Lecture 38: Splatting 4

Where the Blobs Come From

CS 453 — Computer Graphics

Fakhir Shaheen

Forman Christian University

Today: blobs that place themselves

a photo



Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

Today: blobs that place themselves

a photo



500 blobs, at random



Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

Today: blobs that place themselves

a photo



500 blobs, at random



100 nudges later



Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

Today: blobs that place themselves



Nobody placed these blobs. They moved themselves.

Lecture 37 asked: who made the courtyard's blobs? This.

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

Today: three rounds of slides, then you try

1 **The start**



then You Try 1

2 **The loop**



then You Try 2, 3

3 **Grow and prune**



then You Try 4, 5

Open the Fit Lab now: the course calendar, lecture 38's row.

Pairs: one screen for two. Any browser: no WebGPU today.

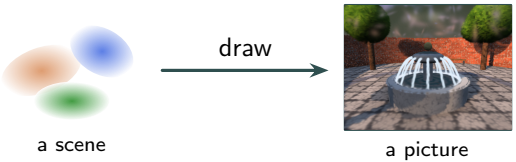
Round 1

The start

photos, cameras, and a first guess

Until now a scene went in. Today photos go in

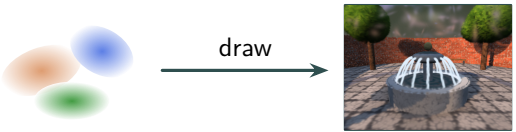
Lectures 13 to 37



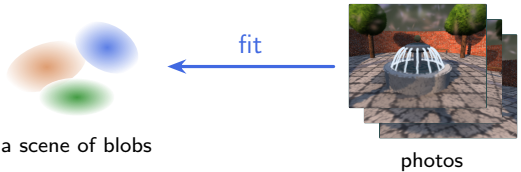
- A scene in, a picture out.

Until now a scene went in. Today photos go in

Lectures 13 to 37



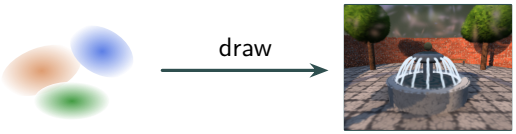
Today



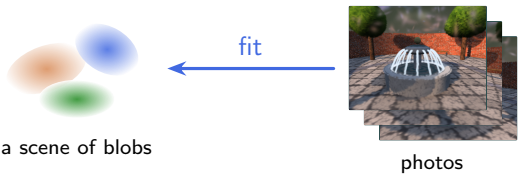
- A scene in, a picture out.
- Today: backwards.

Until now a scene went in. Today photos go in

Lectures 13 to 37

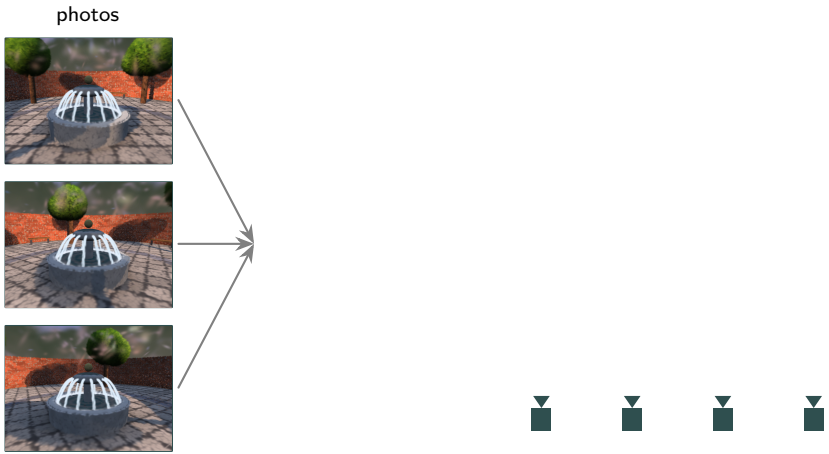


Today



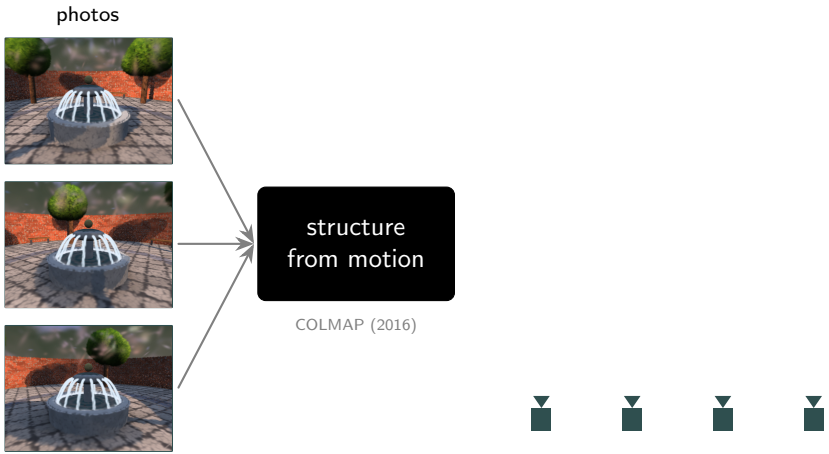
- A scene in, a picture out.
- Today: backwards.
- Blobs that draw the photos.

Where was each photo taken? A program works it out



Kerbl et al. 2023, section 3: cameras "calibrated by SfM". Schönberger and Frahm, CVPR 2016. Photos: lecture 37's stand-in.

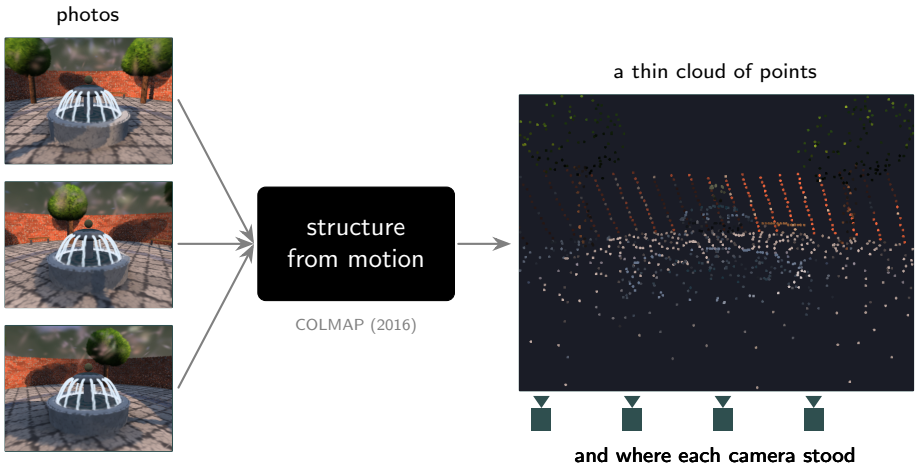
Where was each photo taken? A program works it out



A black box: we do not open it.

Kerbl et al. 2023, section 3: cameras "calibrated by SfM". Schönberger and Frahm, CVPR 2016. Photos: lecture 37's stand-in.

Where was each photo taken? A program works it out

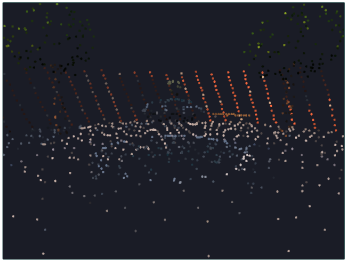


A black box: we do not open it.

Points: spots seen in two photos.

Kerbl et al. 2023, section 3: cameras "calibrated by SfM". Schönberger and Frahm, CVPR 2016. Photos: lecture 37's stand-in.

