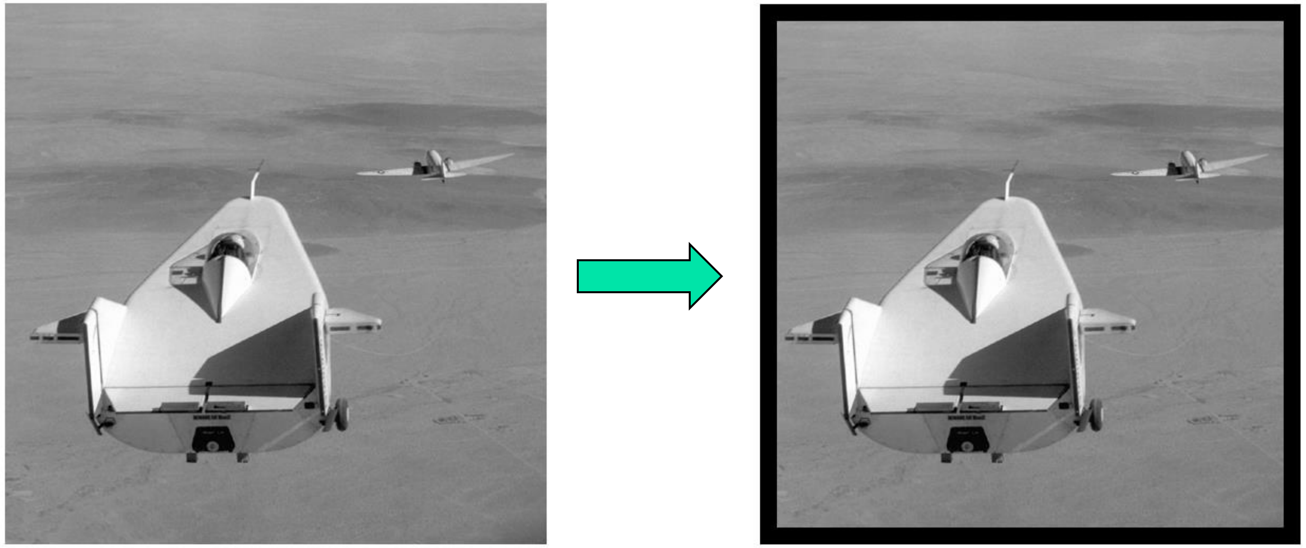
- Previous Lecture:
  - Image processing
    - Add frame, grayscale
- Today's Lecture:
  - More image processing
    - Mirror, vectorized code
    - Color → grayscale, `uint8`
    - "Noise" filtering
    - (Read in book: Edge-finding example)

- Announcements:
  - Discussion via Zoom; see Canvas for link
  - Project 4 due Mon 4/13
  - Consulting resumes today via Zoom, hours extended
  - Be sure to review—re-do—Prelim 1 now so that you have a firm foundation

Where did we leave off?

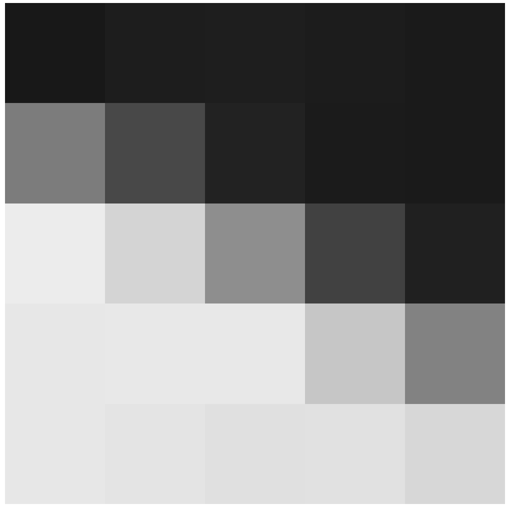


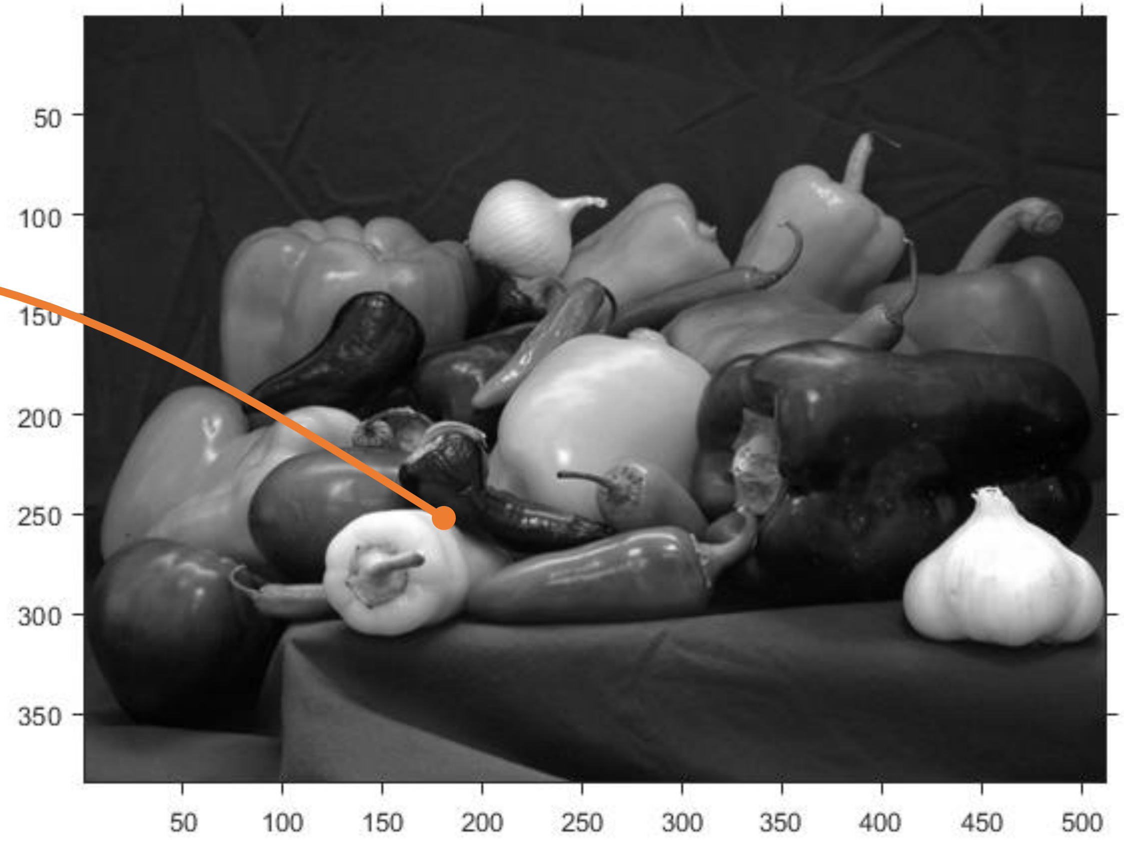
How to put a picture in a frame

Two approaches:

1. Ask every pixel whether it is covered by the frame
   - Easy to understand
2. Identify which subarrays are covered by the frame
   - More efficient; easy to vectorize

Pictures as matrices





24	29	30	28	26
124	72	34	27	26
236	212	142	65	32
231	232	232	198	130
231	228	224	225	215

Pixel: an element in a matrix (location corresponds to row, column index)

“Greyness”: a value in 0..255

A color picture is made up of RGB matrices → 3D array

114	114	112	112	114	111	114	115	112	113
114	113	111	109	113	111	113	115	112	113
115	114	112	111	111	112	112	111	112	112
116	117	116	114	112	115	113	112	115	114
113	112	112	112	112	110	111	113	116	115
115	115	115	115	113	111	111	113	116	114
112	113	116	117	113	112	112	113	114	113
115	116	118	118	113	112	112	113	114	114
116	116	117	117	114	114	112	112	114	115

153	153	150	150	154	151	152	153	150	151
153	152	149	147	153	151	151	153	150	151
154	153	151	150	151	152	150	149	150	150
155	156	155	152	152	155	151	150	153	153
151	150	150	150	150	148	149	151	152	151
153	153	153	153	151	149	149	151	152	150
150	151	152	153	151	150	150	151	152	151
153	154	154	154	151	150	150	151	152	152
154	154	153	153	149	149	150	150	152	153

212	212	212	212	216	213	215	216	213	213
212	211	211	209	215	213	214	216	213	213
213	212	210	209	212	214	213	212	213	212
214	215	214	214	213	216	214	213	215	212
213	212	212	212	212	210	211	213	214	211
215	215	216	216	213	211	211	213	212	210
212	213	214	215	213	212	212	213	214	213
215	216	216	216	213	212	212	213	214	214
216	216	215	215	213	213	213	213	214	215

E.g., color image data is stored in a 3-d array **A**:

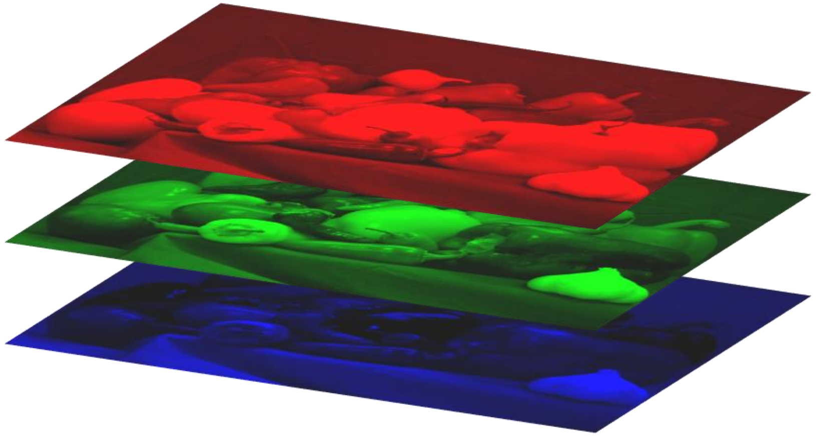
$$0 \leq A(i,j,1) \leq 255$$

$$0 \leq A(i,j,2) \leq 255$$

$$0 \leq A(i,j,3) \leq 255$$

Visualize a 3D array as a stack of “layers” which are 2D arrays

Color image



3-d Array

$0 \leq$ `A(i,j,1)` ≤ 255

$0 \leq$ `A(i,j,2)` ≤ 255

$0 \leq$ `A(i,j,3)` ≤ 255

Beware the two different “3”s:

- `dims = size(A)  % [720, 1280, 3]`
- `length(dims) == 3` % A has 3 dimensions: rows, columns, layers
- `dims(3) == 3` % A has **3** layers: red, green, blue

Example: Mirror Image

`LawSchool.jpg`

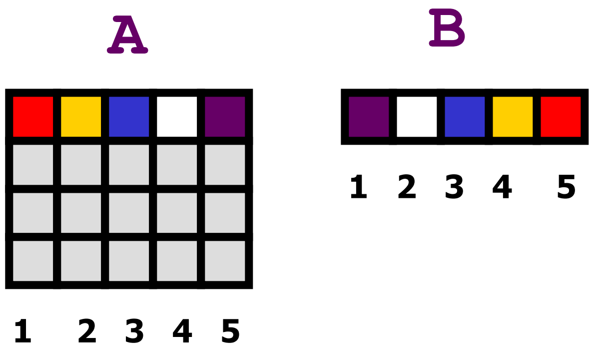
`LawSchoolMirror.jpg`

1. Read **LawSchool.jpg** from memory and convert it into an array.
2. Manipulate the Array.
3. Convert the array to a jpg file and write it to memory.

