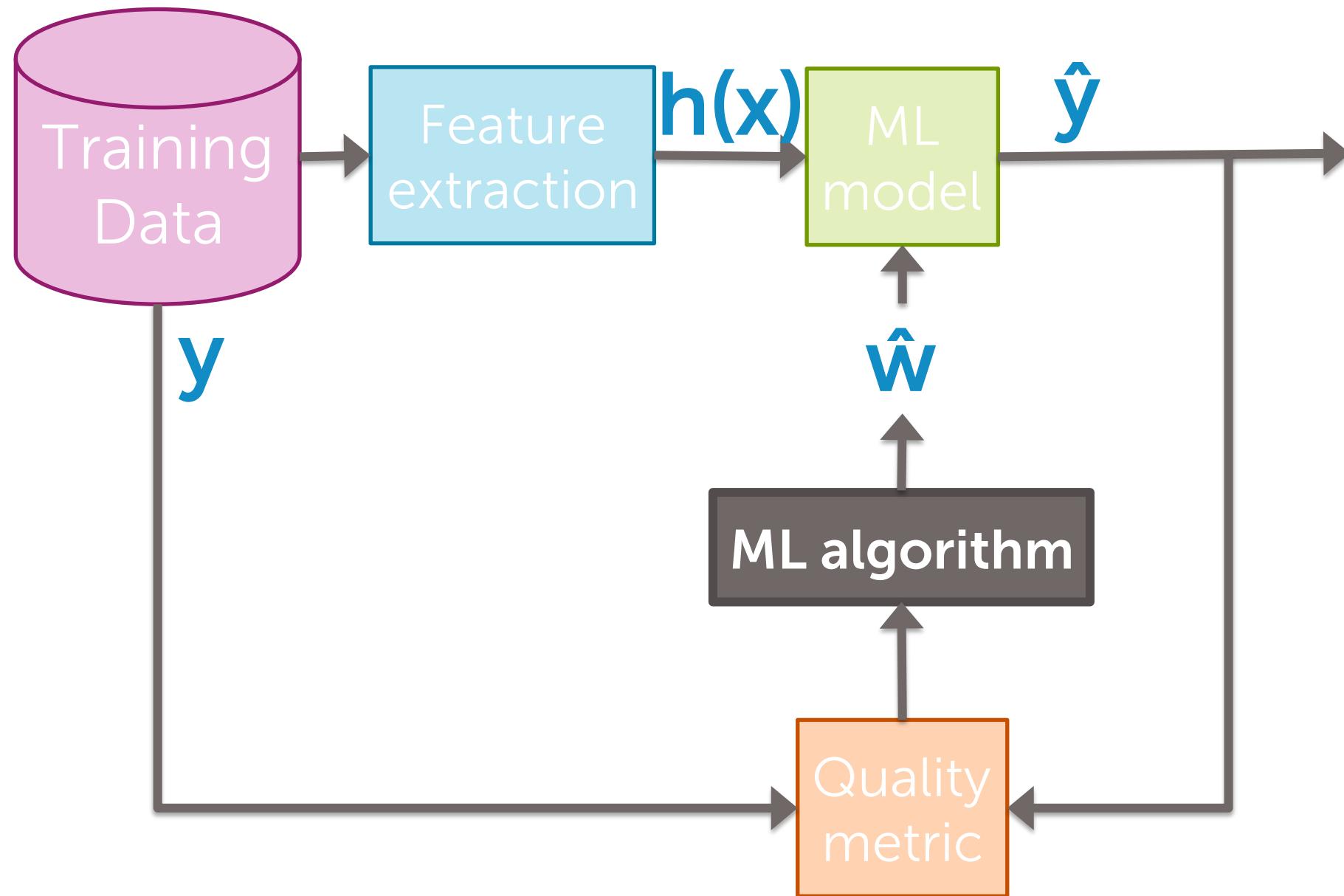
$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1 = \sum_{i=1}^N (y_i - w_0 h_0(\mathbf{x}_i) - w_1 h_1(\mathbf{x}_i))^2 + \lambda (|w_0| + |w_1|)$$

Revisit polynomial fit demo

What happens if we refit our high-order polynomial, but now using lasso regression?

Will consider a few settings of λ ...

Fitting the lasso regression model (for given λ value)



How we optimized past objectives

To solve for \hat{w} , previously took gradient of total cost objective and either:

- 1) Derived closed-form solution
- 2) Used in gradient descent algorithm

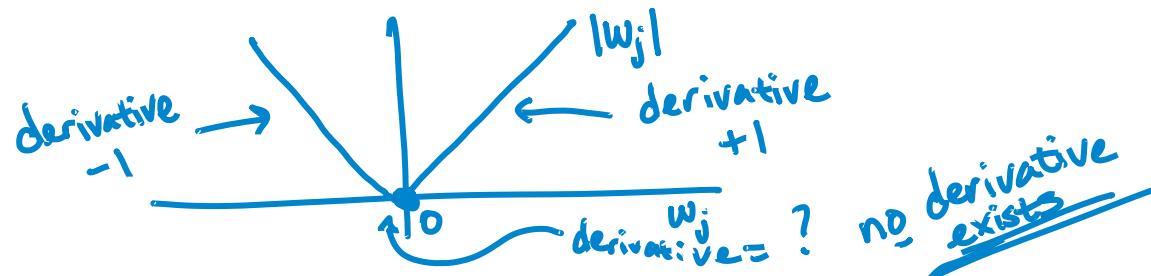
Optimizing the lasso objective

Lasso total cost: $\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1$

$\|\mathbf{w}\|_1 = \sum_{j=0}^n |w_j|$

Issues:

- 1) What's the derivative of $|w_j|$?



gradients → subgradients

- 2) Even if we could compute derivative, no closed-form solution

can use subgradient descent

Aside 1: Coordinate descent

Coordinate descent

Goal: Minimize some function g

$$\min_{\mathbf{w}} g(\mathbf{w})$$

$$g(\mathbf{w}) = g(w_0, w_1, \dots, w_D)$$

Often, hard to find minimum for all coordinates, but easy for each coordinate

when keeping others fixed

Coordinate descent:

Initialize $\hat{\mathbf{w}} = 0$ (or smartly...)

while not converged

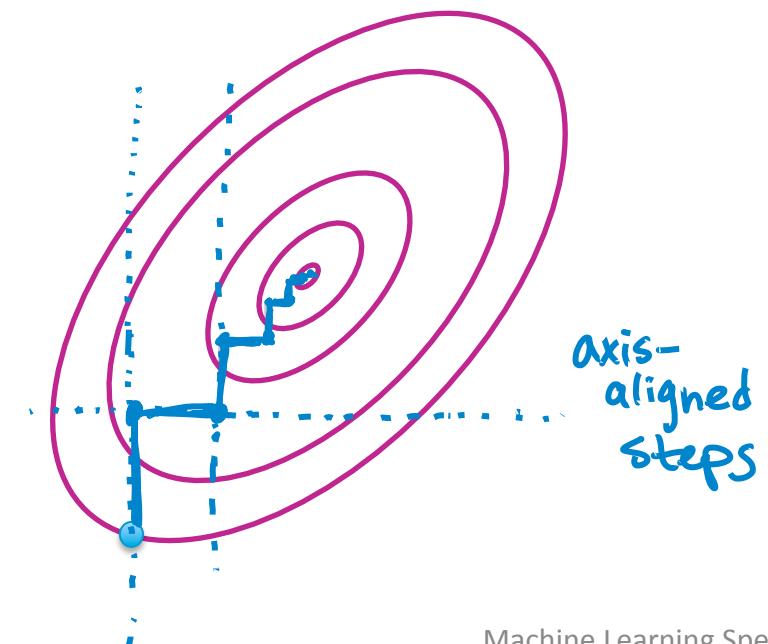
pick a coordinate j

$$\hat{w}_j \leftarrow$$

$$\min_{w_j} g(\hat{w}_0, \dots, \hat{w}_{j-1}, w_j, \hat{w}_{j+1}, \dots, \hat{w}_D)$$

values from previous iterations

just min over j'th coordinate



Comments on coordinate descent

How do we pick next coordinate?

- At random (“random” or “stochastic” coordinate descent), round robin, ...

No stepsize to choose!

Super useful approach for *many* problems

- Converges to optimum in some cases (e.g., “strongly convex”)
- Converges for lasso objective

Aside 2: Normalizing features

Normalizing features

Scale training **columns** (**not rows!**)
as:

$$\underline{h}_j(\mathbf{x}_k) = \frac{h_j(\mathbf{x}_k)}{\sqrt{\sum_{i=1}^N h_j(\mathbf{x}_i)^2}}$$

Normalizer: Z_j

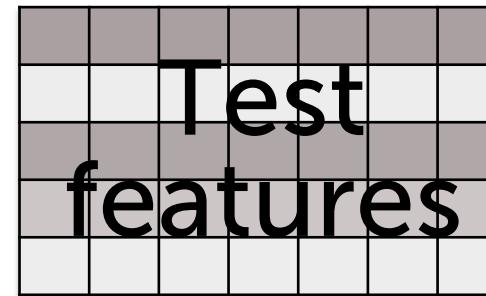
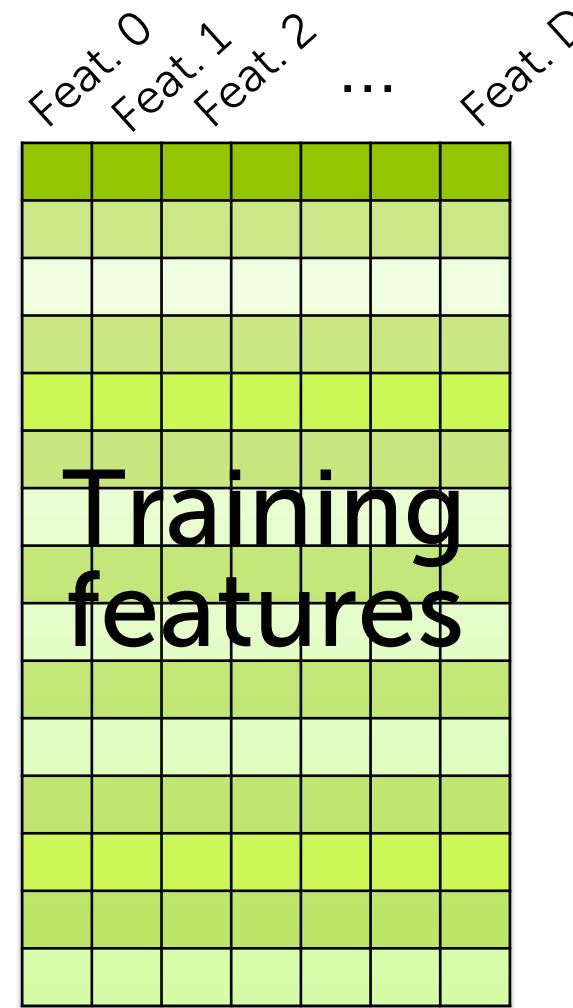
Apply same training scale factors
to test data:

$$\underline{h}_j(\mathbf{x}_k) = \frac{h_j(\mathbf{x}_k)}{\sqrt{\sum_{i=1}^N h_j(\mathbf{x}_i)^2}}$$

Normalizer: Z_j

apply to
test point

summing over
training points



Aside 3: Coordinate descent for unregularized regression (for normalized features)