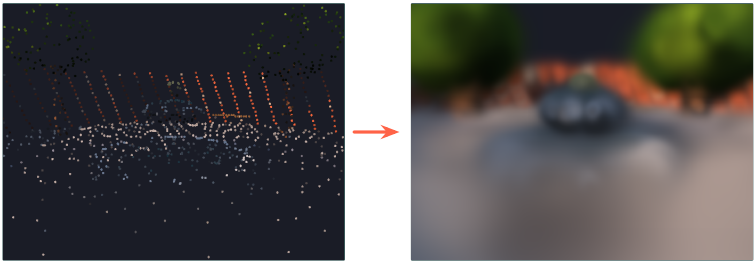
One round blob on each point



the points

Kerbl et al. 2023, section 5.1

One round blob on each point



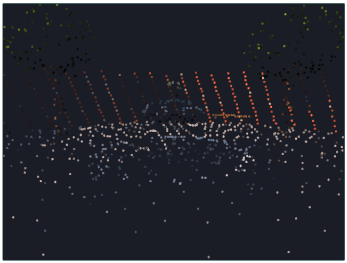
the points

a blob on each

- Round, the point's colour.

Kerbl et al. 2023, section 5.1

One round blob on each point



the points



a blob on each

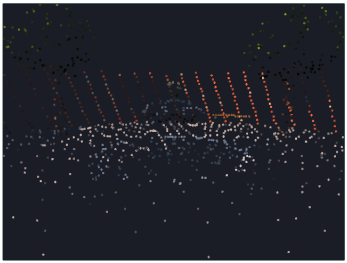
- Round, the point's colour.



size: the mean distance to its 3 nearest points

Kerbl et al. 2023, section 5.1

One round blob on each point



the points



a blob on each

- Round, the point's colour.
- A blur: only a start.



size: the mean distance to its 3 nearest points

Kerbl et al. 2023, section 5.1

Today in 2D: one photo, blobs on random pixels

the photo: the scene



▶ **Run it in the Fit Lab:**
The fit: 500 blobs

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

Today in 2D: one photo, blobs on random pixels

the photo: the scene



500 blobs, at step 0



- Anywhere, all one size.

▶ **Run it in the Fit Lab:**
The fit: 500 blobs

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

Today in 2D: one photo, blobs on random pixels

the photo: the scene



500 blobs, at step 0



- Anywhere, all one size.
- Colour: the photo under it.

▶ **Run it in the Fit Lab:**
The fit: 500 blobs

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

Today in 2D: one photo, blobs on random pixels

the photo: the scene



500 blobs, at step 0



- Anywhere, all one size.
- Colour: the photo under it.

The paper starts its made-up scenes at random too: 100,000 blobs.

Kerbl et al. 2023, section 7.2.

▶ **Run it in the Fit Lab:**
The fit: 500 blobs

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

You Try 1: start in a corner

In the Fit Lab, choose **You Try 1**. Guess first, then change a setting.

```
start = "random";
```

change this line

the room, at step 100

- **All in the top left.**
- Guess: what fills the rest?

now



after your change



You Try 1: start in a corner

In the Fit Lab, choose **You Try 1**. Guess first, then change a setting.

```
start = "random";
```

change this line

the room, at step 100

answer: `start = "corner";`

now



after your change



- **All in the top left.**
- Guess: what fills the rest?
- They stream out. Slow, and worse.

You Try 1: start in a corner

In the Fit Lab, choose **You Try 1**. Guess first, then change a setting.

```
start = "random";
```

change this line

the room, at step 100

answer: `start = "corner";`

now



after your change



- **All in the top left.**
- Guess: what fills the rest?
- They stream out. Slow, and worse.

step 2000: 5 times the error



Round 2

The loop

draw, compare, nudge, repeat

The loop: draw, compare, nudge, repeat

1. draw



the blobs, as they are

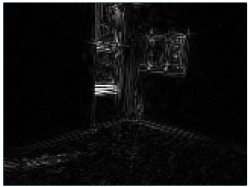
The loop: draw, compare, nudge, repeat

1. draw



the blobs, as they are

2. compare



with the photo: one number

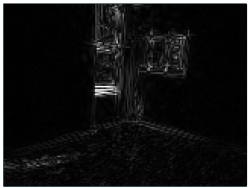
The loop: draw, compare, nudge, repeat

1. draw



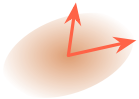
the blobs, as they are

2. compare



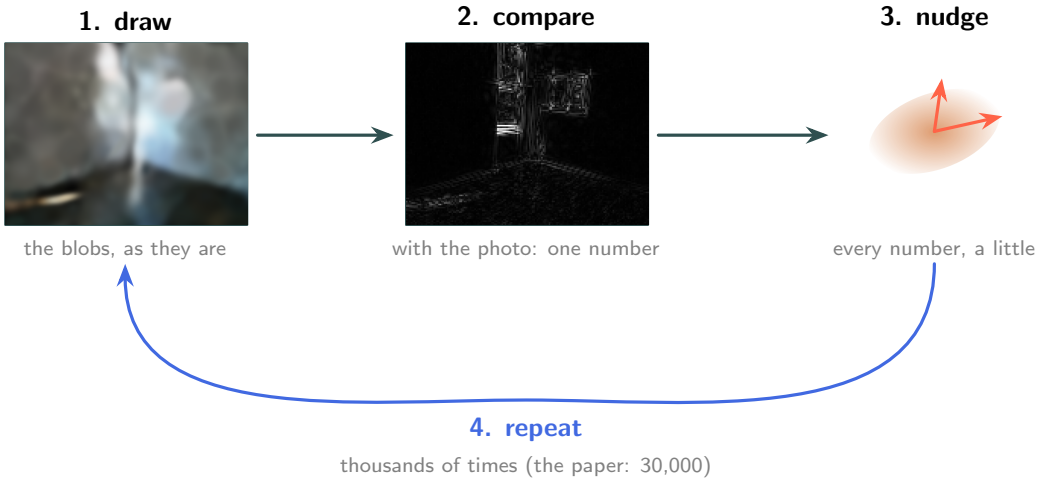
with the photo: one number

3. nudge



every number, a little

The loop: draw, compare, nudge, repeat



The error: one number for the whole picture

the blobs (step 100)



—

the photo



Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

The error: one number for the whole picture

the blobs (step 100)



—

the photo



=

the difference

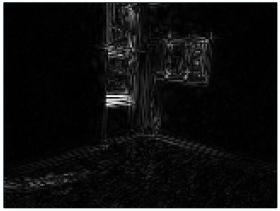


Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

The error: one number for the whole picture

the blobs (step 100)



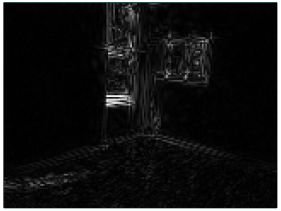
$-$

the photo



$=$

the difference



error $=$ the average, over every pixel, of $(\text{blobs} - \text{photo})^2$

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

The error: one number for the whole picture

the blobs (step 100)



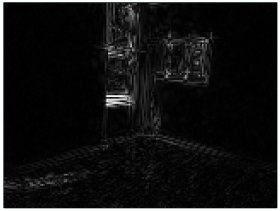
$-$

the photo



$=$

the difference



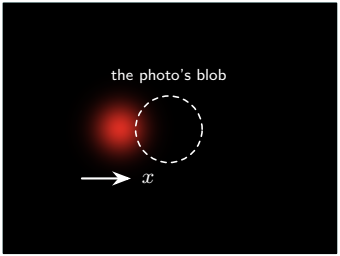
error $=$ the average, over every pixel, of $(\text{blobs} - \text{photo})^2$

here: 0.0008. Perfect: 0.

