



# E298A/EE290B – Proximity Correction

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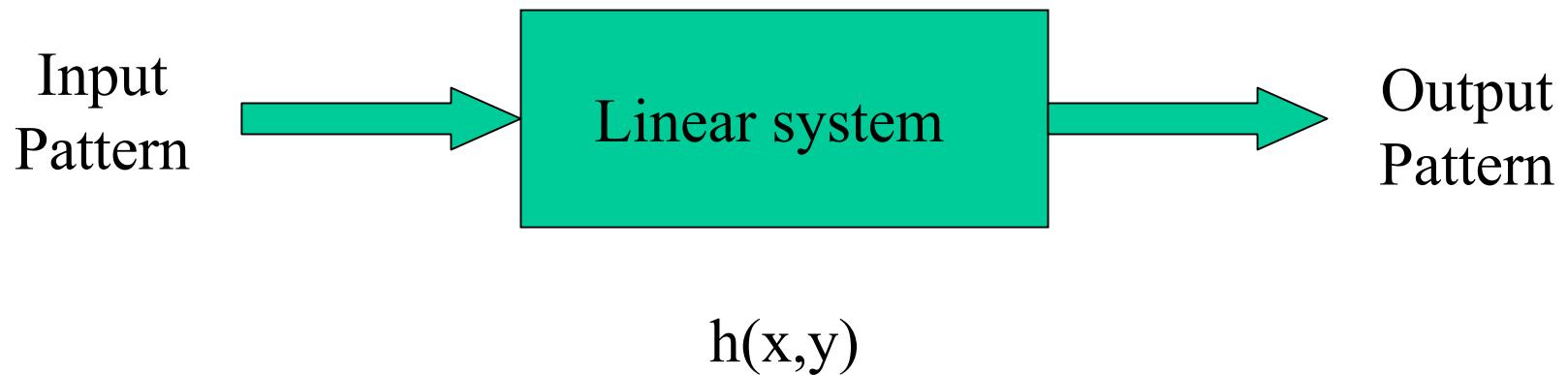
- Purpose: Understand 3 methods for Proximity correction
  - Goal: Convolution of Scattering Point Spread Function with modified data set to give desired dose.
    - Matrix approach
    - “Ghost” approach
    - Iterative convolution approach





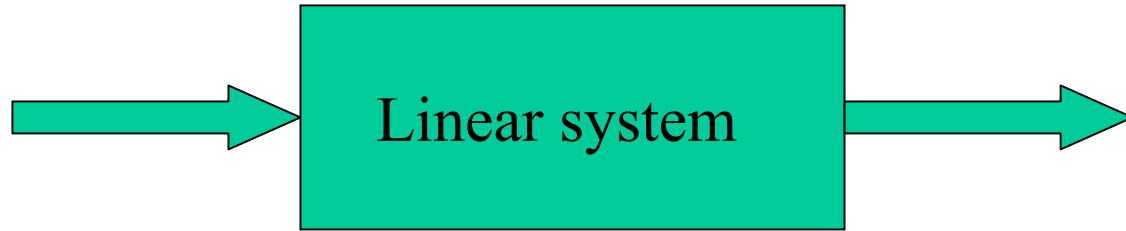
# Proximity Correction – Linear system model

Idealize the exposure process to represent the scattering as a linear time and position independent invariant system





# Proximity Correction - Convolution



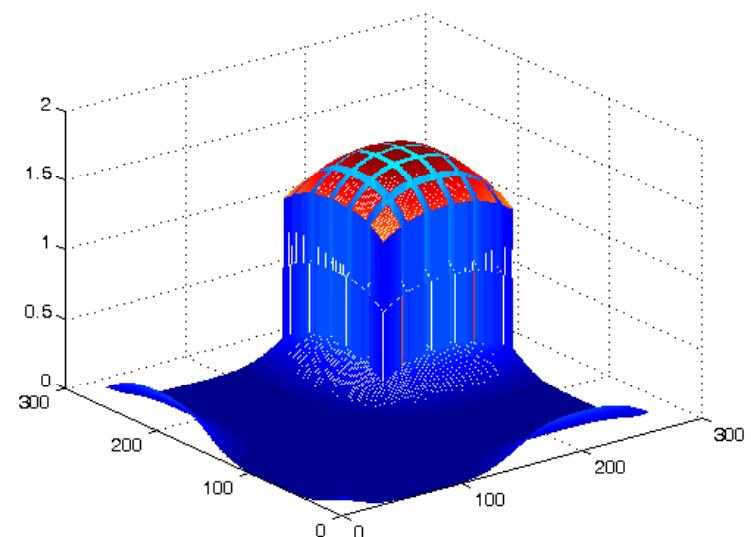
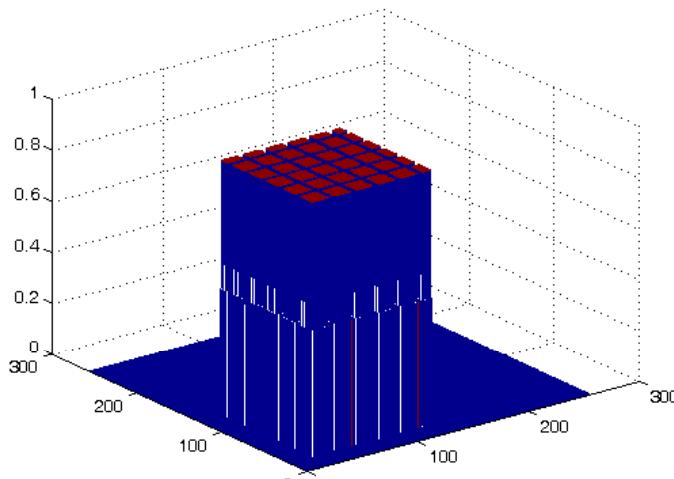
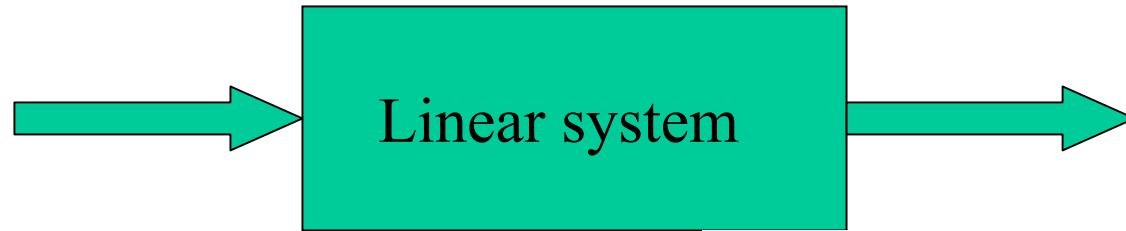
$$p_{\text{output}} = p_{\text{input}} \otimes h$$