Reading and writing jpg files

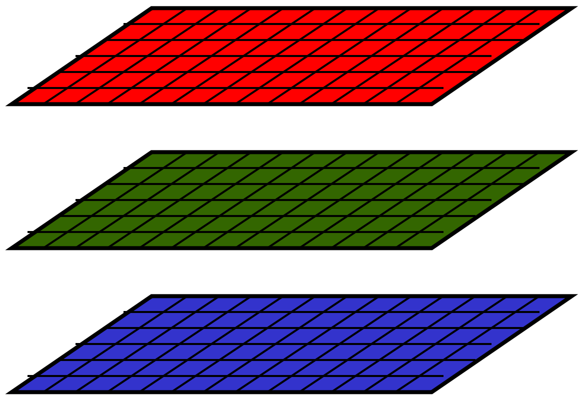
```
% Read jpg image, uncompress to a
% a 3D array A of type uint8
  A = imread('LawSchool.jpg');

% Write 3D array B to memory as
% a jpg image
  imwrite(B,'LawSchoolMirror.jpg')
```

```
%Store mirror image of A in array B

[nr,nc,np]= size(A);
for r = 1:nr
   for c = 1:nc

      B(r,c  )= A(r,nc-c+1  );

   end
end
```



```
%Store mirror image of A in array B

[nr,nc,np]= size(A);
for r = 1:nr
  for c = 1:nc
    for p = 1:np
      B(r,c,p)= A(r,nc-c+1,p);
    end
  end
end
```

```
[nr,nc,np]= size(A);
for r= 1:nr
  for c= 1:nc
    for p= 1:np
      B(r,c,p)= A(r,nc-c+1,p);
    end
  end
end
```



```
[nr,nc,np]= size(A);
for p= 1:np
  for r= 1:nr
    for c= 1:nc
      B(r,c,p)= A(r,nc-c+1,p);
    end
  end
end
```

Both fragments create a mirror image of **A** .

A true

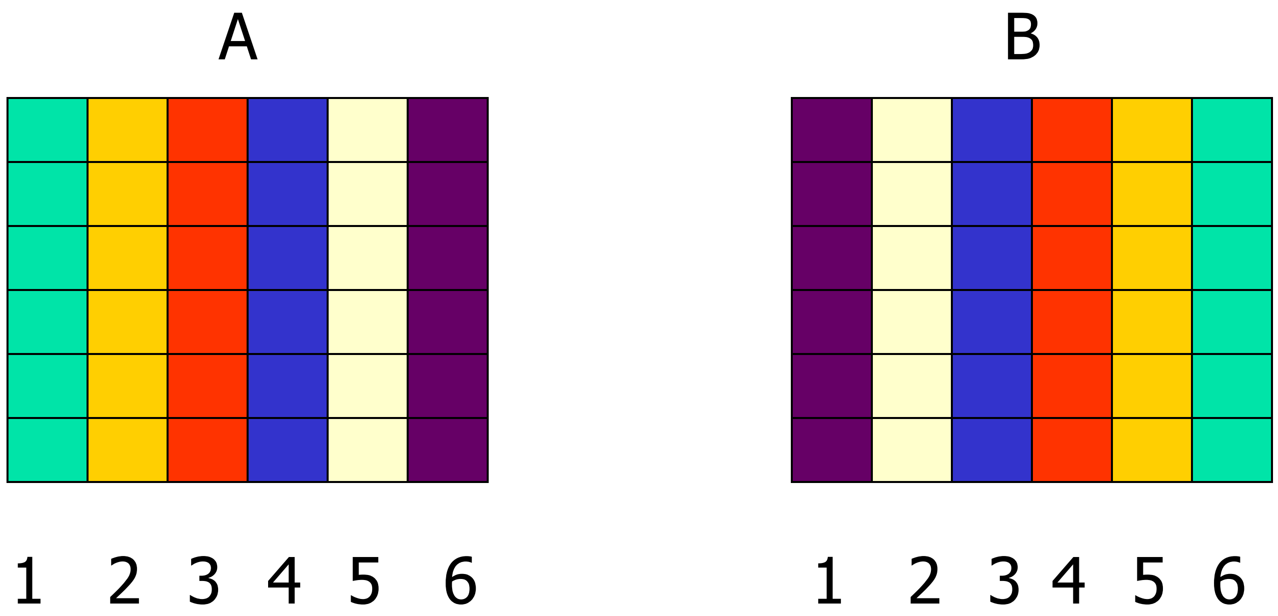
B false

```
% Make mirror image of A -- the whole thing

A= imread('LawSchool.jpg');
[nr,nc,np]= size(A);




for r= 1:nr
  for c= 1:nc
    for p= 1:np
      B(r,c,p)= A(r,nc-c+1,p);
    end
  end
end
imshow(B)  % Show 3-d array data as an image
imwrite(B,'LawSchoolMirror.jpg')
```

```matlab
% Make mirror image of A -- the whole thing

A= imread('LawSchool.jpg');
[nr,nc,np]= size(A);

B= zeros(nr,nc,np);   % zeros returns type double
B= uint8(B);          % Convert B to type uint8

for r= 1:nr
  for c= 1:nc
    for p= 1:np
      B(r,c,p)= A(r,nc-c+1,p);
    end
  end
end
imshow(B)  % Show 3-d array data as an image
imwrite(B,'LawSchoolMirror.jpg')
```

Vectorized code simplifies things…

Work with a whole column at a time



Column c in B
is column nc-c+1 in A

Consider a single matrix (just one layer)

```
[nr,nc,np] = size(A);
for c= 1:nc
    B( all rows ,c ) = A( all rows ,nc-c+1 );


end
```

Consider a single matrix (just one layer)

```
[nr,nc,np] = size(A);
for c= 1:nc
    B(1:nr,c ) = A(1:nr,nc-c+1 );


end
```

Consider a single matrix (just one layer)

```
[nr,nc,np] = size(A);
for c= 1:nc
    B( :   ,c ) = A( :   ,nc-c+1 );


end
```

The colon says "all indices in this dimension." In this case it says "all rows."

Now repeat for all layers

```
[nr,nc,np] = size(A);
for c= 1:nc
    B(:,c,1) = A(:,nc-c+1,1)
    B(:,c,2) = A(:,nc-c+1,2)
    B(:,c,3) = A(:,nc-c+1,3)
end
```

Vectorized code to create a mirror image

```
A = imread('LawSchool.jpg')
[nr,nc,np] = size(A);
for c= 1:nc
    B(:,c,1) = A(:,nc-c+1,1)
    B(:,c,2) = A(:,nc-c+1,2)
    B(:,c,3) = A(:,nc-c+1,3)
end
imwrite(B,'LawSchoolMirror.jpg')
```

Even more compact vectorized code to create a mirror image…

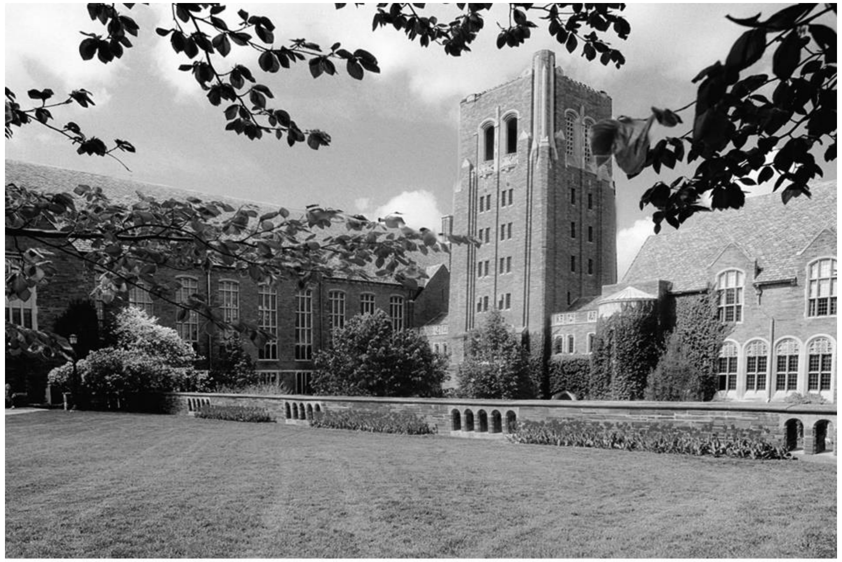
```
for c= 1:nc
    B(:,c,1) = A(:,nc-c+1,1)
    B(:,c,2) = A(:,nc-c+1,2)
    B(:,c,3) = A(:,nc-c+1,3)
end
```

↓

```
B = A(:,nc:-1:1,:)
```

Example: color → black and white

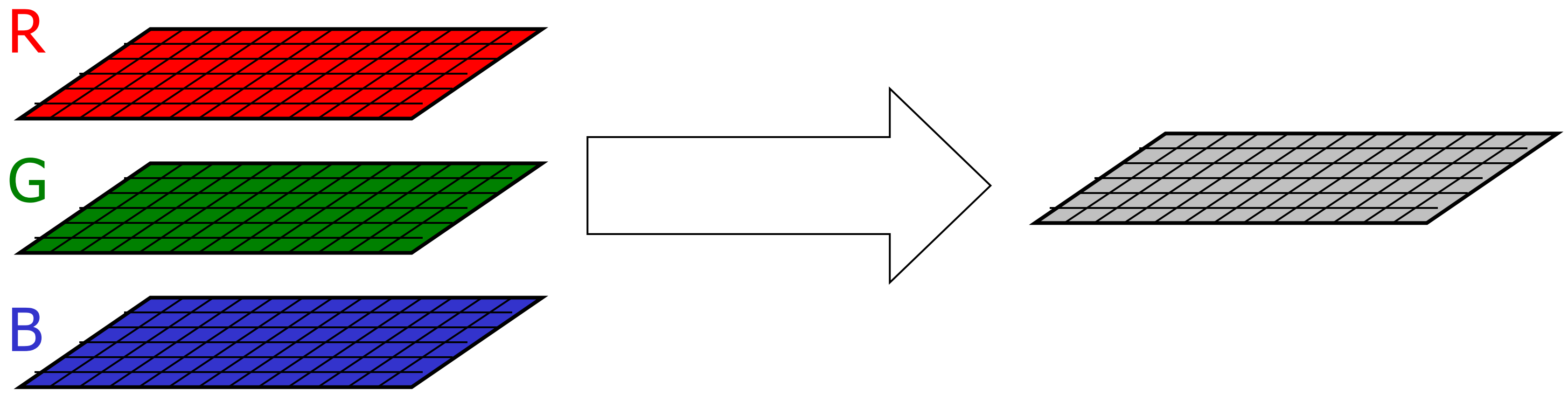
Cornell University Law School
Photograph by Cornell University Photography