The paper's error adds a measure of structure: $0.8\,L_1 + 0.2$ D-SSIM (Kerbl et al. 2023, section 5.1).

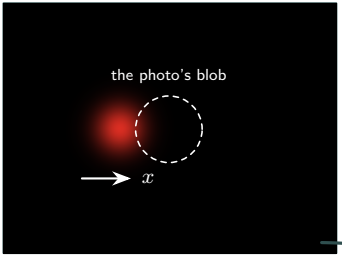
Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

One blob, one number: slide it sideways

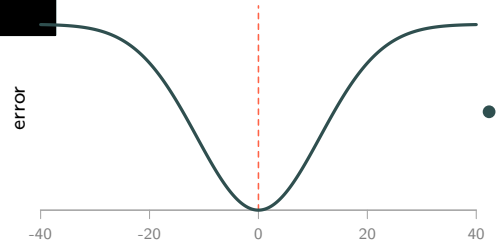


ours: only x may move

One blob, one number: slide it sideways

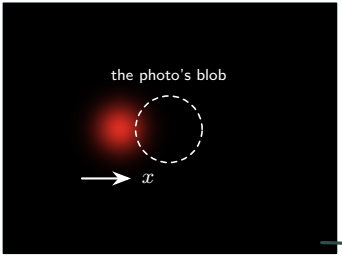


ours: only x may move

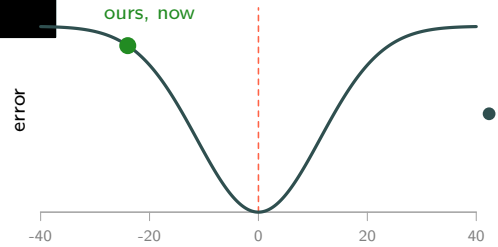


- Try every x: a valley.

One blob, one number: slide it sideways

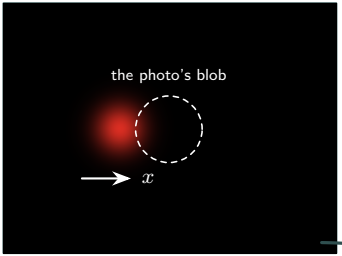


ours: only x may move

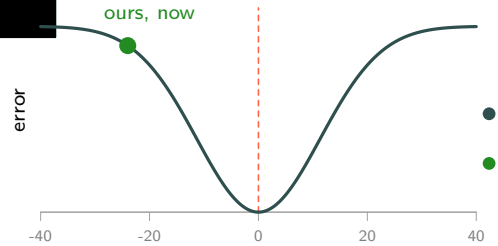


- Try every x: a valley.

One blob, one number: slide it sideways



ours: only x may move



- Try every x: a valley.
- The bottom: on the photo's blob.

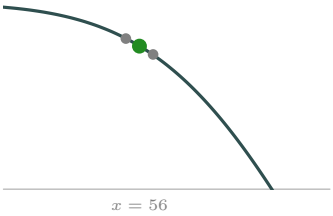
Worked: which way is downhill?

Ours is at $x = 56$. Draw it twice, a pixel to each side:

error at $x = 55$: 4.99 error at $x = 57$: 4.78 (thousandths)

rate $= 20$

Try first: the slope at 56, then the new x.



Worked: which way is downhill?

Ours is at $x = 56$. Draw it twice, a pixel to each side:

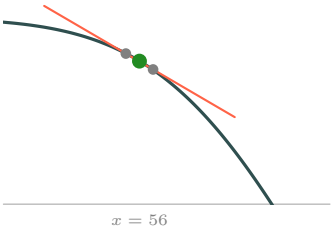
error at $x = 55$: 4.99 error at $x = 57$: 4.78 (thousandths)

rate $= 20$

Try first: the slope at 56, then the new x.

slope $= (4.78 - 4.99) / 2 = -0.105$

lecture 33's normal: ask a little to each side



Worked: which way is downhill?

Ours is at $x = 56$. Draw it twice, a pixel to each side:

error at $x = 55$: 4.99 error at $x = 57$: 4.78 (thousandths)

rate $= 20$

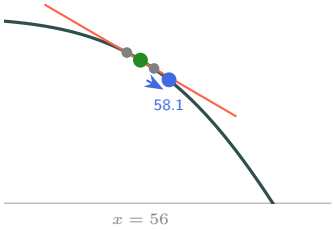
Try first: the slope at 56, then the new x.

slope $= (4.78 - 4.99) / 2 = -0.105$

lecture 33's normal: ask a little to each side

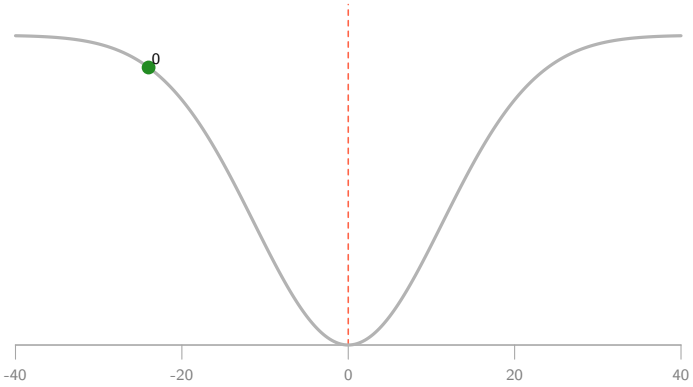
new $x = 56 - 20 \times (-0.105) = 58.1$

downhill is to the right: towards the photo's blob



Walk downhill: big steps where it is steep

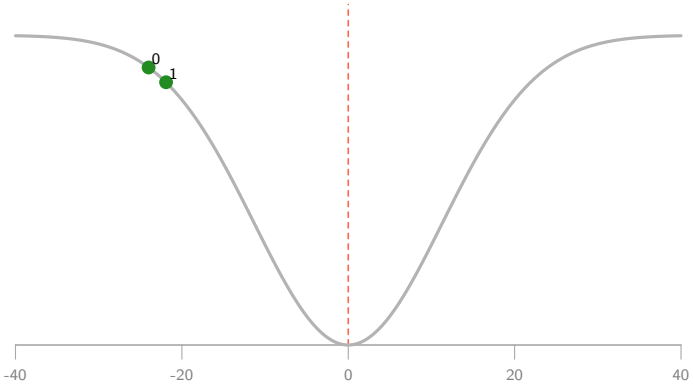
$$x \leftarrow x - \text{rate} \times \text{slope}$$



▶ **Run it in the Fit Lab:**
One blob, one number

Walk downhill: big steps where it is steep

$$x \leftarrow x - \text{rate} \times \text{slope}$$

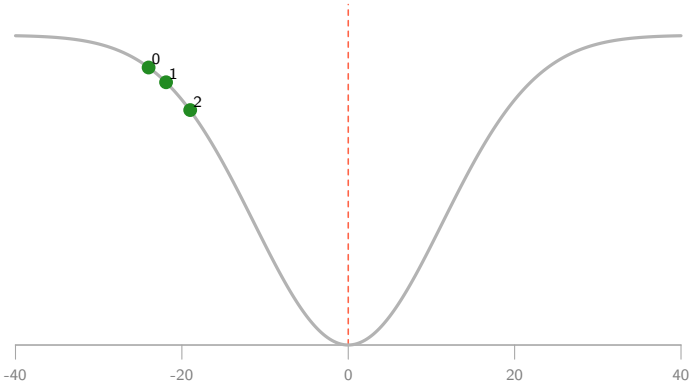


- Steep: a big step.