Optimizing least squares objective one coordinate at a time

$$\text{RSS}(\mathbf{w}) = \sum_{i=1}^N \left(y_i - \sum_{j=0}^D w_j h_j(\mathbf{x}_i) \right)^2$$

normalized
features

Fix all coordinates w_{-j} and take partial w.r.t. w_j

$$\begin{aligned} \frac{\partial}{\partial w_j} \text{RSS}(\mathbf{w}) &= -2 \sum_{i=1}^N h_j(\mathbf{x}_i) \left(y_i - \sum_{k=0}^D w_k h_k(\mathbf{x}_i) \right) \\ &= -2 \sum_{i=1}^N h_j(\mathbf{x}_i) \left(y_i - \sum_{k \neq j} w_k h_k(\mathbf{x}_i) - w_j h_j(\mathbf{x}_i) \right) \\ &= -2 \sum_{i=1}^N h_j(\mathbf{x}_i) (y_i - \underbrace{\sum_{k \neq j} w_k h_k(\mathbf{x}_i)}_{\triangleq p_j}) + 2 w_j \underbrace{\sum_{i=1}^N h_j(\mathbf{x}_i)^2}_{\text{by definition of normalized features, } = 1} \\ &= -2 p_j + 2 w_j \end{aligned}$$

all w_k for $k \neq j$

Id optimization coordinate by coordinate

Optimizing least squares objective one coordinate at a time

$$\text{RSS}(\mathbf{w}) = \sum_{i=1}^N (y_i - \sum_{j=0}^D w_j h_j(\mathbf{x}_i))^2$$

Set partial = 0 and solve

$$\frac{\partial}{\partial w_j} \text{RSS}(\mathbf{w}) = -2\rho_j + 2w_j = 0$$
$$\hat{w}_j = \rho_j$$

Coordinate descent for least squares regression

Initialize $\hat{\mathbf{w}} = 0$ (or smartly...)

while not converged

for $j=0,1,\dots,D$

compute: $\rho_j = \sum_{i=1}^N h_j(\mathbf{x}_i) \underbrace{(y_i - \hat{y}_i(\hat{\mathbf{w}}_{-j}))}_{\begin{array}{l} \text{residual} \\ \text{without feature } j \end{array}}$

set: $\hat{w}_j = \rho_j$

\uparrow
*prediction
without feature j*

Coordinate descent for lasso (for normalized features)

Coordinate descent for least squares regression

Initialize $\hat{\mathbf{w}} = 0$ (or smartly...)

while not converged

for $j=0,1,\dots,D$

compute: $\rho_j = \sum_{i=1}^N h_j(\mathbf{x}_i)(y_i - \hat{y}_i(\hat{\mathbf{w}}_{-j}))$

set: $\hat{\mathbf{w}}_j = \rho_j$

*residual
without feature j*
 \uparrow
*prediction
without feature j*

Coordinate descent for lasso

Initialize $\hat{\mathbf{w}} = 0$ (or smartly...)

while not converged

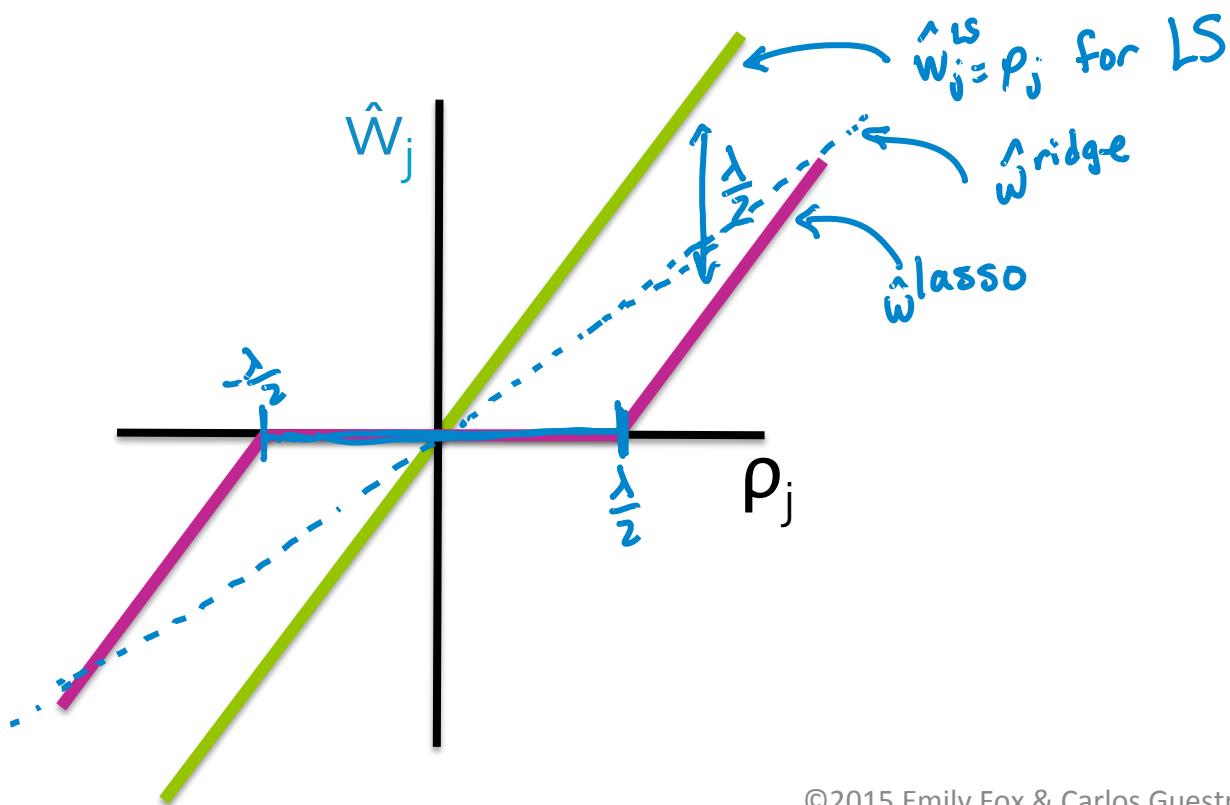
for $j=0,1,\dots,D$

compute: $\rho_j = \sum_{i=1}^N h_j(\mathbf{x}_i)(y_i - \hat{y}_i(\hat{\mathbf{w}}_{-j}))$

set: $\hat{w}_j = \begin{cases} \rho_j + \lambda/2 & \text{if } \rho_j < -\lambda/2 \\ 0 & \text{if } \rho_j \text{ in } [-\lambda/2, \lambda/2] \\ \rho_j - \lambda/2 & \text{if } \rho_j > \lambda/2 \end{cases}$

Soft thresholding

$$\hat{w}_j = \begin{cases} \rho_j + \lambda/2 & \text{if } \rho_j < -\lambda/2 \\ 0 & \text{if } \rho_j \text{ in } [-\lambda/2, \lambda/2] \\ \rho_j - \lambda/2 & \text{if } \rho_j > \lambda/2 \end{cases}$$



How to assess convergence?