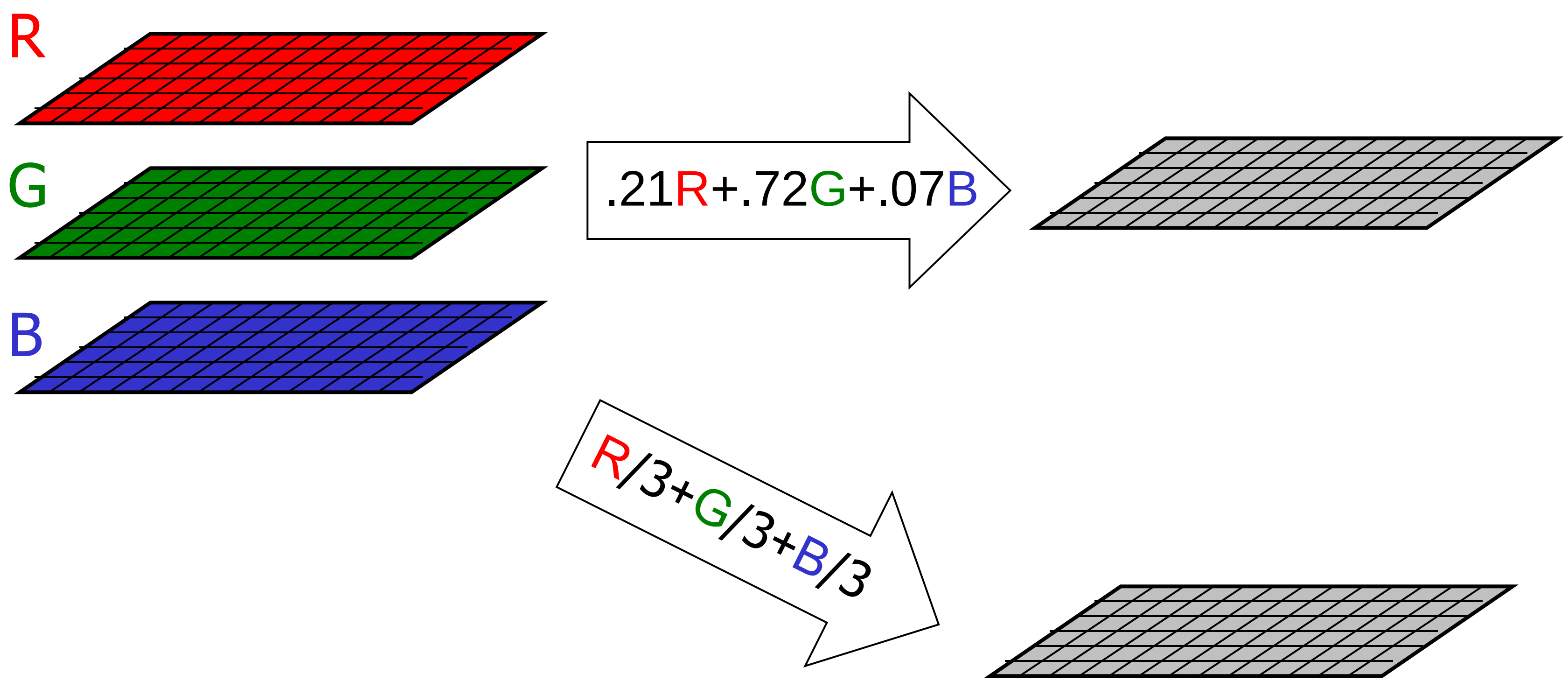
Cornell University Law School
Photograph by Cornell University Photography

Can "average" the three color values to get one gray value.

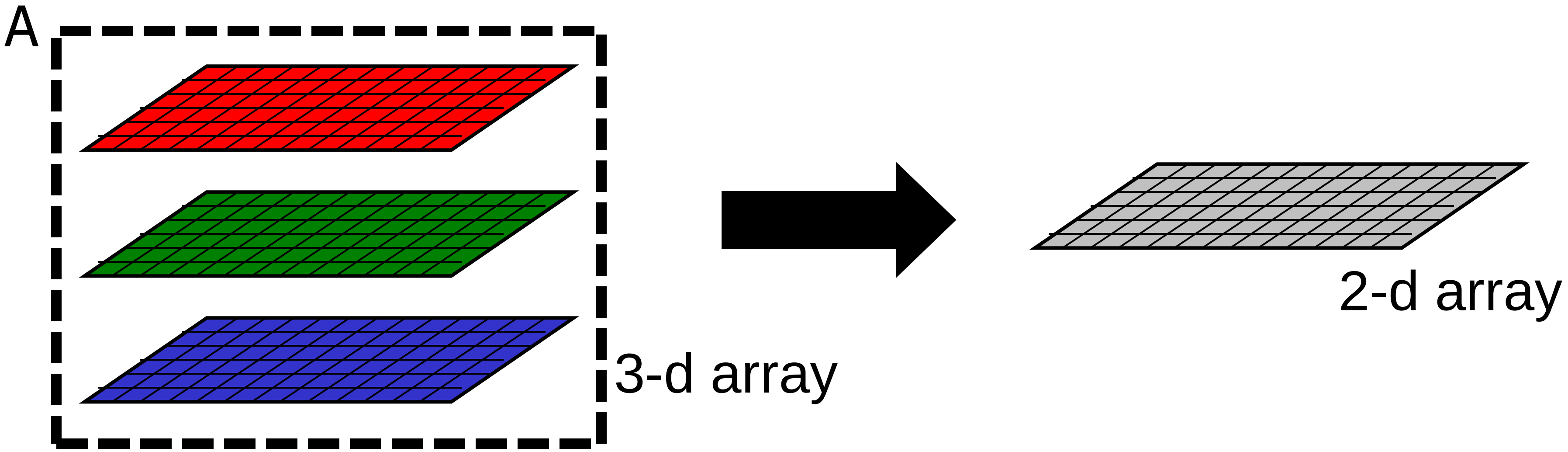
Converting from color (RGB) to grayscale



Averaging the RGB values to get a gray value

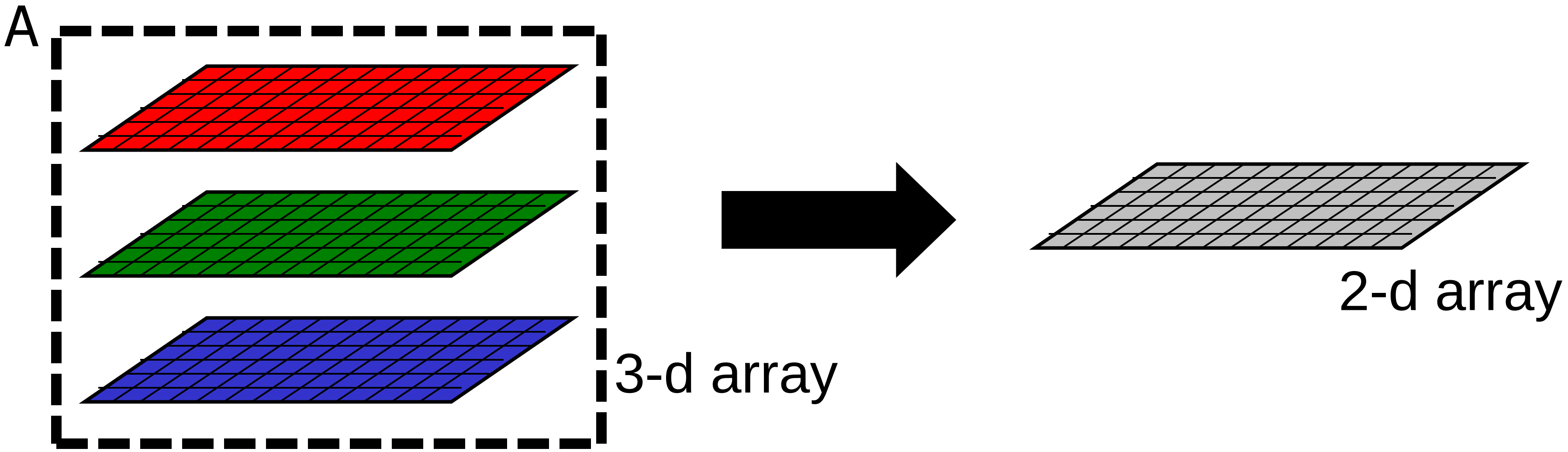


Averaging the RGB values to get a gray value



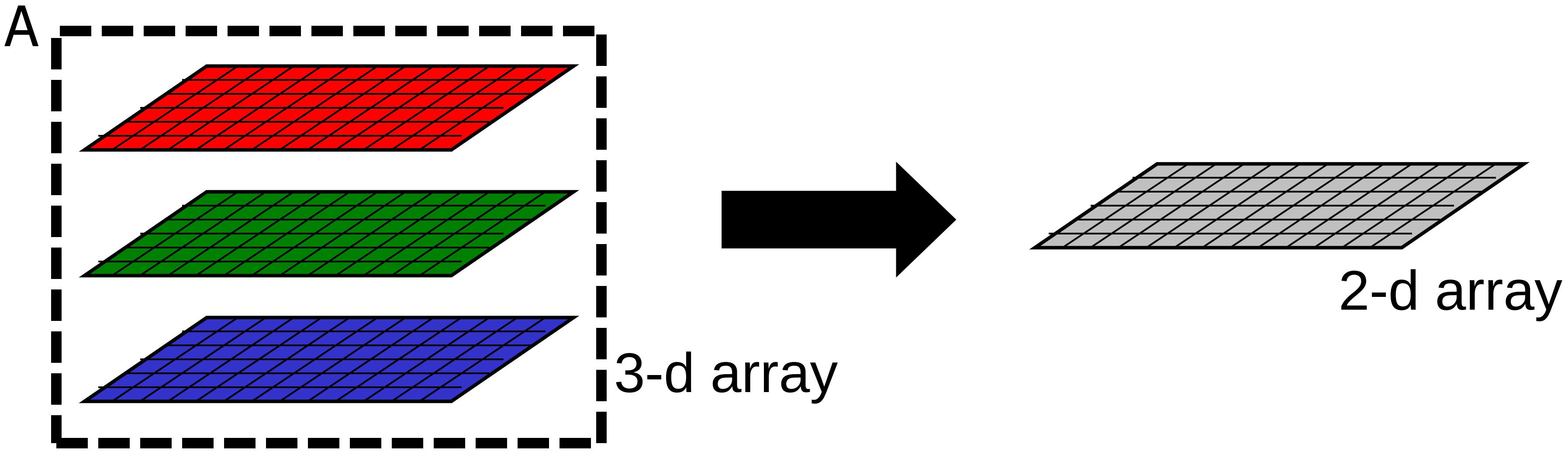

```
for  i= 1:m
    for j= 1:n
        M(i,j)= .21*R(i,j  ) + .72*G(i,j  ) + .07*B(i,j  )
    end
end
```

Averaging the RGB values to get a gray value




```
for  i= 1:m
    for j= 1:n
        M(i,j)= .21*A(i,j,1) + .72*A(i,j,2) + .07*A(i,j,3)
    end
end
```

Averaging the RGB values to get a gray value



Non-vectorized

```
for  i= 1:m
    for j= 1:n
        M(i,j)= .21*A(i,j,1) + .72*A(i,j,2) + .07*A(i,j,3)
    end
end
```

Vectorized

```
M = .21*A(:,:,1) + .72*A(:,:,2) + .07*A(:,:,3)
```

Computing in type uint8

- Respect the range [0..255]
- Arithmetic on uint8's results in uint8's
- Saturation (also called "capped")
  - uint8(90) + uint8(200) → 255 (type uint8)
  - uint8(90) - uint8(200) → 0 (type uint8)
- Rounding (not truncation)
  - uint8(32)/uint8(3) → 11 (type uint8)
- Arithmetic between a uint8 and a double results in a uint8
  - uint8(90) + 200 → 255 (type uint8)

Here are 2 ways to calculate the average. Are gray value matrices g and h the same given `uint8` image data A?

```
for r= 1:nr
  for c= 1:nc
    g(r,c)= A(r,c,1)/3 + A(r,c,2)/3 + ...
            A(r,c,3)/3;
    h(r,c)= ...
             ( A(r,c,1)+A(r,c,2)+A(r,c,3) )/3;
  end
end
```