▶ **Run it in the Fit Lab:**
One blob, one number

Walk downhill: big steps where it is steep

$$x \leftarrow x - \text{rate} \times \text{slope}$$

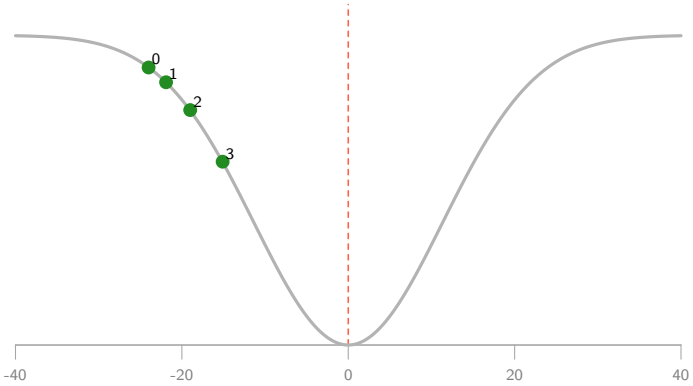


- Steep: a big step.

▶ **Run it in the Fit Lab:**
One blob, one number

Walk downhill: big steps where it is steep

$$x \leftarrow x - \text{rate} \times \text{slope}$$

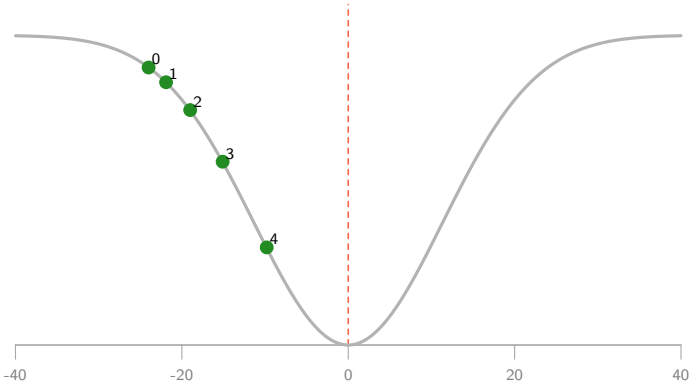


- Steep: a big step.

▶ **Run it in the Fit Lab:**
One blob, one number

Walk downhill: big steps where it is steep

$$x \leftarrow x - \text{rate} \times \text{slope}$$

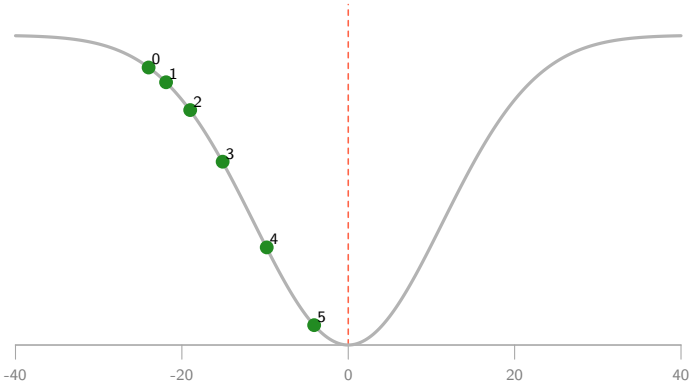


- Steep: a big step.

▶ **Run it in the Fit Lab:**
One blob, one number

Walk downhill: big steps where it is steep

$$x \leftarrow x - \text{rate} \times \text{slope}$$

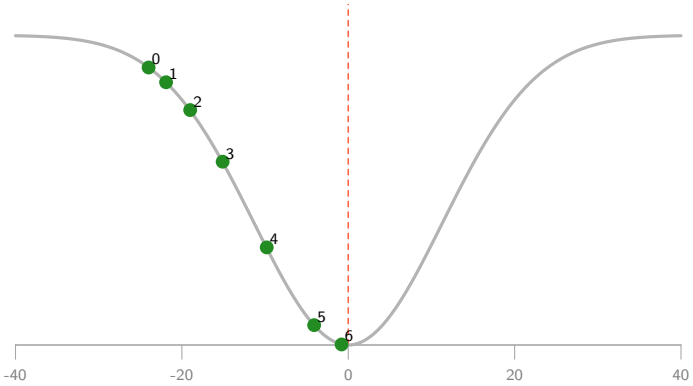


- Steep: a big step.
- Flat at the bottom: it stops.

▶ **Run it in the Fit Lab:**
One blob, one number

Walk downhill: big steps where it is steep

$$x \leftarrow x - \text{rate} \times \text{slope}$$



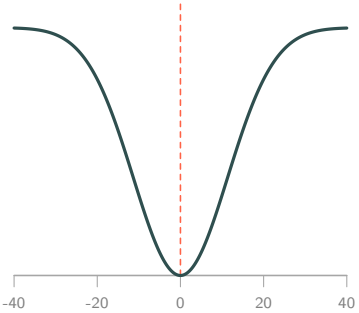
- Steep: a big step.
- Flat at the bottom: it stops.

▶ **Run it in the Fit Lab:**
One blob, one number

A hard edge has no slope

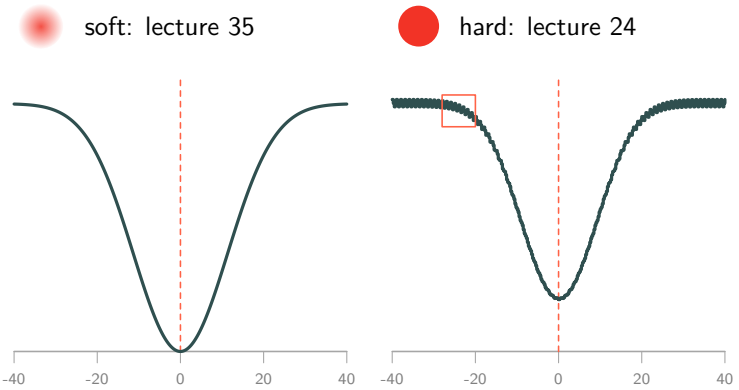


soft: lecture 35



x, pixels from the photo's blob

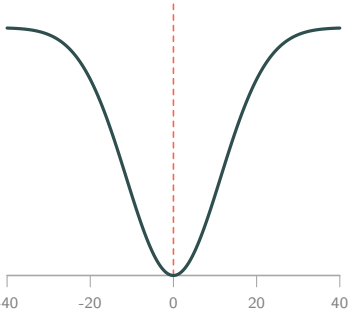
A hard edge has no slope



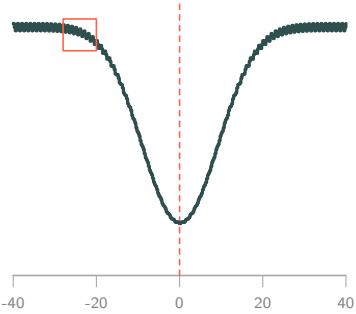
x, pixels from the photo's blob

A hard edge has no slope

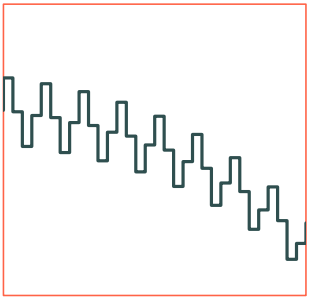
soft: lecture 35



hard: lecture 24



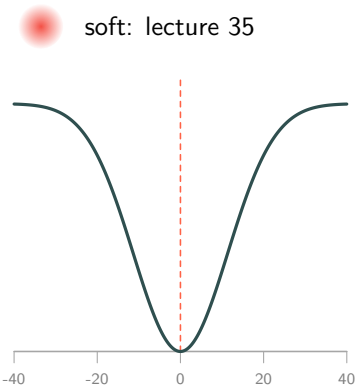
close up

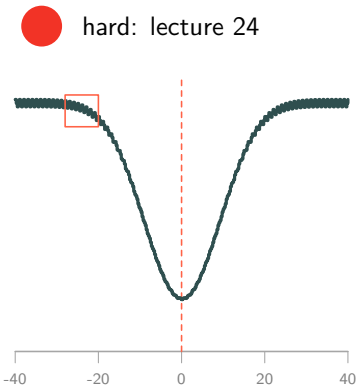


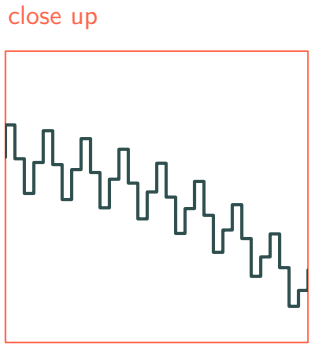
flat, then a jump

x, pixels from the photo's blob

A hard edge has no slope







x, pixels from the photo's blob

Flat: the slope is 0. Only the soft edge says which way to move.