Initialize $\hat{\mathbf{w}} = 0$ (or smartly...)

while not converged

for $j=0,1,\dots,D$

compute: $\rho_j = \sum_{i=1}^N h_j(\mathbf{x}_i)(y_i - \hat{y}_i(\hat{\mathbf{w}}_{-j}))$

set: $\hat{w}_j = \begin{cases} \rho_j + \lambda/2 & \text{if } \rho_j < -\lambda/2 \\ 0 & \text{if } \rho_j \text{ in } [-\lambda/2, \lambda/2] \\ \rho_j - \lambda/2 & \text{if } \rho_j > \lambda/2 \end{cases}$

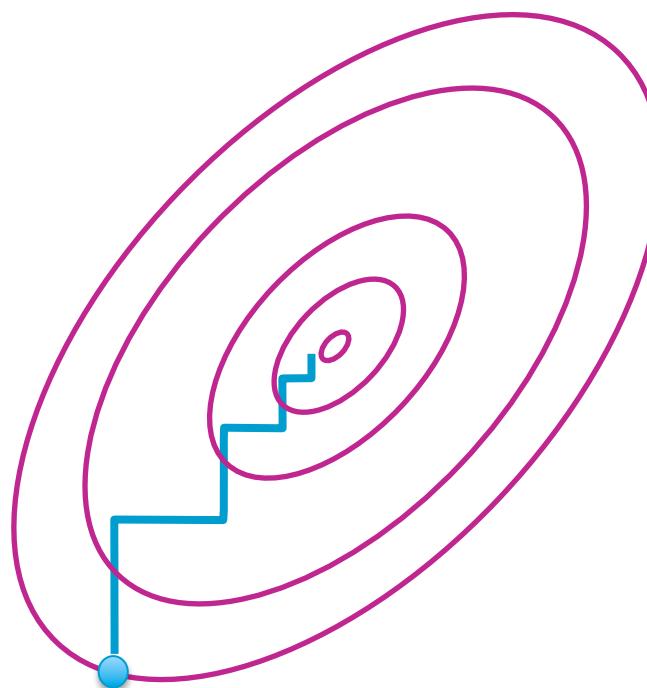
Convergence criteria

When to stop?

For convex problems, will start to take **smaller and smaller steps**

Measure size of steps taken in a full loop over all features

- stop when **max step < ϵ**



Other lasso solvers

Classically: Least angle regression (LARS) [Efron et al. '04]

Then: Coordinate descent algorithm

[Fu '98, Friedman, Hastie, & Tibshirani '08]

Now:

- Parallel CD (e.g., Shotgun, [Bradley et al. '11])
- Other parallel learning approaches for linear models
 - Parallel stochastic gradient descent (SGD) (e.g., Hogwild! [Niu et al. '11])
 - Parallel independent solutions then averaging [Zhang et al. '12]
- Alternating directions method of multipliers (ADMM) [Boyd et al. '11]

Coordinate descent for lasso (for unnormalized features)

Coordinate descent for lasso with normalized features

Initialize $\hat{\mathbf{w}} = 0$ (or smartly...)

when $j = 0$, w 对应常数项，因此 w_0 直接等于 ρ_0 即可

while not converged

for $j=0,1,\dots,D$

compute: $\rho_j = \sum_{i=1}^N h_j(\mathbf{x}_i)(y_i - \hat{y}_i(\hat{\mathbf{w}}_{-j}))$

set: $\hat{w}_j = \begin{cases} \rho_j + \lambda/2 & \text{if } \rho_j < -\lambda/2 \\ 0 & \text{if } \rho_j \in [-\lambda/2, \lambda/2] \\ \rho_j - \lambda/2 & \text{if } \rho_j > \lambda/2 \end{cases}$

Coordinate descent for lasso with unnormalized features

Precompute: $z_j = \sum_{i=1}^N h_j(\mathbf{x}_i)^2$

Initialize $\hat{\mathbf{w}} = 0$ (or smartly...)

while not converged

for $j=0,1,\dots,D$

compute: $\rho_j = \sum_{i=1}^N h_j(\mathbf{x}_i)(y_i - \hat{y}_i(\hat{\mathbf{w}}_{-j}))$

set: $\hat{w}_j = \begin{cases} (\rho_j + \lambda/2)/z_j & \text{if } \rho_j < -\lambda/2 \\ 0 & \text{if } \rho_j \in [-\lambda/2, \lambda/2] \\ (\rho_j - \lambda/2)/z_j & \text{if } \rho_j > \lambda/2 \end{cases}$

Deriving the lasso coordinate descent update

OPTIONAL



Optimizing lasso objective one coordinate at a time

$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1 = \sum_{i=1}^N \left(y_i - \sum_{j=0}^D w_j h_j(\mathbf{x}_i) \right)^2 + \lambda \sum_{j=0}^D |w_j|$$

Fix all coordinates w_{-j} and take partial w.r.t. w_j

derive *without* normalizing features

Part 1: Partial of RSS term

$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1 = \sum_{i=1}^N \left(y_i - \sum_{j=0}^D w_j h_j(\mathbf{x}_i) \right)^2 + \lambda \sum_{j=0}^D |w_j|$$