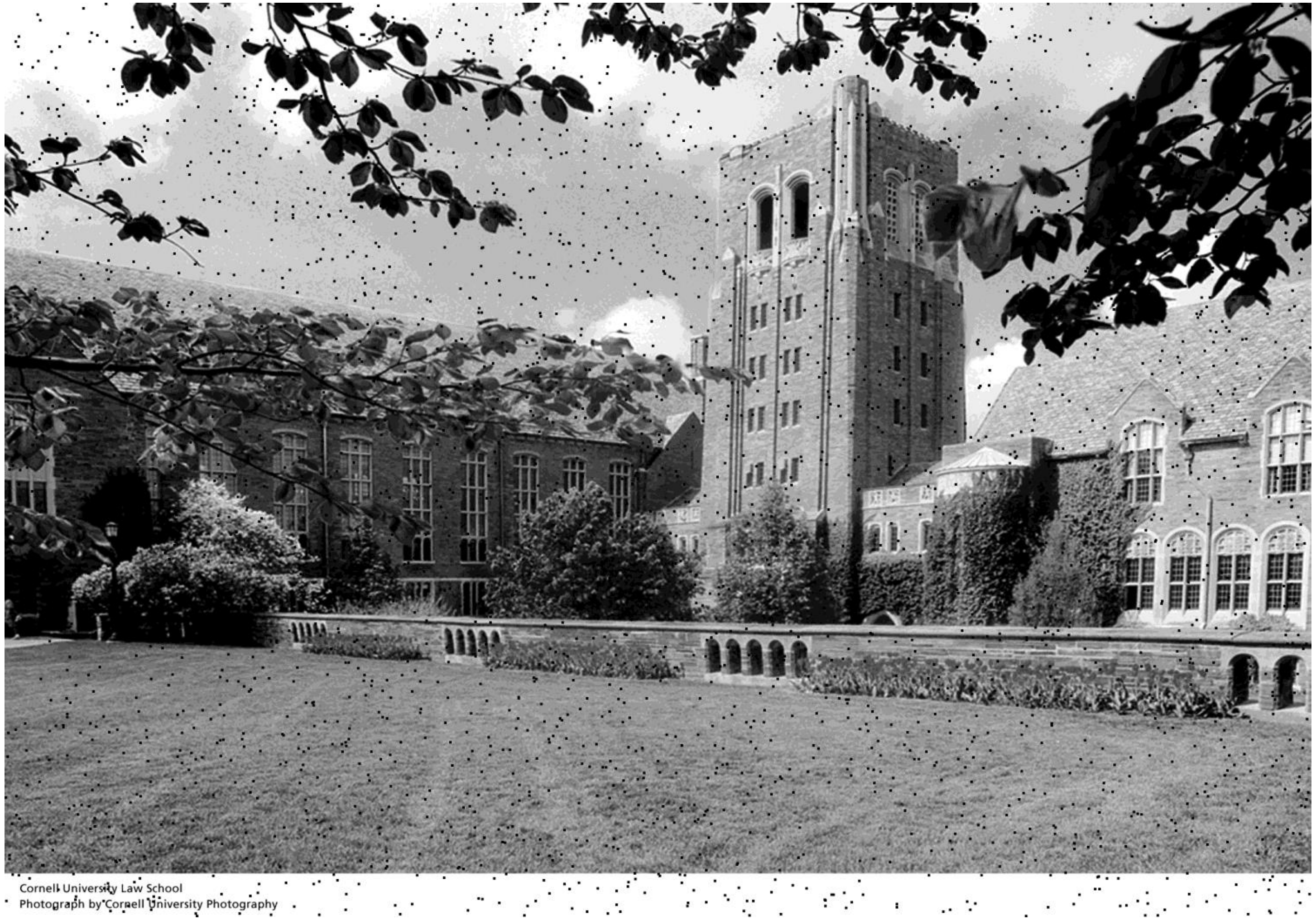
A: yes

B: not quite (rounding)

C: no (saturation)

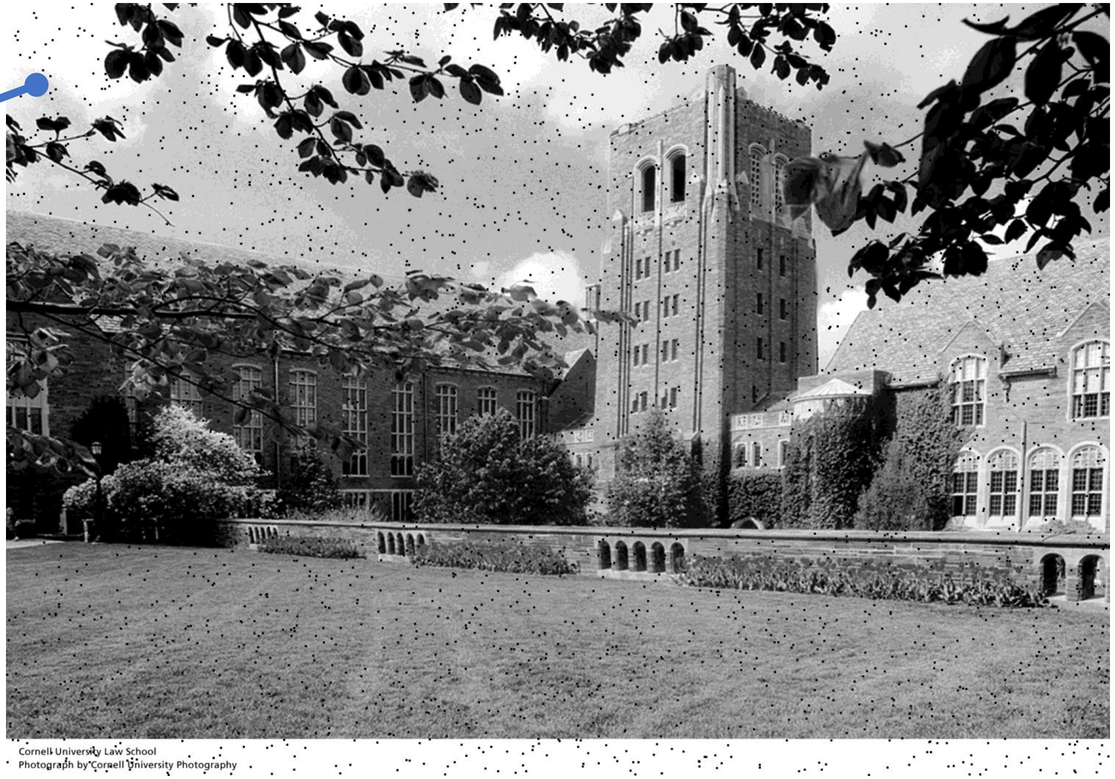
Application: median filtering

How can we remove noise?



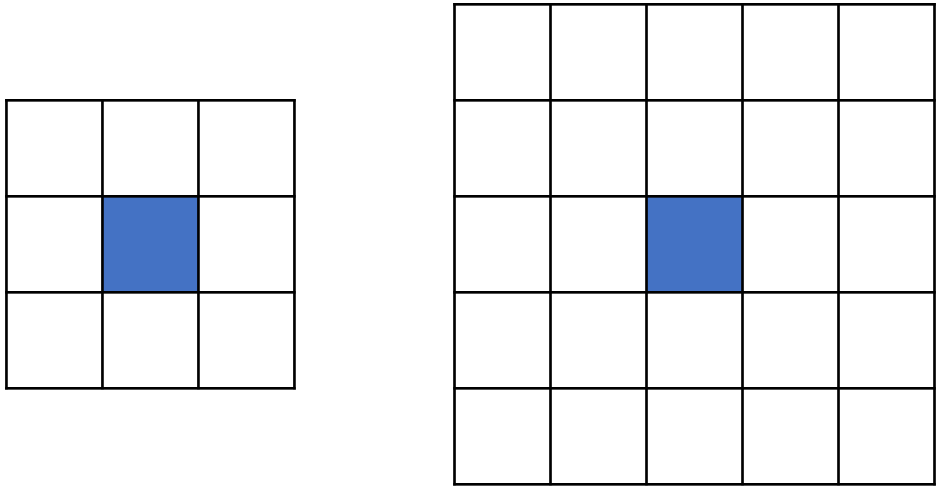
Dirty pixels look out-of-place

150	149	152	153	152	155
151	150	153	154	153	156
153	2	3	156	155	158
154	2	1	157	156	159
156	154	158	159	158	161
157	156	159	160	159	162



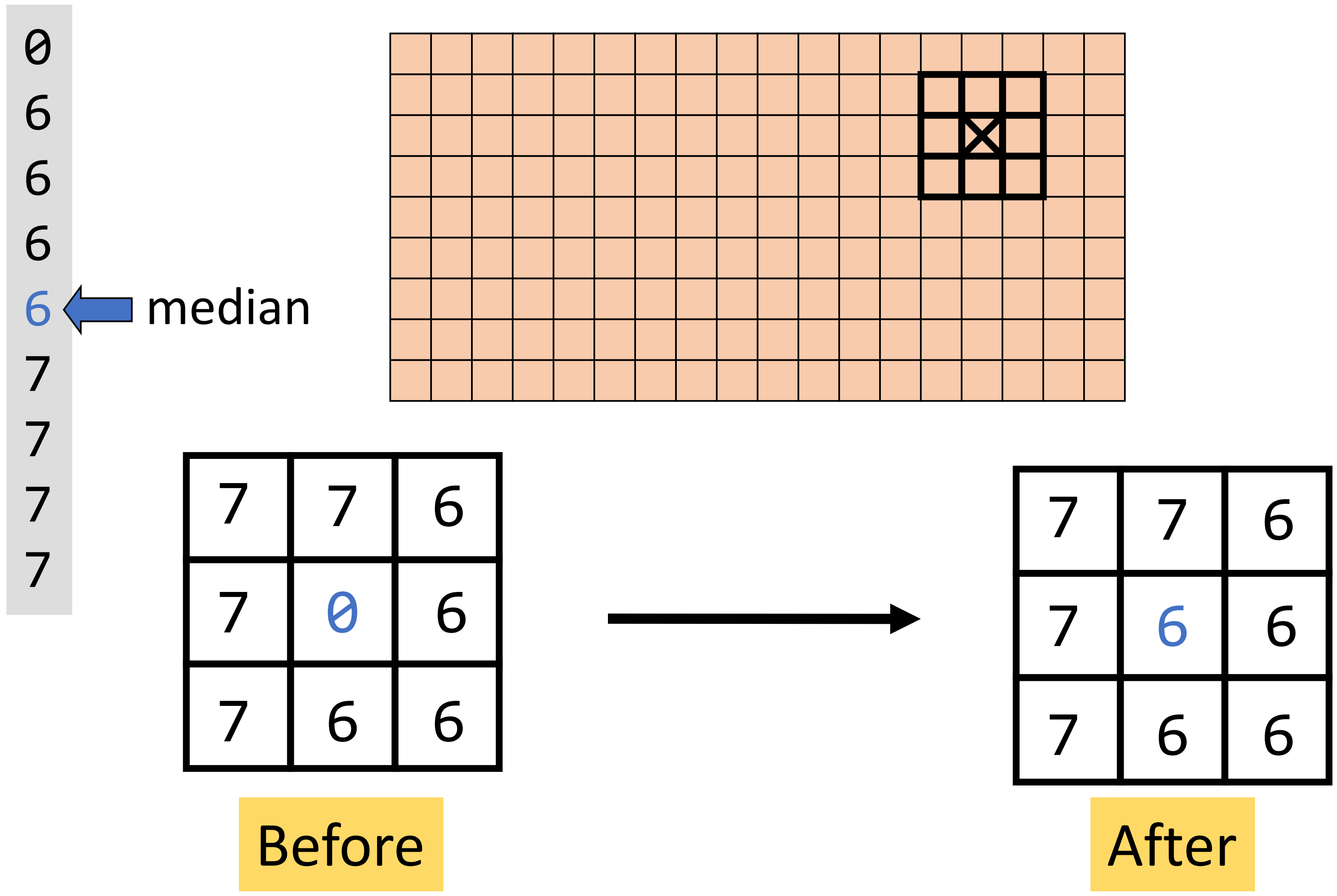
How to fix “bad” pixels?