One slope by trying costs two draws



nudge one number, draw again

(lecture 33's normal; slide 14)

One slope by trying costs two draws



nudge one number, draw again

(lecture 33's normal; slide 14)

ours 500 blobs $\times$ 9 numbers $\times$ 2 draws $= 9{,}000$ draws a step

One slope by trying costs two draws



nudge one number, draw again

(lecture 33's normal; slide 14)

ours 500 blobs $\times$ 9 numbers $\times$ 2 draws $= 9{,}000$ draws a step

the paper millions of blobs $\times$ 59 numbers: hundreds of millions

59: position 3, sizes 3, turn 4, opacity 1, colour 48 (lecture 37, slide 16)

One slope by trying costs two draws



nudge one number, draw again

(lecture 33's normal; slide 14)

ours 500 blobs $\times$ 9 numbers $\times$ 2 draws $= 9{,}000$ draws a step

the paper millions of blobs $\times$ 59 numbers: hundreds of millions

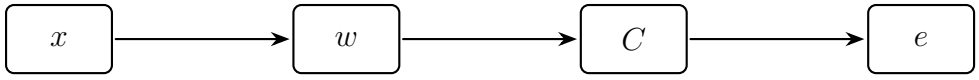
59: position 3, sizes 3, turn 4, opacity 1, colour 48 (lecture 37, slide 16)

Too slow. Work the slope out by hand instead.

The slope by hand: a chain from x to the error



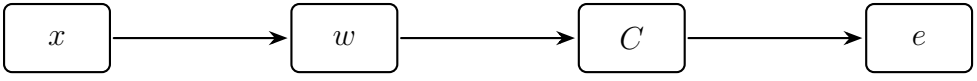
The slope by hand: a chain from x to the error



$$w \cdot \frac{p - x}{s^2}$$

lecture 35's $e^{-(p-x)^2/2s^2}$

The slope by hand: a chain from x to the error



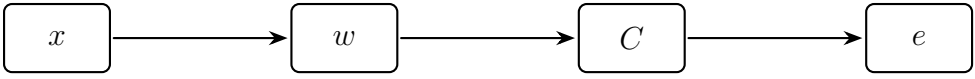
$$w \cdot \frac{p - x}{s^2}$$

lecture 35's $e^{-(p-x)^2/2s^2}$

$$\text{opacity}\,(\text{colour} - \text{behind})$$

lecture 35's blend

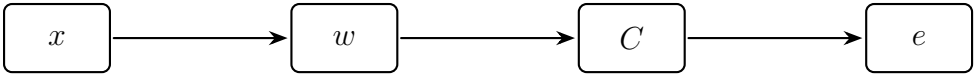
The slope by hand: a chain from x to the error



$$w \cdot \frac{p - x}{s^2} \qquad \text{opacity}\,(\text{colour} - \text{behind}) \qquad 2\,(C - \text{photo})$$

lecture 35's $e^{-(p-x)^2/2s^2}$ lecture 35's blend slide 12's square

The slope by hand: a chain from x to the error

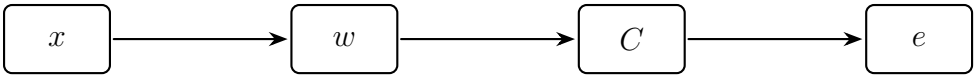


$$w \cdot \frac{p - x}{s^2} \qquad \text{opacity}\,(\text{colour} - \text{behind}) \qquad 2\,(C - \text{photo})$$

lecture 35's $e^{-(p-x)^2/2s^2}$ | lecture 35's blend | slide 12's square

slope of e for x = the three, multiplied, added over every pixel

The slope by hand: a chain from x to the error



$$w \cdot \frac{p - x}{s^2} \qquad \text{opacity}\,(\text{colour} - \text{behind}) \qquad 2\,(C - \text{photo})$$

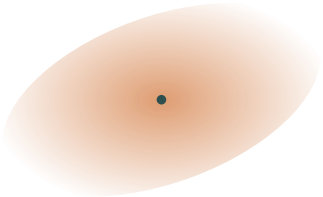
lecture 35's $e^{-(p-x)^2/2s^2}$ | lecture 35's blend | slide 12's square

slope of e for x = the three, multiplied, added over every pixel

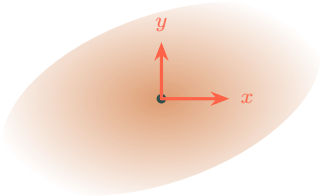
One draw, then back through each pixel's blobs: every slope at once.

fit.js, draw(), "the slopes". p: the pixel; s: the blob's size. Machine learning calls this backpropagation.

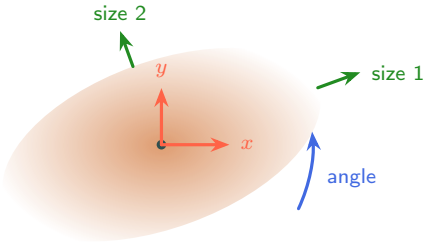
Every number of every blob, nudged at once



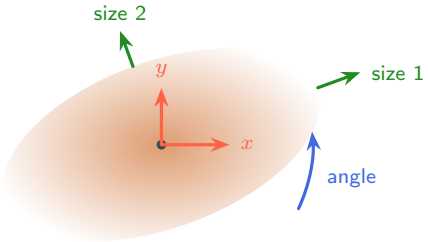
Every number of every blob, nudged at once



Every number of every blob, nudged at once



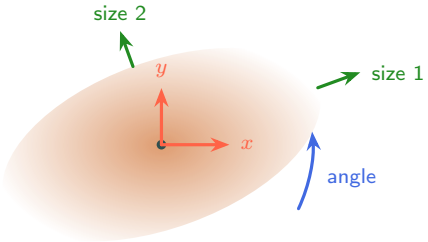
Every number of every blob, nudged at once

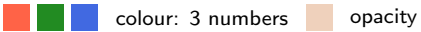


colour: 3 numbers opacity

- 9 numbers a blob.

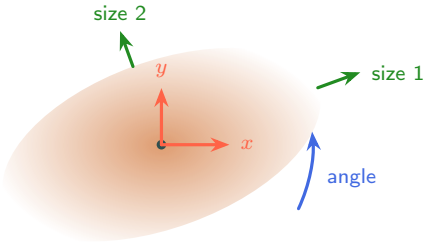
Every number of every blob, nudged at once





- 9 numbers a blob.
- 500 blobs: 4,500, every step.

Every number of every blob, nudged at once



colour: 3 numbers opacity

- 9 numbers a blob.
- 500 blobs: 4,500, every step.
- Each its own slope, its own nudge.