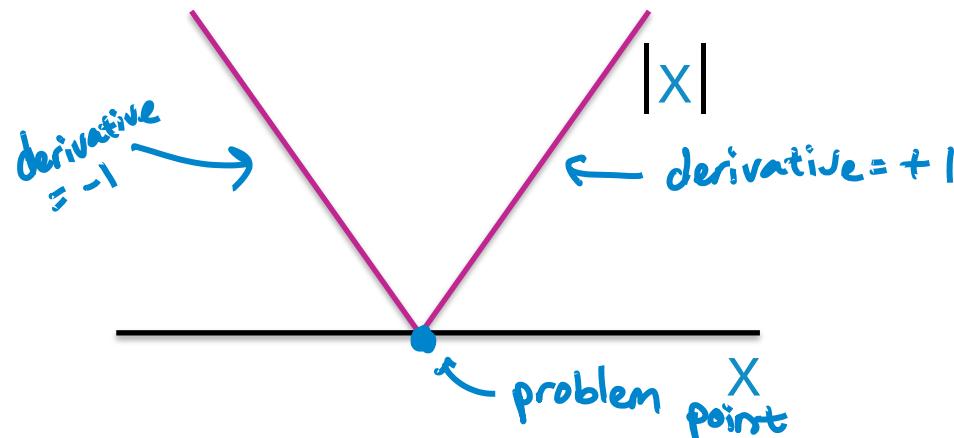
$$\begin{aligned} \frac{\partial}{\partial w_j} \text{RSS}(\mathbf{w}) &= -2 \sum_{i=1}^N h_j(\mathbf{x}_i) \left(y_i - \sum_{k=0}^D w_k h_k(\mathbf{x}_i) \right) \\ &= -2 \sum_{i=1}^N h_j(\mathbf{x}_i) \left(y_i - \sum_{k \neq j} w_k h_k(\mathbf{x}_i) - w_j h_j(\mathbf{x}_i) \right) \\ &= -2 \sum_{i=1}^N h_j(\mathbf{x}_i) \left(y_i - \sum_{k \neq j} w_k h_k(\mathbf{x}_i) \right) + 2 w_j \sum_{i=1}^N h_j(\mathbf{x}_i)^2 \\ &= -2 p_0 + 2 w_j z_j \end{aligned}$$

$\triangleq p_j$ $\triangleq z_j$

Part 2: Partial of L_1 penalty term

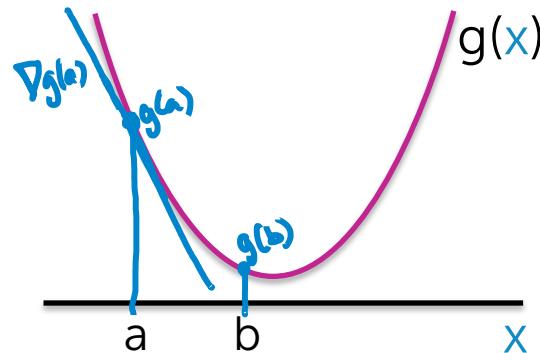
$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1 = \sum_{i=1}^N \left(y_i - \sum_{j=0}^D w_j h_j(\mathbf{x}_i) \right)^2 + \lambda \sum_{j=0}^D |w_j|$$

$$\lambda \frac{\partial}{\partial w_j} |w_j| = ???$$



Subgradients of convex functions

Gradients lower bound convex functions:

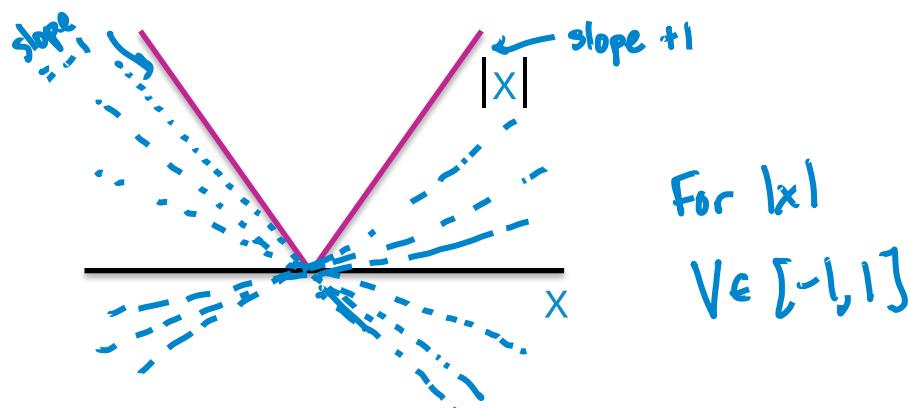


$$g(b) \geq g(a) + \underline{\nabla g(a)(b-a)}$$

unique at x if function
differentiable at x

Subgradients: Generalize gradients to non-differentiable points:

- Any plane that lower bounds function



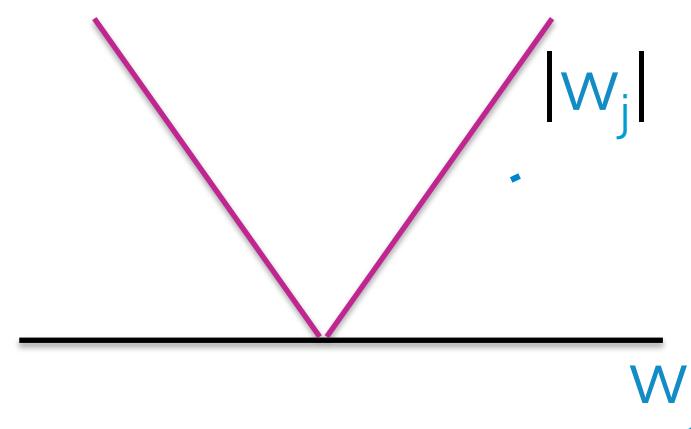
For $|x|$
 $\forall c \in [-1, 1]$

$\forall c \in \partial g(x)$ subgradient of g at x
if
 $g(b) \geq g(a) + V(b-a)$

Part 2: *Subgradient* of L₁ term

$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1 = \sum_{i=1}^N \left(y_i - \sum_{j=0}^D w_j h_j(\mathbf{x}_i) \right)^2 + \lambda \sum_{j=0}^D |w_j|$$

$$\lambda \partial_{w_j} |w_j| = \begin{cases} -\lambda & \text{when } w_j < 0 \\ [-\lambda, \lambda] & \text{when } w_j = 0 \\ \lambda & \text{when } w_j > 0 \end{cases}$$



Putting it all together...