- Visit each pixel
- Replace with typical values from its neighborhood
  - How to choose “typical” value?
  - How big is the neighborhood?



- “Typical”: mean vs. median
  - Median better for rejecting noise, preserving edges
- Neighborhood: moving window of radius *r*

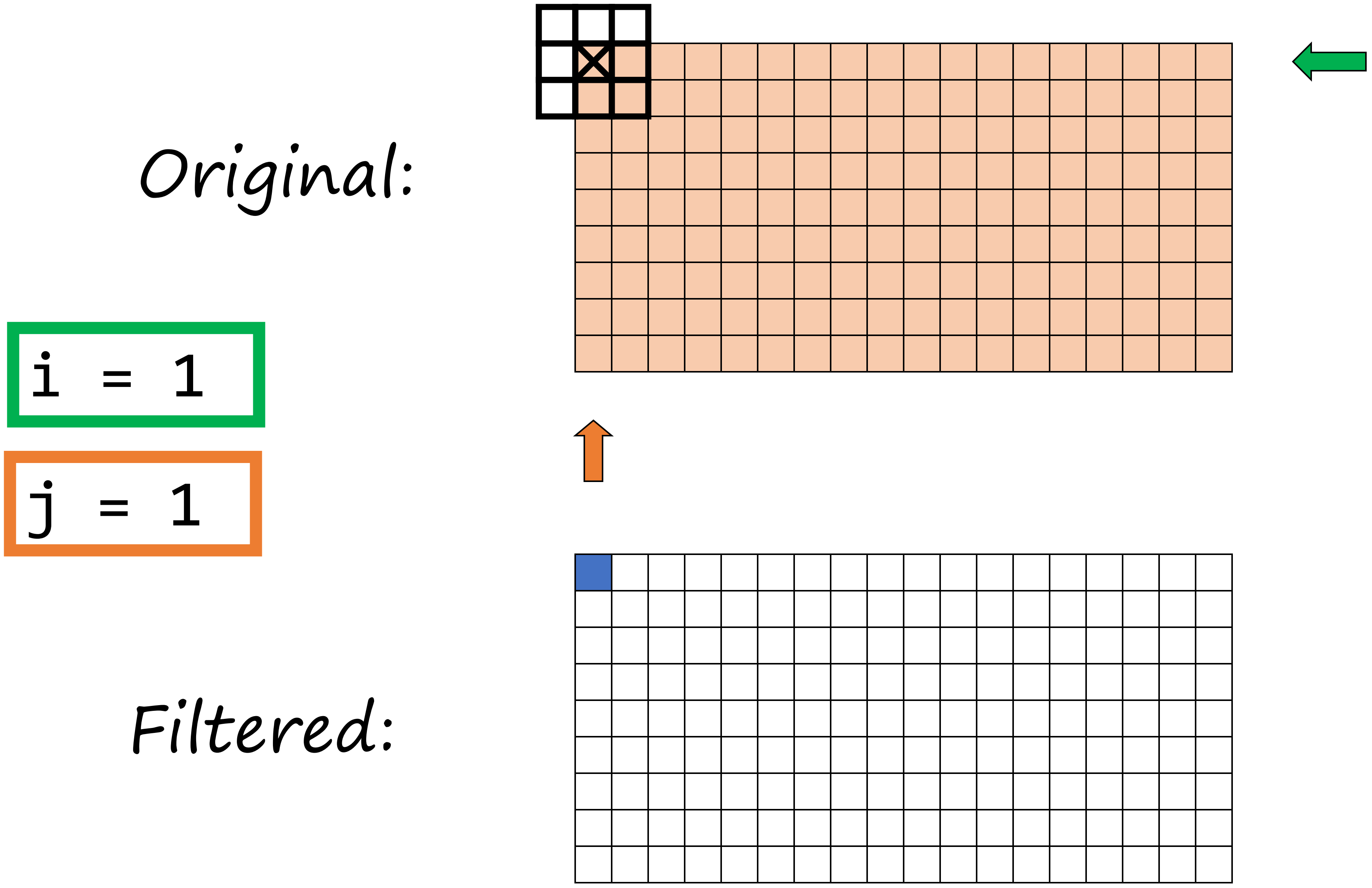
Using a radius-1 neighborhood



Top-down design

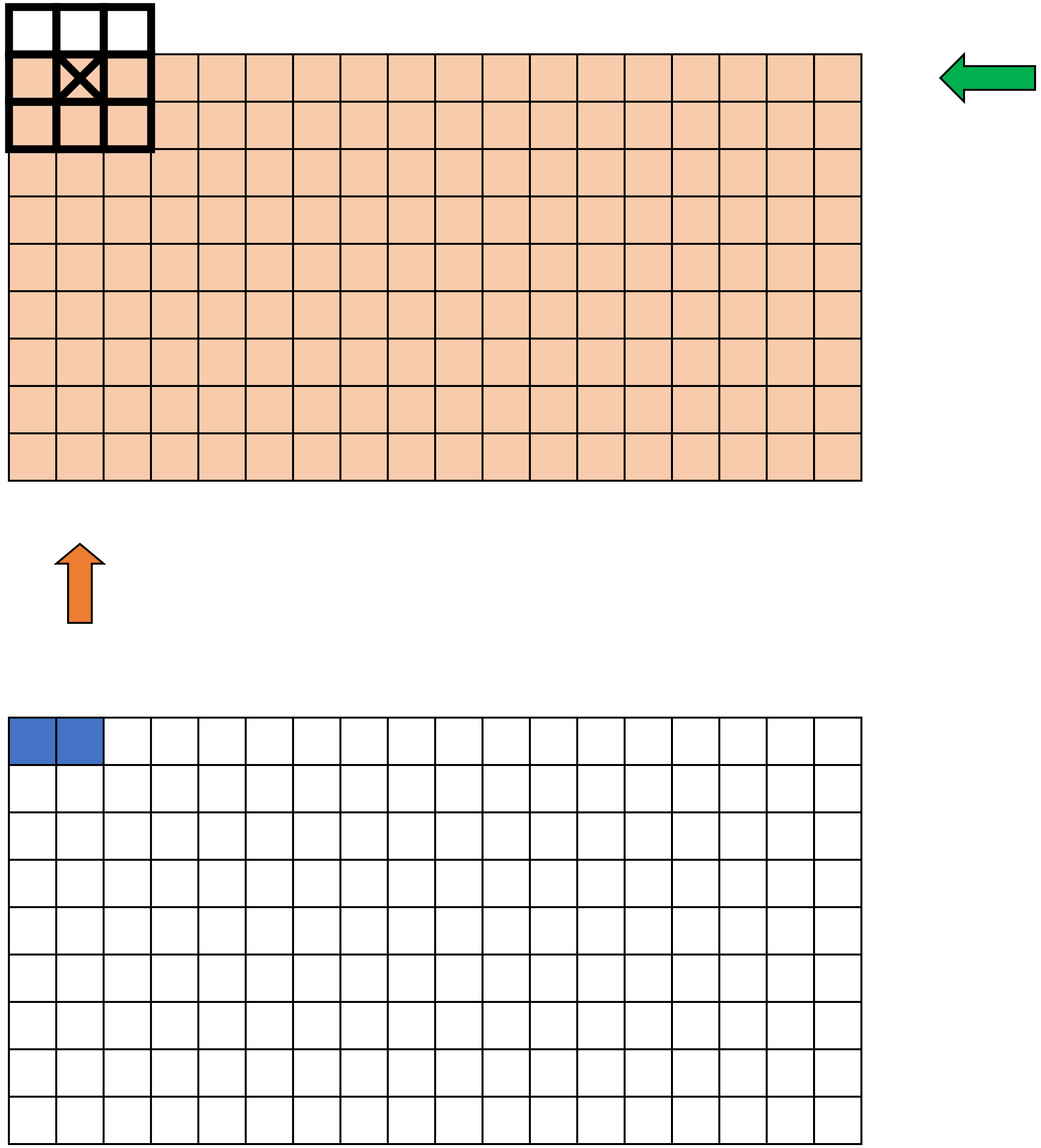
- Visit each pixel
- Choose a new gray value equal to the median of the old gray values in the "neighborhood"

```
[nr,nc] = size(A);  % A is 2d array of image data
B = uint8(zeros(nr,nc));
for i = 1:nr
    for j = 1:nc
        C = neighborhood of pixel (i,j)
        B(i,j) = median of elements in C
    end
end
```



Replace ☒ with the median of the values under the window.

Original:



i = 1

j = 2

Filtered:

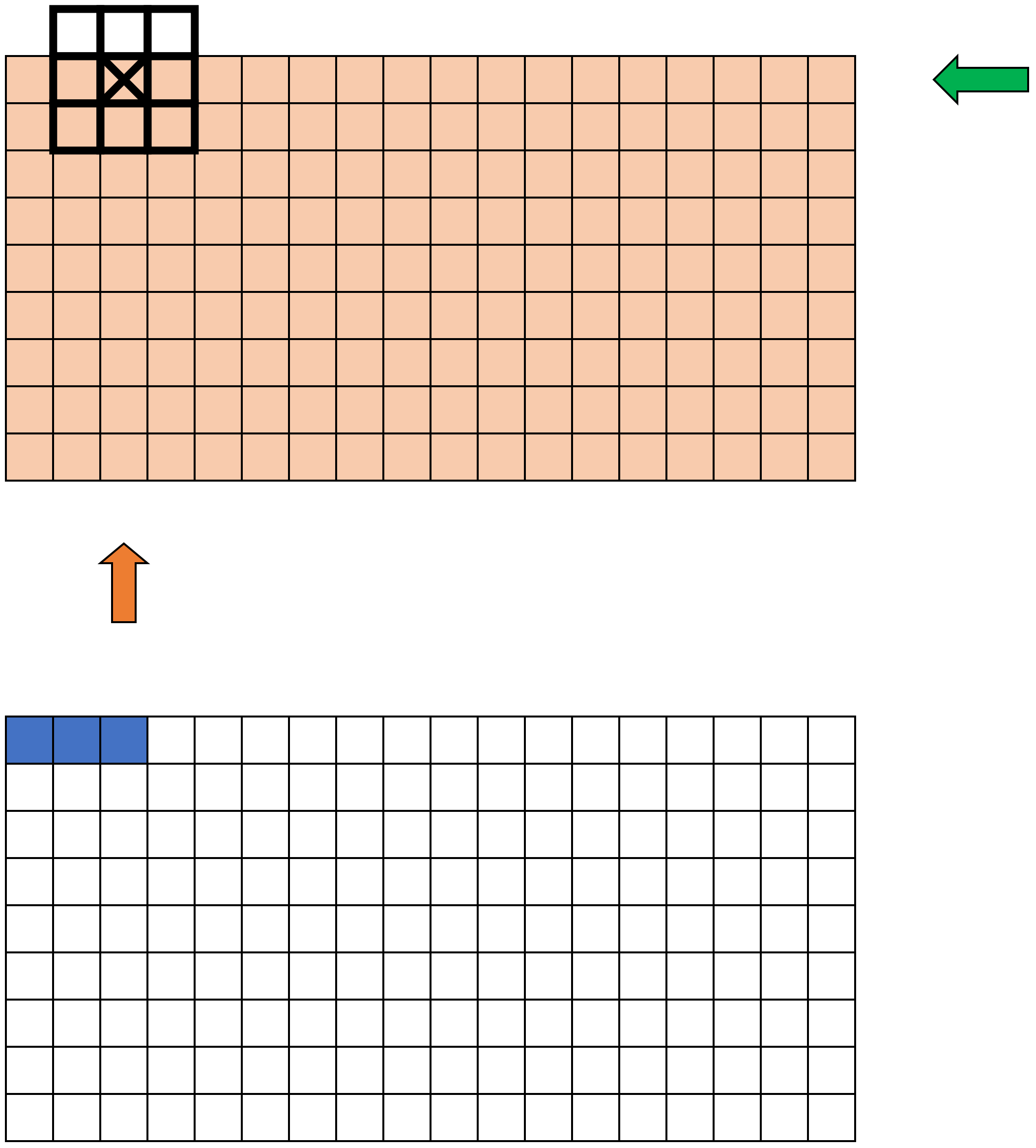
Replace ⊠ with the median of the values under the window.