Our nudge, like the paper's code: Adam (Kingma and Ba, 2015), a steadier step.

The fit at steps 0, 10, 100, 1000 and 10,000

step 0



▶ **Run it in the Fit Lab:**
The fit: 500 blobs

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

The fit at steps 0, 10, 100, 1000 and 10,000

step 0



step 10



▶ **Run it in the Fit Lab:**
The fit: 500 blobs

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

The fit at steps 0, 10, 100, 1000 and 10,000

step 0



step 10



step 100

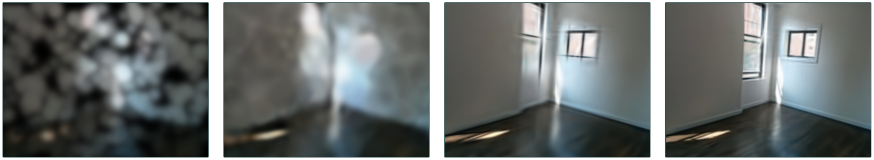


▶ **Run it in the Fit Lab:**
The fit: 500 blobs

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

The fit at steps 0, 10, 100, 1000 and 10,000

step 0 | step 10 | step 100 | step 1000



▶ **Run it in the Fit Lab:**
The fit: 500 blobs

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

The fit at steps 0, 10, 100, 1000 and 10,000

step 0



step 10



step 100



step 1000



step 10,000



▶ **Run it in the Fit Lab:**
The fit: 500 blobs

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

The fit at steps 0, 10, 100, 1000 and 10,000

step 0 | step 10 | step 100 | step 1000 | step 10,000



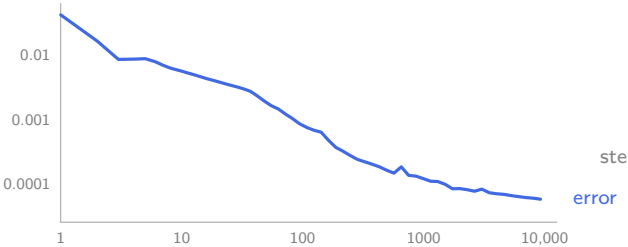


Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

▶ **Run it in the Fit Lab:**
The fit: 500 blobs

You Try 2: a hard edge

In the Fit Lab, choose **You Try 2**. Guess first, then change a setting.

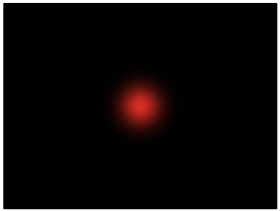
```
edge = "soft";
```

change this line

one blob, after 150 steps

- **Lecture 24's edge.**
- Guess: does it still walk?

now



after your change



You Try 2: a hard edge

In the Fit Lab, choose **You Try 2**. Guess first, then change a setting.

```
edge = "soft";
```

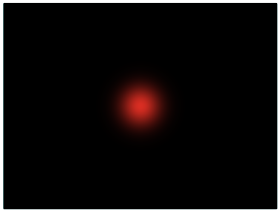
change this line

one blob, after 150 steps

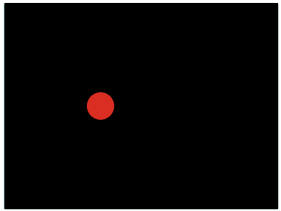
answer: `edge = "hard";`

- **Lecture 24's edge.**
- Guess: does it still walk?
- It never moves: slope 0.

now



after your change



You Try 3: steps 20 times too big

In the Fit Lab, choose **You Try 3**. Guess first, then change a setting.

```
step_size = 1;
```

change this line

the room, at step 2000

- **20 times bigger.**
- Guess: faster?

now



after your change



You Try 3: steps 20 times too big

In the Fit Lab, choose **You Try 3**. Guess first, then change a setting.

`step_size = 1;` change this line

the room, at step 2000

answer: `step_size = 20;`

- **20 times bigger.**
- Guess: faster?
- Overshoots. Blobs blow up.

now



after your change



You Try 3: steps 20 times too big

In the Fit Lab, choose **You Try 3**. Guess first, then change a setting.

`step_size = 1;` change this line

the room, at step 2000

answer: `step_size = 20;`

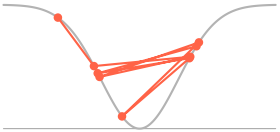
now



after your change



- **20 times bigger.**
- Guess: faster?
- Overshoots. Blobs blow up.



one blob, rate 100: it bounces

Round 3

Grow and prune

blobs where the detail is

Where detail is missing, blobs are pushed hardest

50 blobs, step 99



- 50: too few.

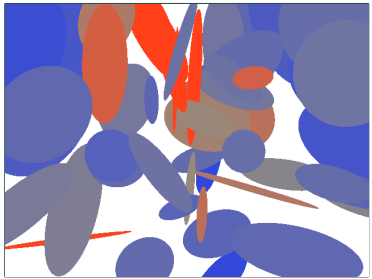
Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

Where detail is missing, blobs are pushed hardest

50 blobs, step 99



each blob: how hard it was pushed





least hardest

- 50: too few.
- Red: a big push, step after step.

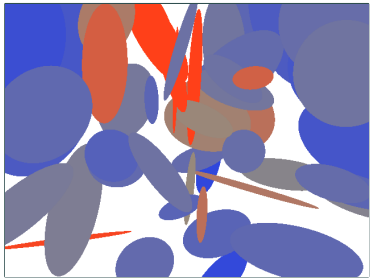
Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

Where detail is missing, blobs are pushed hardest

50 blobs, step 99



each blob: how hard it was pushed



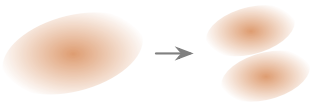


- 50: too few.
- Red: a big push, step after step.
- Push: its x and y slopes.

Photo: "Empty apartment room with corner windows" by aismallard, CC BY-SA 3.0.

Split the big, copy the small, delete the clear

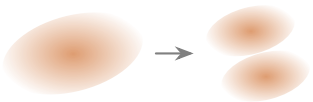
Split



big and pushed hard:
two, sizes $\div 1.6$

Split the big, copy the small, delete the clear

Split



big and pushed hard:
two, sizes $\div 1.6$

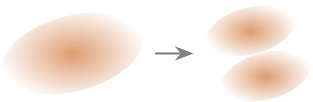
Copy



small and pushed
hard: two the same

Split the big, copy the small, delete the clear

Split



big and pushed hard: two, sizes $\div 1.6$

Copy



small and pushed hard: two the same

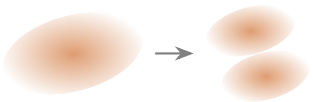
Delete



nearly clear: opacity < 0.005

Split the big, copy the small, delete the clear

Split



big and pushed hard: two, sizes $\div 1.6$

Copy



small and pushed hard: two the same

Delete



nearly clear: opacity < 0.005

The paper: every 100 steps, until step 15,000 of 30,000.

Kerbl et al. 2023, section 5.2; their code's settings. Ours grows the third pushed hardest; theirs, every blob pushed more than 0.0002.