$$\text{RSS}(\mathbf{w}) + \lambda \|\mathbf{w}\|_1 = \sum_{i=1}^N \left(y_i - \sum_{j=0}^D w_j h_j(\mathbf{x}_i) \right)^2 + \lambda \sum_{j=0}^D |w_j|$$

$$\begin{aligned} \partial_{w_j} [\text{lasso cost}] &= 2z_j w_j - 2\rho_j + \left\{ \begin{array}{ll} -\lambda & \text{when } w_j < 0 \\ [-\lambda, \lambda] & \text{when } w_j = 0 \\ \lambda & \text{when } w_j > 0 \end{array} \right. \\ &= \left\{ \begin{array}{ll} 2z_j w_j - 2\rho_j - \lambda & \text{when } w_j < 0 \\ [-2\rho_j - \lambda, -2\rho_j + \lambda] & \text{when } w_j = 0 \\ 2z_j w_j - 2\rho_j + \lambda & \text{when } w_j > 0 \end{array} \right. \end{aligned}$$

(from RSS) *(from $\lambda \|\mathbf{w}\|_1$ penalty)*

Optimal solution: Set subgradient = 0

$$\partial_{w_j} [\text{lasso cost}] = \begin{cases} 2z_j w_j - 2\rho_j - \lambda & \text{when } w_j < 0 \\ [-2\rho_j - \lambda, -2\rho_j + \lambda] & \underline{\text{when } w_j = 0} \\ 2z_j w_j - 2\rho_j + \lambda & \text{when } w_j > 0 \end{cases}$$

Case 1 ($w_j < 0$): $2z_j \hat{w}_j - 2\rho_j - \lambda = 0$

$$\hat{w}_j = \frac{2\rho_j + \lambda}{2z_j} = \frac{\rho_j + \frac{\lambda}{2}}{z_j}$$

For $\hat{w}_j < 0$, need

$$\rho_j < -\frac{\lambda}{2}$$

Case 2 ($w_j = 0$): $\hat{w}_j = 0$

For $\hat{w}_j = 0$, need $[-2\rho_j - \lambda, -2\rho_j + \lambda]$ to contain 0:
 $-2\rho_j + \lambda \geq 0 \rightarrow \rho_j \leq \frac{\lambda}{2}$ $-2\rho_j - \lambda \leq 0 \rightarrow \rho_j \geq -\frac{\lambda}{2}$ $\frac{\lambda}{2} \leq \rho_j \leq -\frac{\lambda}{2}$
so that $w_j = 0$ is an optimum

Case 3 ($w_j > 0$): $2z_j \hat{w}_j - 2\rho_j + \lambda = 0$

$$\hat{w}_j = \frac{\rho_j - \frac{\lambda}{2}}{z_j}$$

For $\hat{w}_j > 0$, need

$$\rho_j > \frac{\lambda}{2}$$

Optimal solution: Set subgradient = 0

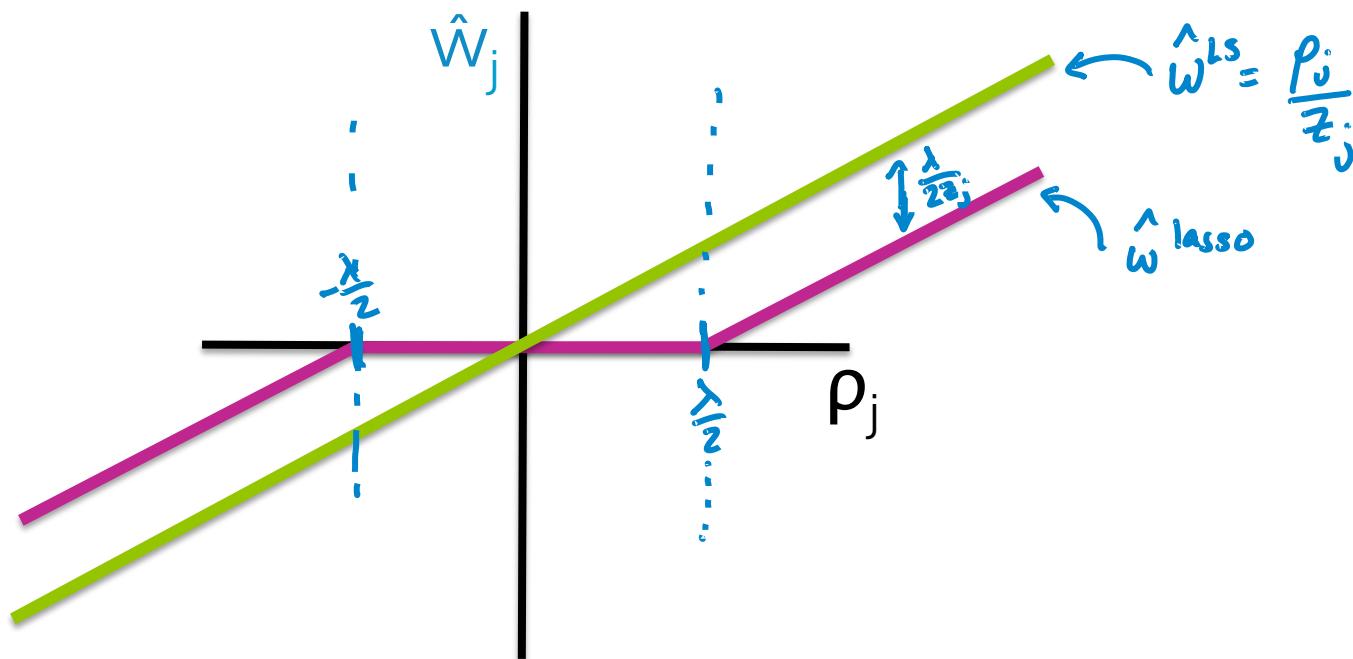
$$\partial_{w_j} [\text{lasso cost}] = \begin{cases} 2z_j w_j - 2\rho_j - \lambda & \text{when } w_j < 0 \\ [-2\rho_j - \lambda, -2\rho_j + \lambda] & \text{when } w_j = 0 \\ 2z_j w_j - 2\rho_j + \lambda & \text{when } w_j > 0 \end{cases}$$



$$\hat{w}_j = \begin{cases} (\rho_j + \lambda/2)/z_j & \text{if } \rho_j < -\lambda/2 \\ 0 & \text{if } \rho_j \in [-\lambda/2, \lambda/2] \\ (\rho_j - \lambda/2)/z_j & \text{if } \rho_j > \lambda/2 \end{cases}$$