Original:

i = 1

j = 3

Filtered:

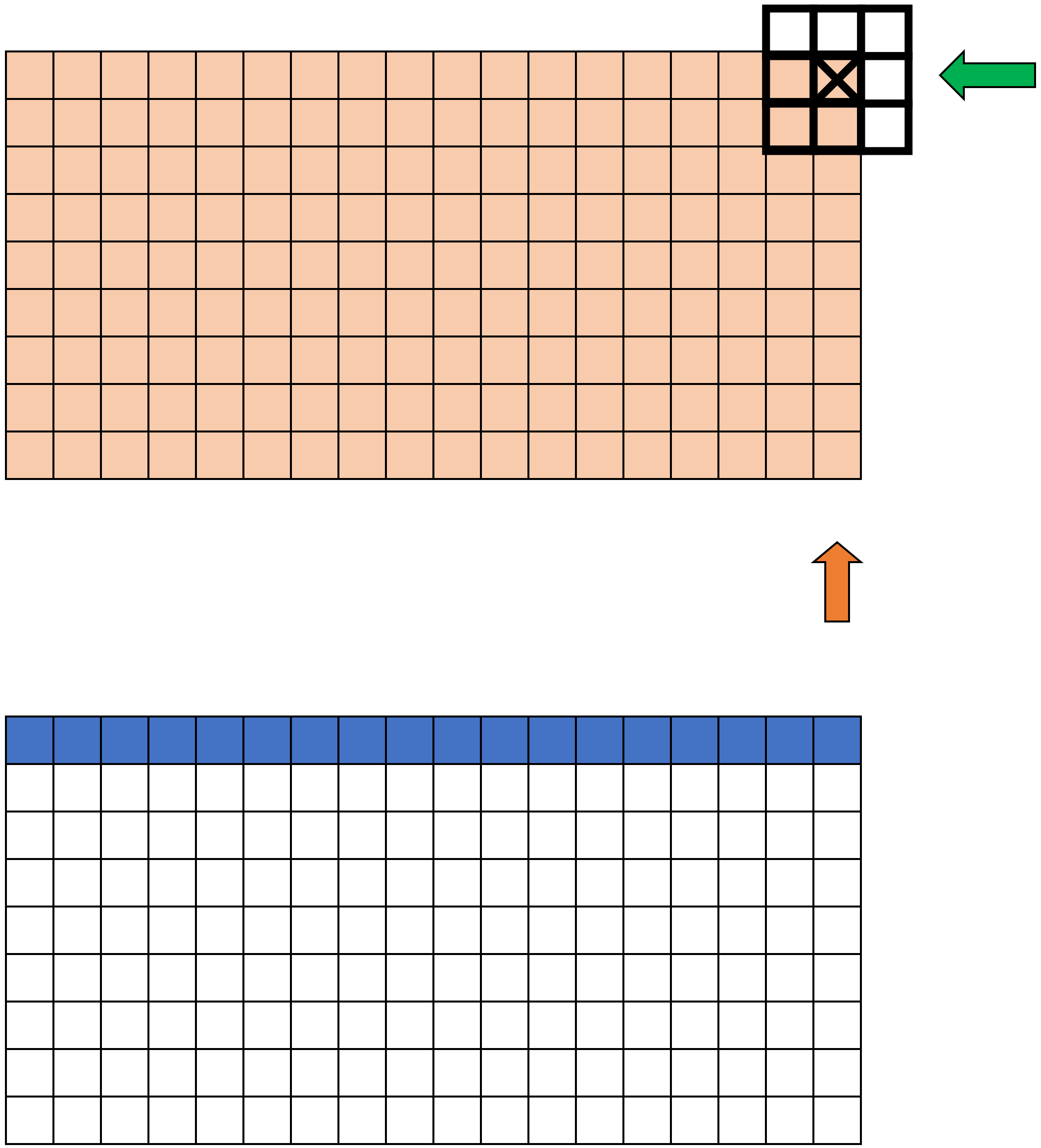


Replace ☒ with the median of the values under the window.

Original:

i = 1

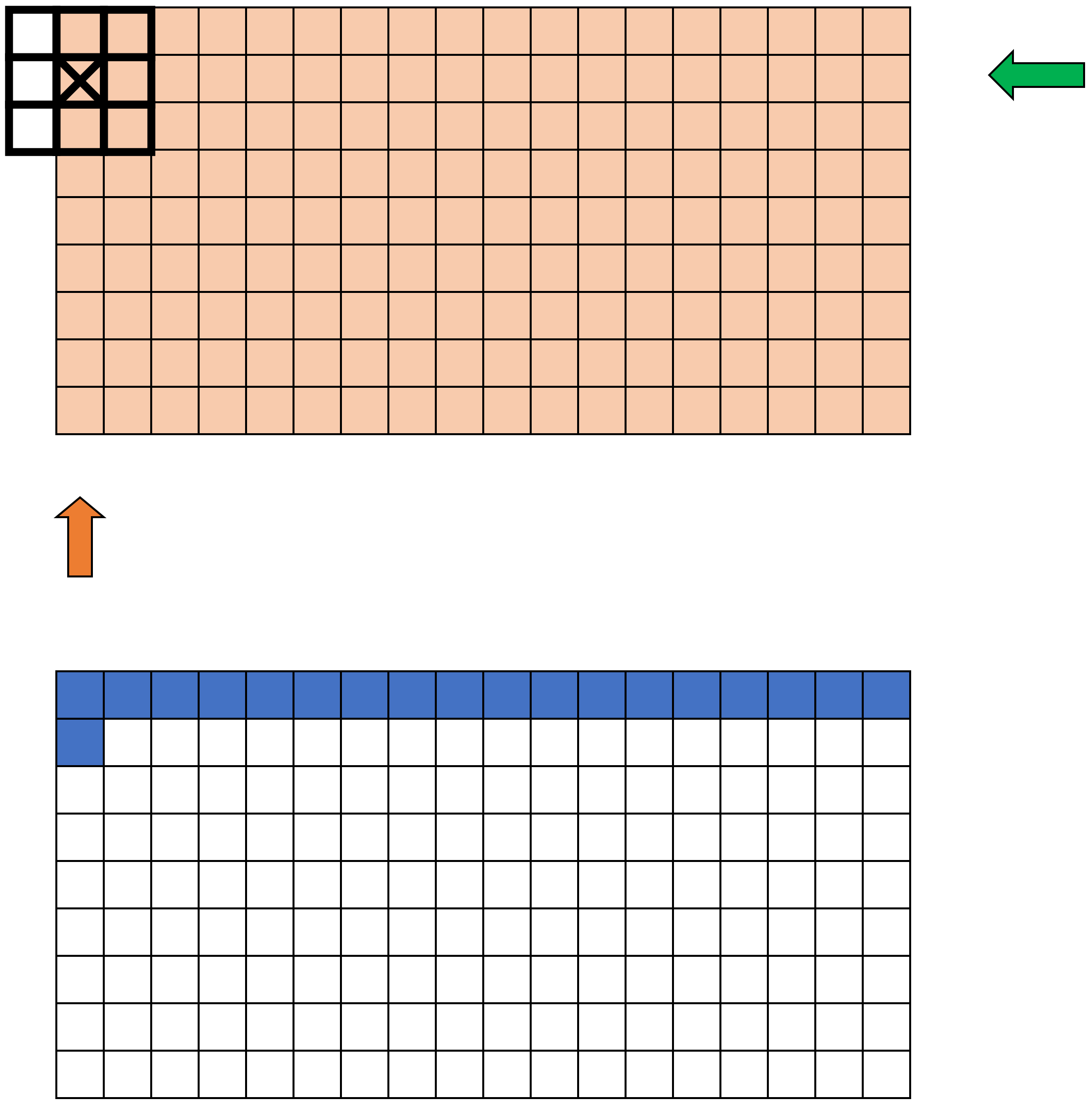
j = nc



Filtered:

Replace ☒ with the median of the values under the window.

Original:

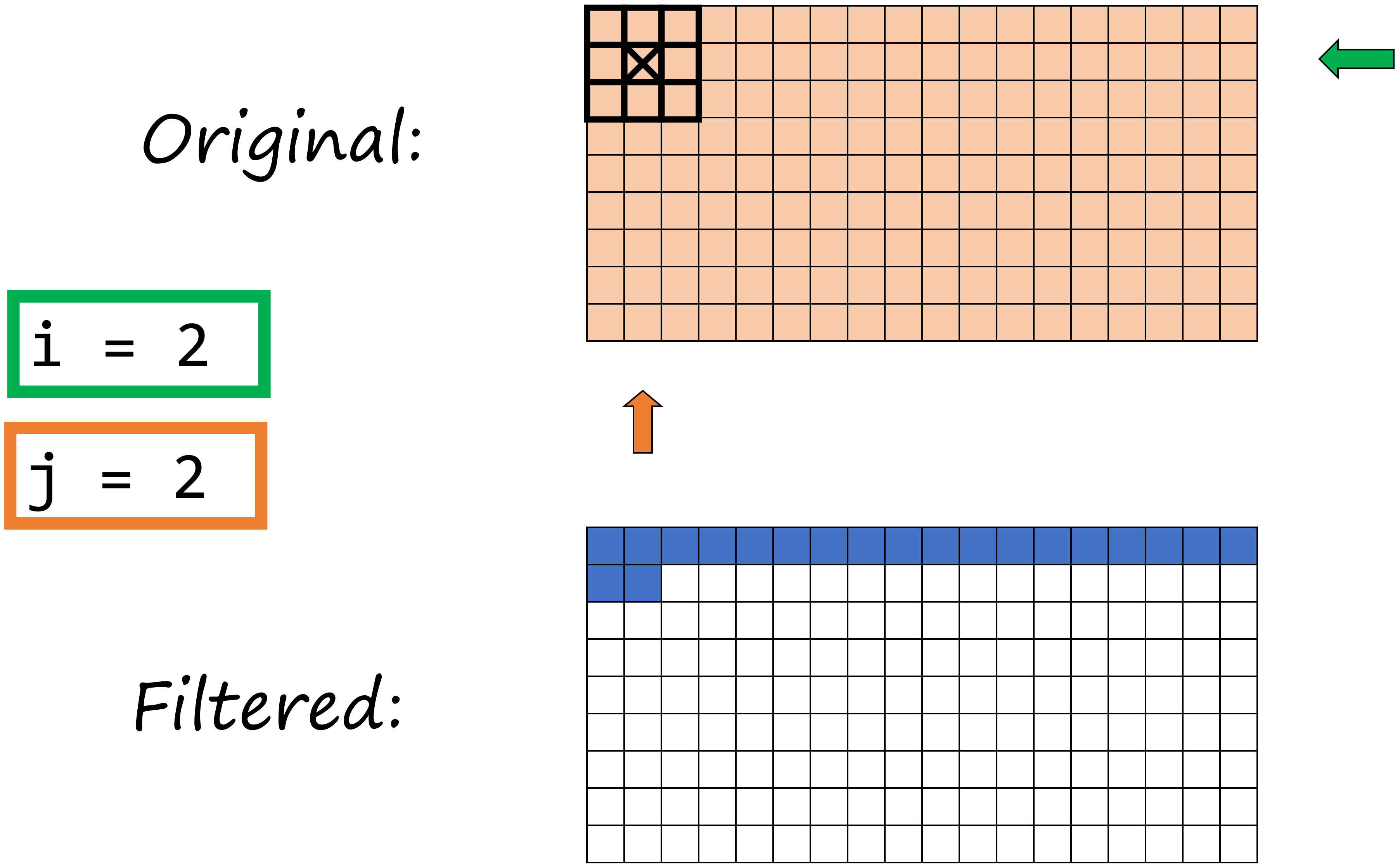


`i = 2`

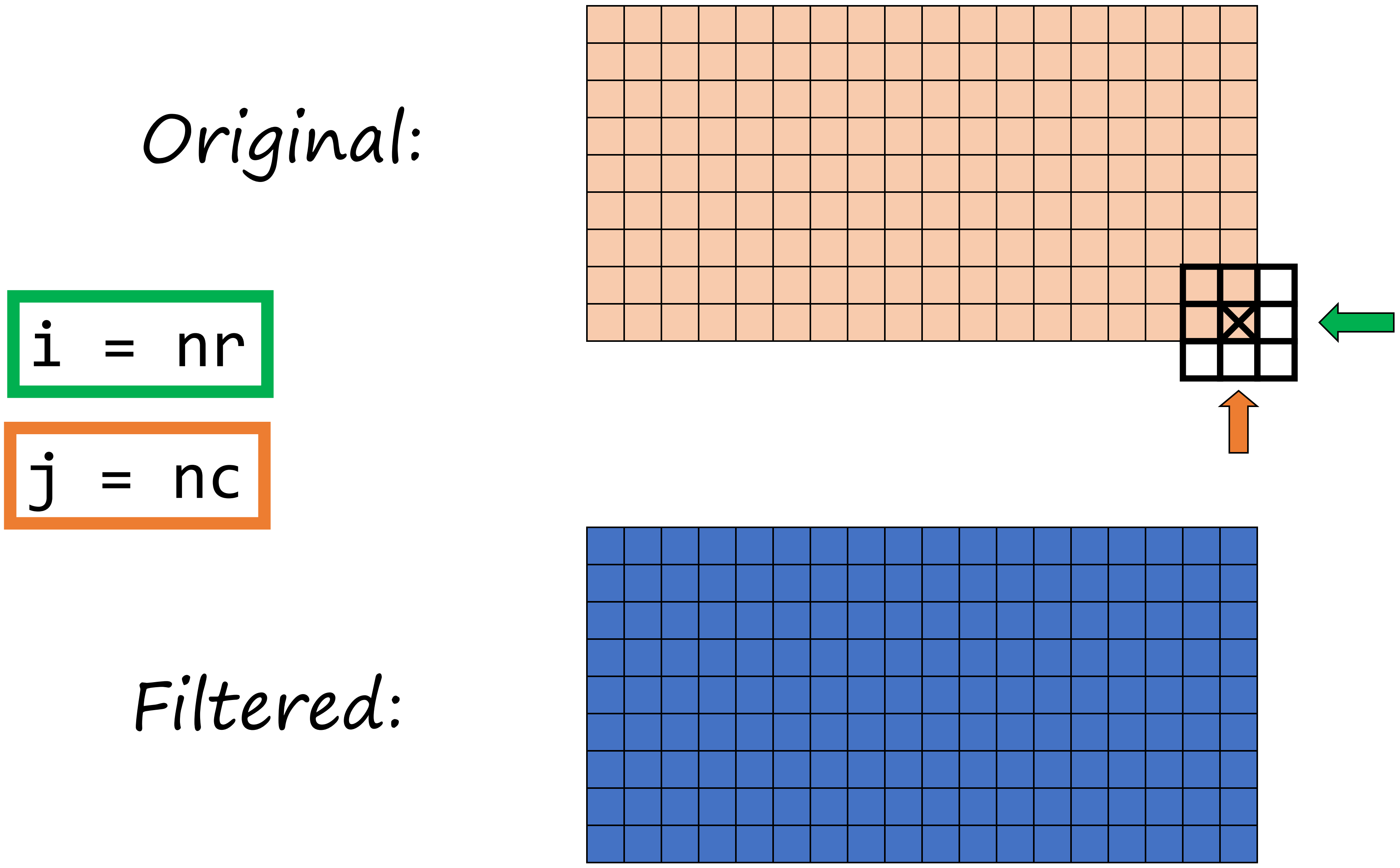
`j = 1`

Filtered:

Replace ⊠ with the median of the values under the window.

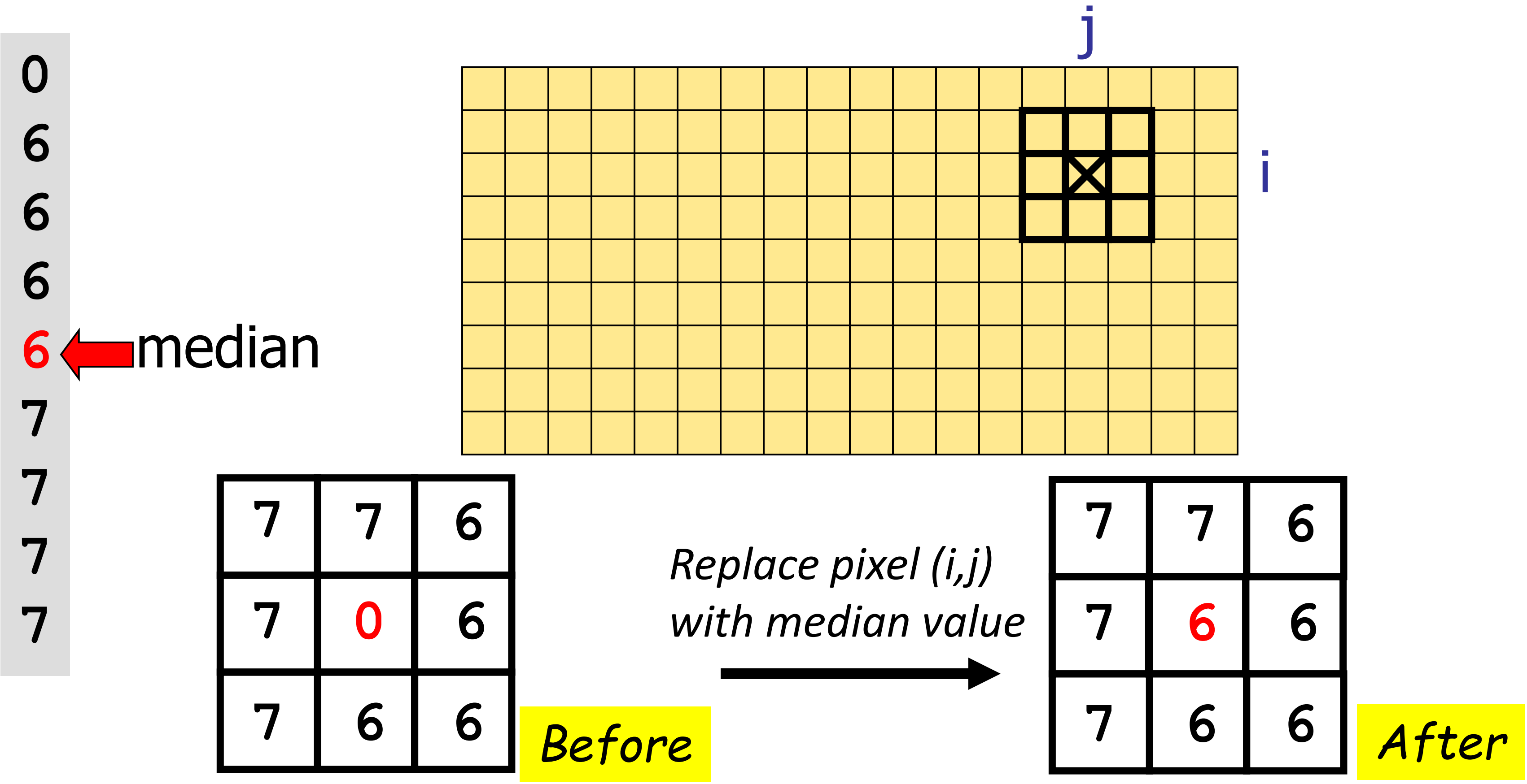


Replace ☒ with the median of the values under the window.



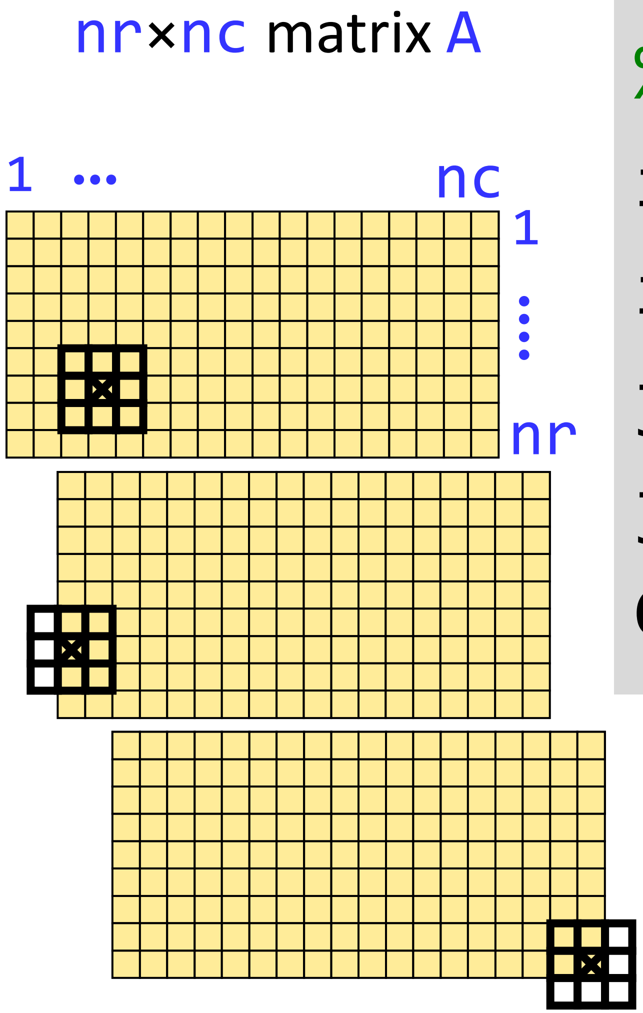
Replace ☒ with the median of the values under the window.