Grow and prune: 50 blobs become 1000

step 0: **50** blobs



▶ **Fit Lab:**
Grow and prune

Grow and prune: 50 blobs become 1000

step 0: **50** blobs



step 300: **116** blobs



▶ **Fit Lab:**
Grow and prune

Grow and prune: 50 blobs become 1000

step 0: **50** blobs



step 300: **116** blobs



step 700: **364** blobs



▶ **Fit Lab:**
Grow and prune

Grow and prune: 50 blobs become 1000

step 0: **50** blobs



step 300: **116** blobs



step 700: **364** blobs



step 2000: **1000** blobs



▶ **Fit Lab:**
Grow and prune

Grow and prune: 50 blobs become 1000

step 0: **50** blobs



step 300: **116** blobs



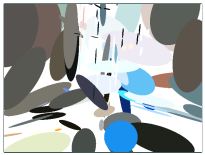
step 700: **364** blobs



step 2000: **1000** blobs



▶ **Fit Lab:**
Grow and prune



each blob as a solid ellipse:
small ones where the detail is



You Try 4: how many blobs?

In the Fit Lab, choose **You Try 4**. Guess first, then change a setting.

```
blobs = 500;
```

run 10, then 100, then 1000

- **10, 100, 1000.**
- Guess: sharpest? slowest?

You Try 4: how many blobs?

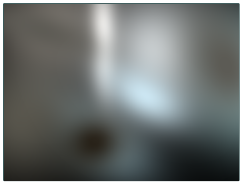
In the Fit Lab, choose **You Try 4**. Guess first, then change a setting.

`blobs = 500;` run 10, then 100, then 1000

answer: `blobs = 10;` `blobs = 100;` `blobs = 1000;`

- **10, 100, 1000.**
- Guess: sharpest? slowest?
- More: sharper.

10 blobs



100 blobs



1000 blobs



You Try 4: how many blobs?

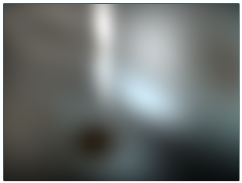
In the Fit Lab, choose **You Try 4**. Guess first, then change a setting.

`blobs = 500;` run 10, then 100, then 1000

answer: `blobs = 10;` `blobs = 100;` `blobs = 1000;`

- **10, 100, 1000.**
- Guess: sharpest? slowest?
- More: sharper.
- And slower.

10 blobs



3.2 ms a step

100 blobs



11.8 ms a step

1000 blobs



34.7 ms a step

node, build machine, steps 200 to 400

You Try 5: no growing

In the Fit Lab, choose **You Try 5**. Guess first, then change a setting.

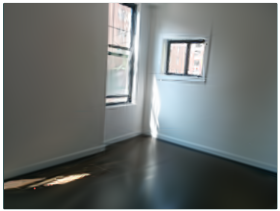
```
grow = true;
```

change this line

50 blobs at the start, step 2000

- **No growing.**
- Guess: how sharp?

now



after your change



You Try 5: no growing

In the Fit Lab, choose **You Try 5**. Guess first, then change a setting.

```
grow = true;
```

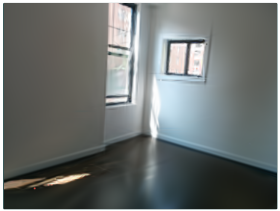
change this line

50 blobs at the start, step 2000

answer: `grow = false;`

- **No growing.**
- Guess: how sharp?
- 50 big blobs: a blur.

now



after your change



You Try 5: no growing

In the Fit Lab, choose **You Try 5**. Guess first, then change a setting.

```
grow = true;
```

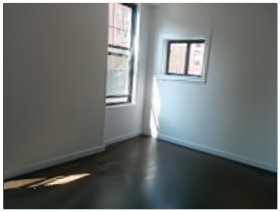
change this line

50 blobs at the start, step 2000

answer: `grow = false;`

- **No growing.**
- Guess: how sharp?
- 50 big blobs: a blur.

now



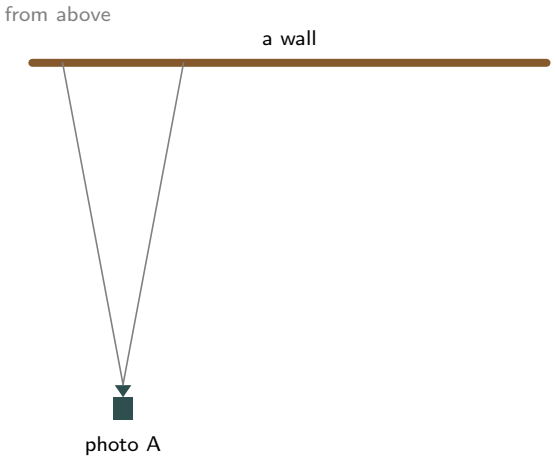
after your change



its 50 blobs

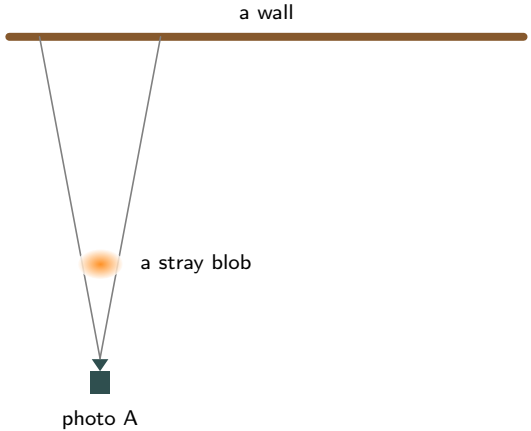


The fit explains the photos, not the scene



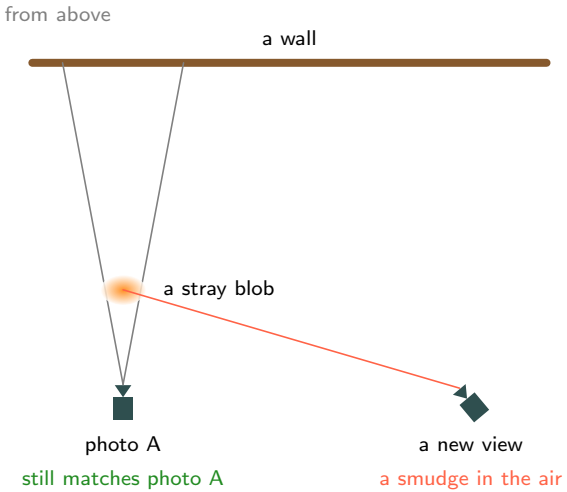
The fit explains the photos, not the scene

from above

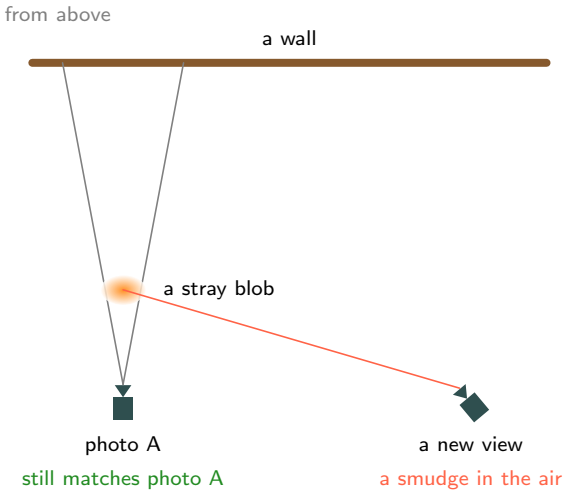


still matches photo A

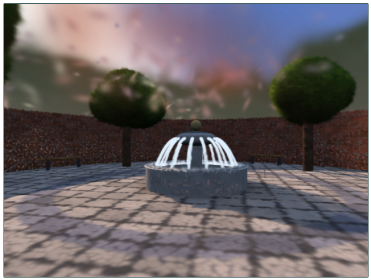
The fit explains the photos, not the scene