Soft thresholding

$$\hat{w}_j = \begin{cases} (\rho_j + \lambda/2)/z_j & \text{if } \rho_j < -\lambda/2 \\ 0 & \text{if } \rho_j \text{ in } [-\lambda/2, \lambda/2] \\ (\rho_j - \lambda/2)/z_j & \text{if } \rho_j > \lambda/2 \end{cases}$$



Coordinate descent for lasso

Precompute: $z_j = \sum_{i=1}^N h_j(\mathbf{x}_i)^2$

Initialize $\hat{\mathbf{w}} = 0$ (or smartly...)

while not converged

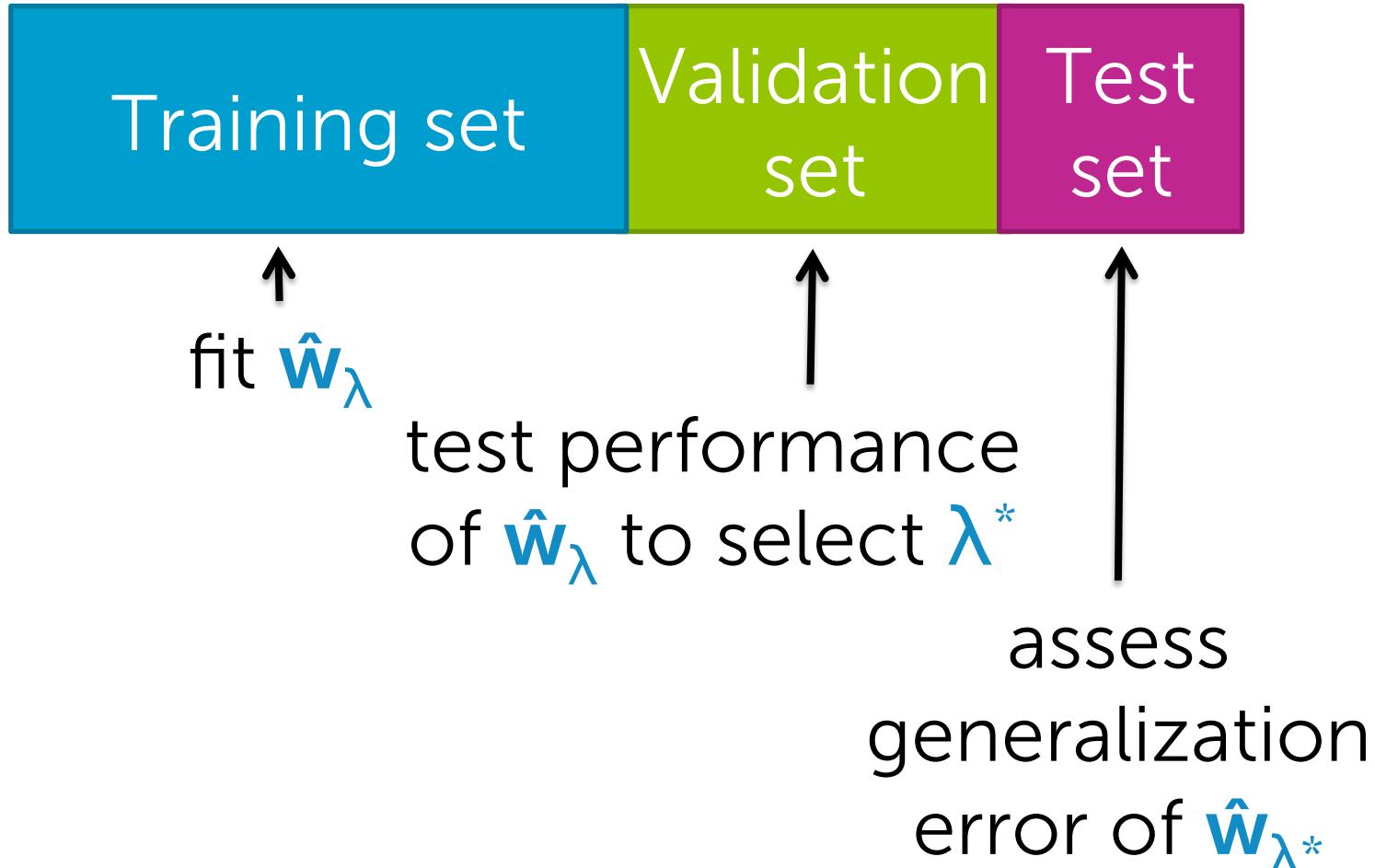
for $j=0,1,\dots,D$

compute: $\rho_j = \sum_{i=1}^N h_j(\mathbf{x}_i)(y_i - \hat{y}_i(\hat{\mathbf{w}}_{-j}))$