Details at a pixel (i,j) with a radius 1 “neighborhood”



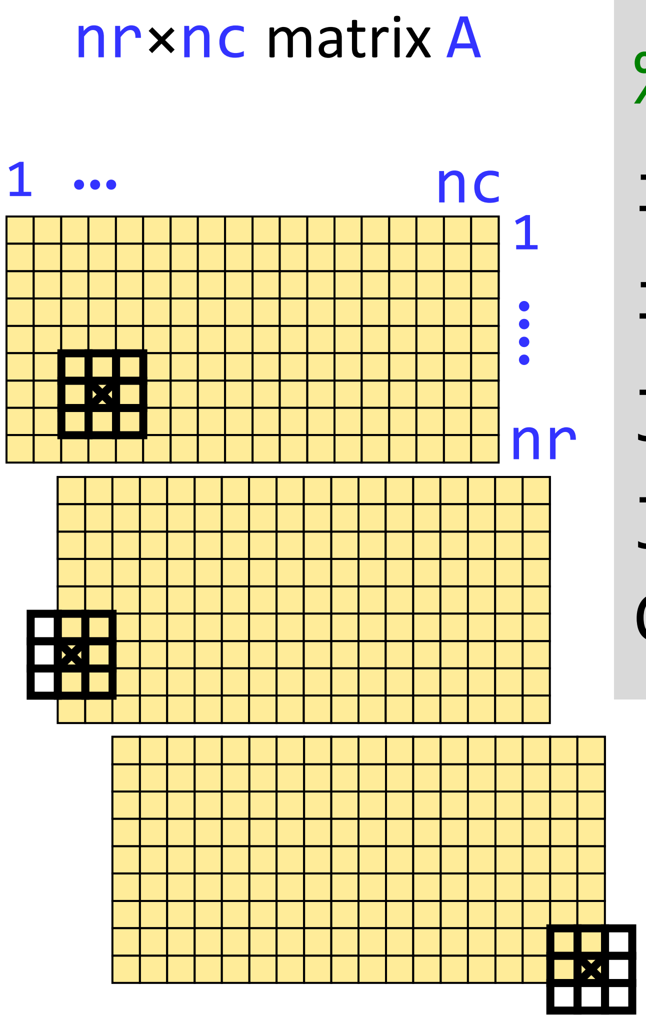

```
% Get median value in a matrix xMat
xVec= xMat(:)                 % Convert matrix to vector
medianVal= median(xVec) % Use built-in function
```

Deal with boundary issues – moving window



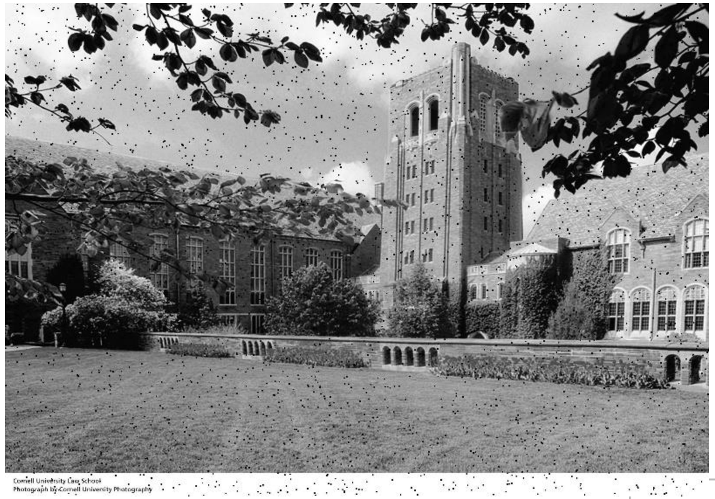

```
% Get C, the radius r
% neighborhood of pixel (i,j)
iMin=          i-r
iMax=          i+r
jMin=          j-r
jMax=          j+r
C= A(iMin:iMax,jMin:jMax)
```

Deal with boundary issues – moving window



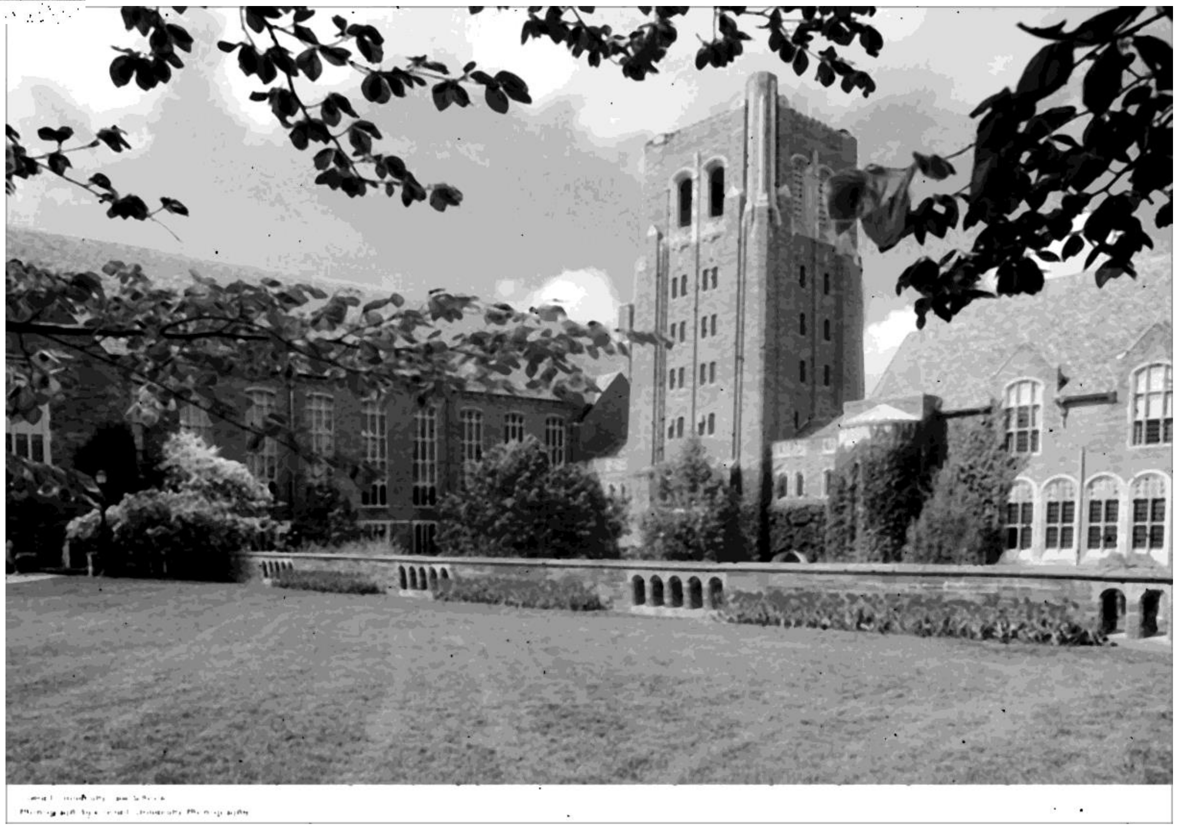

```
% Get C, the radius r
% neighborhood of pixel (i,j)
iMin= max( 1,i-r)
iMax= min(nr,i+r)
jMin= max( 1,j-r)
jMax= min(nc,j+r)
C= A(iMin:iMax,jMin:jMax)
```

See *Insight* §12.4 for complete code: **`MedianFilter.m`**

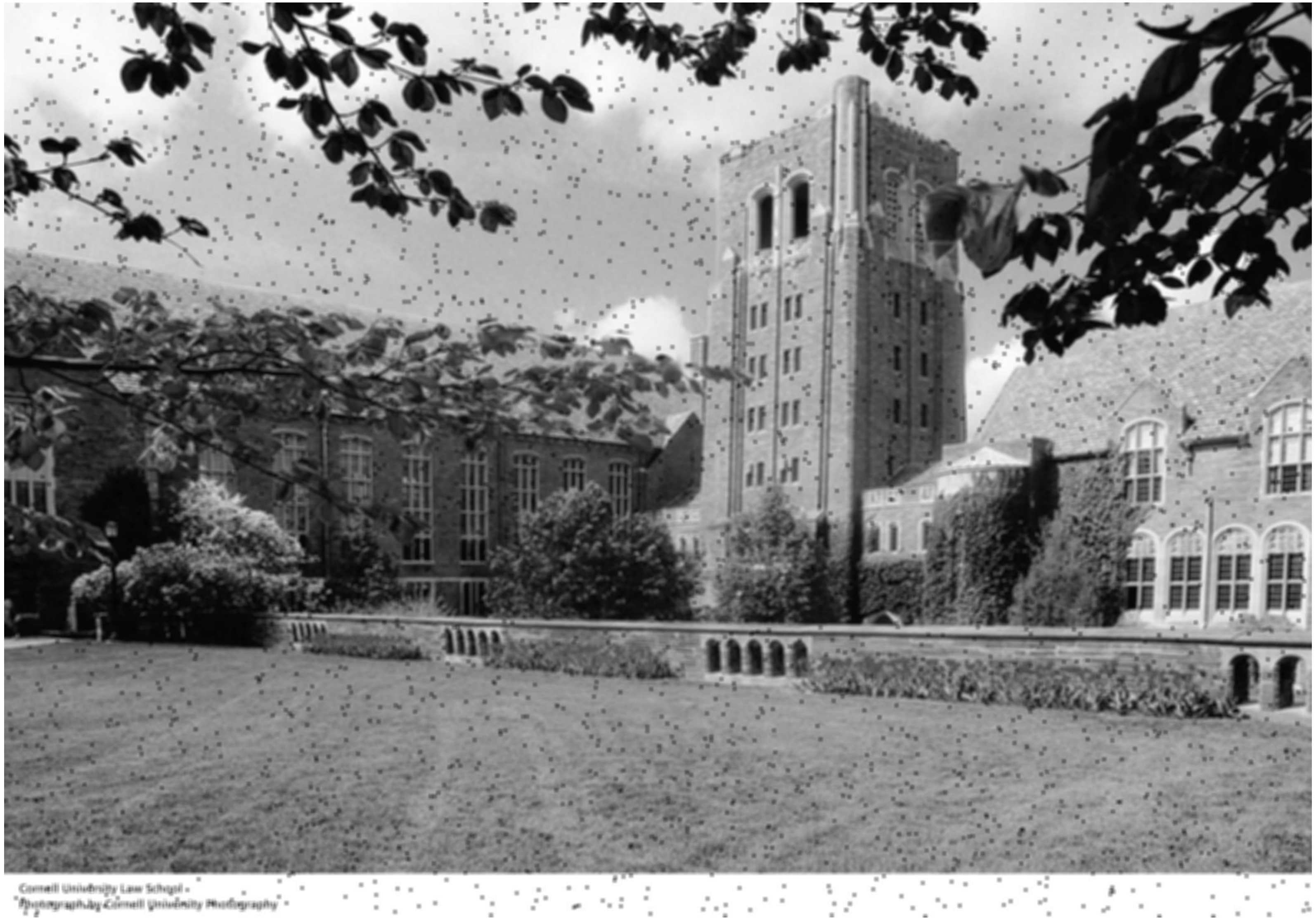


A

B = medianFilter(A,3)



Mean Filter with radius 3



Mean Filter with radius 10

Mean filter fails because the mean does not capture representative values.

150	149	152	153	152	155
151	150	153	154	153	156
153	2	3	156	155	158
154	2	1	157	156	159
156	154	158	159	158	161
157	156	159	160	159	162

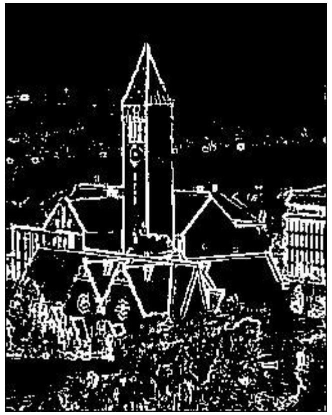
85	86
87	88

mean-filtered values with radius 1 neighborhood

150	150
153	154

median-filtered values with radius 1 neighborhood

Finding Edges: read example in Sec 12.4



Identify “sharp changes” in image data—a kind of outliers.

Subtracting **`uint8`** values correctly to prevent “underflow”

“Thresholding”—use a parameter to control the amount of details extracted from image