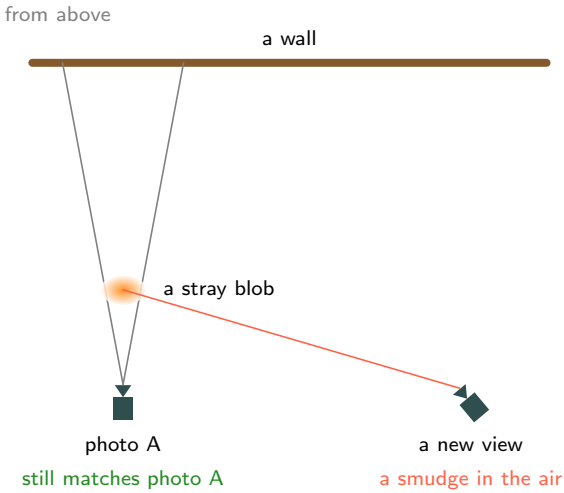
The fit explains the photos, not the scene



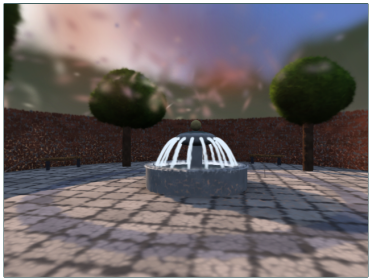
lecture 37: off the path



The fit explains the photos, not the scene



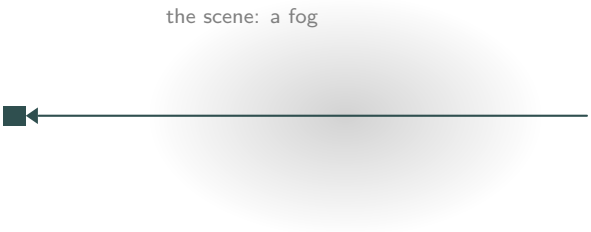
lecture 37: off the path



The paper: every 3000 steps, every opacity near 0. Useful blobs come back; strays fade.

Kerbl et al. 2023, section 5.2

Before blobs: NeRF (2020) marched through a learned fog

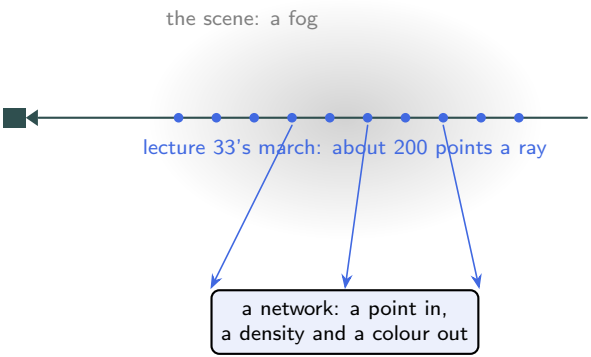


Before blobs: NeRF (2020) marched through a learned fog



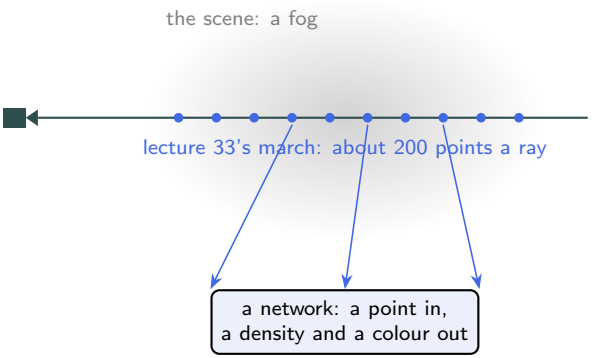
Mildenhall et al., NeRF, ECCV 2020: 64 + 192 points a ray; 1 to 2 days to fit on one GPU. Mip-NeRF 360: Barron et al., CVPR 2022.

Before blobs: NeRF (2020) marched through a learned fog



Mildenhall et al., NeRF, ECCV 2020: 64 + 192 points a ray; 1 to 2 days to fit on one GPU. Mip-NeRF 360: Barron et al., CVPR 2022.

Before blobs: NeRF (2020) marched through a learned fog



the same scenes:

Mip-NeRF 360

48 hours to fit; 0.06 frames a second

blobs

41 minutes; 134 frames a second

Kerbl et al. 2023, Table 1

Mildenhall et al., NeRF, ECCV 2020: 64 + 192 points a ray; 1 to 2 days to fit on one GPU. Mip-NeRF 360: Barron et al., CVPR 2022.

Since 2023



Flat blobs for surfaces

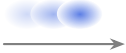
2D Gaussian Splatting, SIGGRAPH 2024

Since 2023



Flat blobs for surfaces

2D Gaussian Splatting, SIGGRAPH 2024



Scenes that move

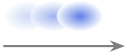
4D Gaussian Splatting, CVPR 2024

Since 2023



Flat blobs for surfaces

2D Gaussian Splatting, SIGGRAPH 2024



Scenes that move

4D Gaussian Splatting, CVPR 2024



Files 15 times smaller

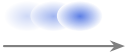
LightGaussian, NeurIPS 2024

Since 2023



Flat blobs for surfaces

2D Gaussian Splatting, SIGGRAPH 2024



Scenes that move

4D Gaussian Splatting, CVPR 2024



Files 15 times smaller

LightGaussian, NeurIPS 2024



No fitting: two photos in, blobs out

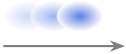
pixelSplat, CVPR 2024

Since 2023



Flat blobs for surfaces

2D Gaussian Splatting, SIGGRAPH 2024



Scenes that move

4D Gaussian Splatting, CVPR 2024



Files 15 times smaller

LightGaussian, NeurIPS 2024



No fitting: two photos in, blobs out

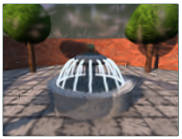
pixelSplat, CVPR 2024

`KHR_gaussian_splatting`

A standard file

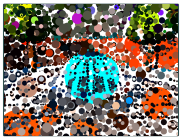
Khronos glTF, release candidate 2026

Now make your own picture



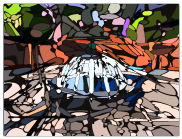
Brush strokes

`shape = "stroke"`



A painting of dots

`look = "dots"`



Stained glass

`look = "glass"`



A charcoal sketch

`colour = "grey"`



A morph

`then_photo = "suzanne"`



From one blob

`blobs = 1; grow = true`

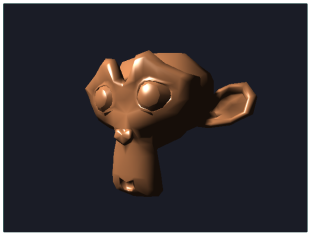
All six are in the Fit Lab, under **Ideas**. Change one. Mix two. Load your own photo.

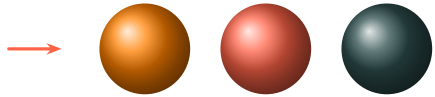
Summary

1	The start	photos $\rightarrow$ cameras and points $\rightarrow$ a blob on each
2	The error	one number: the average of $(\text{blobs} - \text{photo})^2$
3	The slope	soft edges have one; hard edges do not
4	The nudge	$x \leftarrow x - \text{rate} \times \text{slope}$, every number
5	Grow and prune	split the big, copy the small, delete the clear

Next lecture: metal and rough

lecture 29: one highlight





- Two numbers: metal, rough.
- Every engine uses them.

Exit Ticket

Today's question *(2 minutes)*

(a) A blob is at $x = 10$. The error is 2.30 at $x = 9$ and 2.10 at $x = 11$. The rate is 5. What is the slope, and where does the blob go?

(b) A blob of size 0.8 is split. What size are the two new blobs?

CS 453 — Exit Ticket #38

Name: _____

Roll #: _____ Date: _____

Answer:

Hand it to me on your way out.
No name, no attendance.