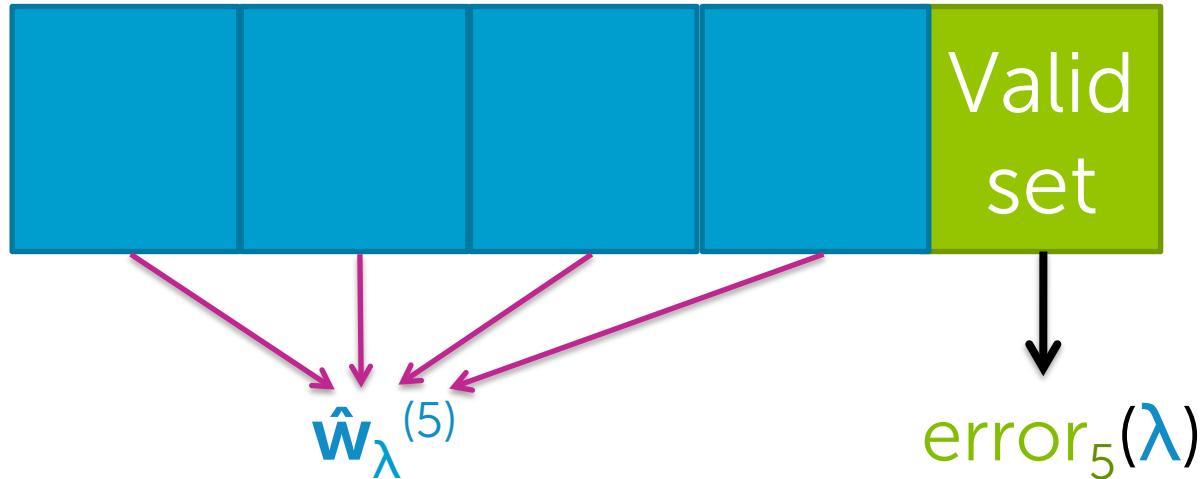
set: $\hat{w}_j = \begin{cases} (\rho_j + \lambda/2)/z_j & \text{if } \rho_j < -\lambda/2 \\ 0 & \text{if } \rho_j \in [-\lambda/2, \lambda/2] \\ (\rho_j - \lambda/2)/z_j & \text{if } \rho_j > \lambda/2 \end{cases}$

How to choose λ

If sufficient amount of data...



K-fold cross validation



For $k=1, \dots, K$

1. Estimate $\hat{w}_\lambda^{(k)}$ on the training blocks
2. Compute error on validation block: $\text{error}_k(\lambda)$

Compute average error: $\text{CV}(\lambda) = \frac{1}{K} \sum_{k=1}^K \text{error}_k(\lambda)$

Choosing λ via cross validation

Cross validation is choosing the λ that provides best predictive accuracy

Tends to favor less sparse solutions, and thus smaller λ , than optimal choice for feature selection

c.f., "Machine Learning: A Probabilistic Perspective", Murphy, 2012 for further discussion

Practical concerns with lasso

Debiasing lasso

Lasso shrinks coefficients
relative to LS solution
→ more bias, less variance

Can reduce bias as follows:

1. Run lasso to select features
2. Run least squares regression with only selected features

"Relevant" features no longer shrunk relative to LS fit of same reduced model

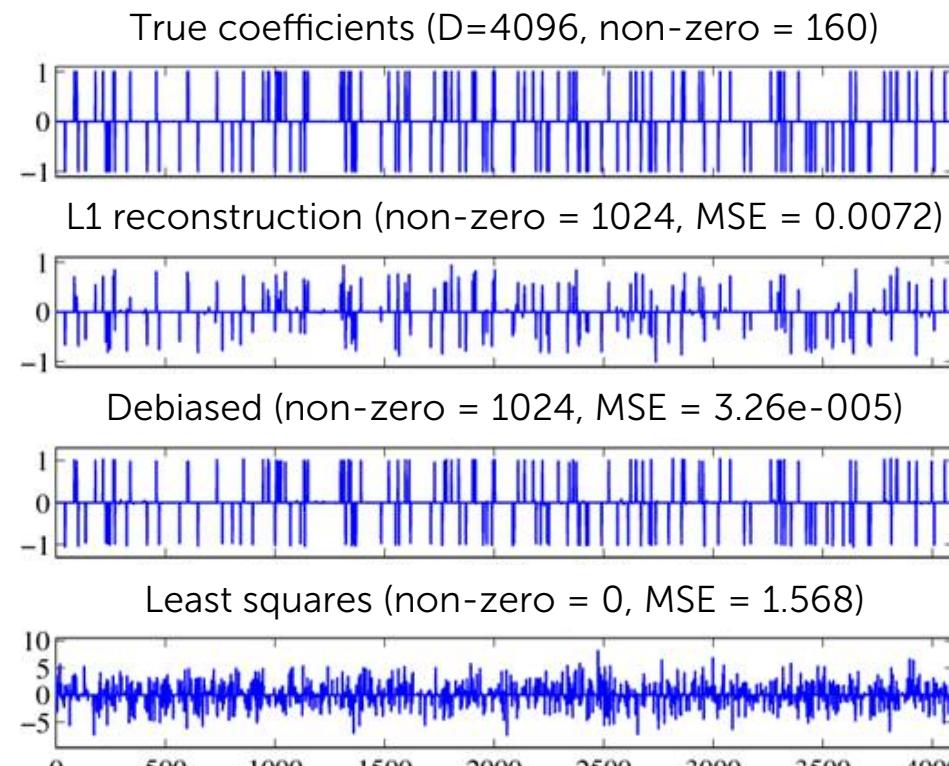


Figure used with permission of Mario Figueiredo
(captions modified to fit course)

Issues with standard lasso objective

1. With group of highly correlated features, lasso tends to select amongst them arbitrarily
 - Often prefer to select all together
2. Often, empirically ridge has better predictive performance than lasso, but lasso leads to sparser solution

Elastic net aims to address these issues

- hybrid between lasso and ridge regression
- uses L_1 and L_2 penalties

See Zou & Hastie '05 for further discussion

Summary for feature selection and lasso regression

Impact of feature selection and lasso

Lasso has changed machine learning,
statistics, & electrical engineering

But, for feature selection in general, be **careful
about interpreting selected features**

- selection only considers features included
- sensitive to correlations between features
- result depends on algorithm used
- there are theoretical guarantees for lasso under certain conditions

What you can do now...

- Perform feature selection using “all subsets” and “forward stepwise” algorithms
- Analyze computational costs of these algorithms
- Contrast greedy and optimal algorithms
- Formulate lasso objective
- Describe what happens to estimated lasso coefficients as tuning parameter λ is varied
- Interpret lasso coefficient path plot
- Contrast ridge and lasso regression
- Describe geometrically why L1 penalty leads to sparsity
- Estimate lasso regression parameters using an iterative coordinate descent algorithm
- Implement K-fold cross validation to select lasso tuning parameter λ