$$p_{\text{input}} \otimes h = \iint p(x-u, y-v) h(u, v) du dv$$





# Proximity Correction - Convolution





# Proximity Correction - Convolution

Calculation of convolution using Fourier Transform

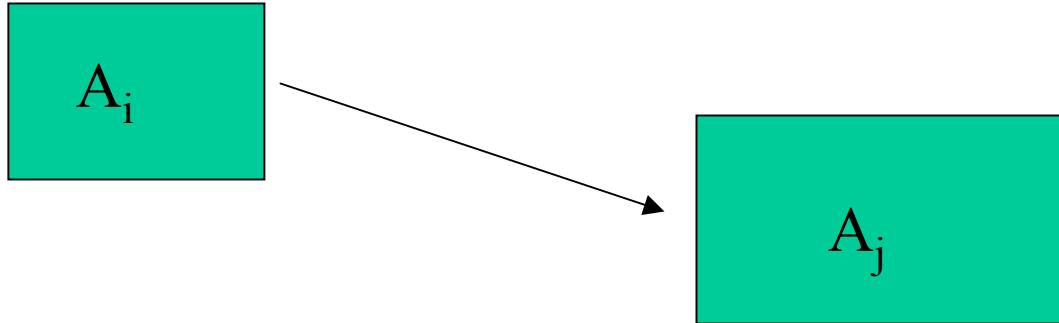
- Convolution Theorem
  - $p = h \otimes u$       the  $P = (1/\pi)^2 H^* U$
  - Where “ $\Leftrightarrow$ ” is the Fourier transform and
  - $p \Leftrightarrow P$ ,  $h \Leftrightarrow H$ , and  $u \Leftrightarrow U$
- Fast Fourier Transform allows efficient calculation of “Periodic Convolution”





# Proximity Correction – Matrix approach

If we apply unity dose to rectangle “A” how much extra dose does rectangle “B” get?



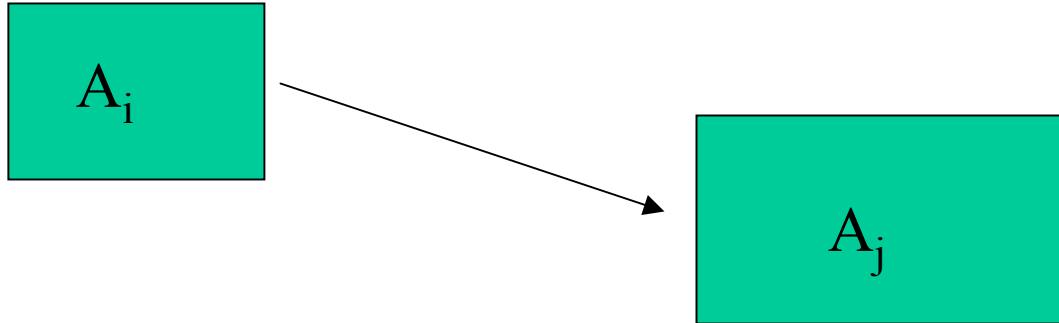
First do convolution, then integrate.





# Proximity Correction – Matrix approach

If we apply unity dose to rectangle “A” how much extra dose does rectangle “B” get?



Analytic solution possible if  $h$  is a gaussian or sum of gaussians.

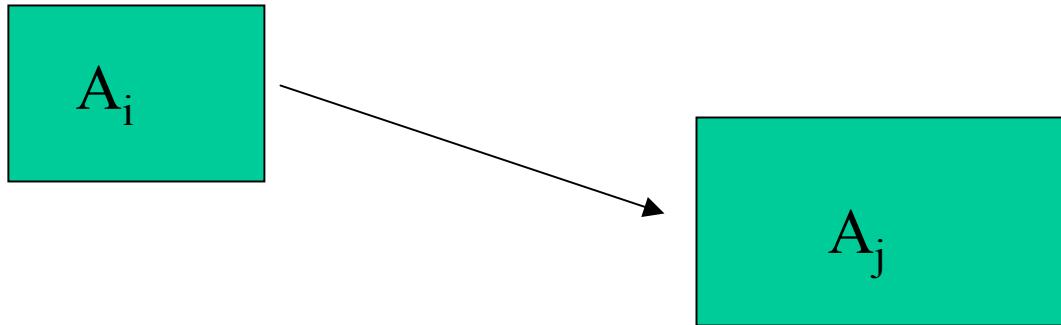
*M. Parikh, "Self-consistent proximity effect correction technique for resist exposure (SPECTRE)," J. Vac. Sci. Technol. 15(3), 931-933 (1978).*





# Proximity Correction – Matrix approach

$$I_{ij} = \iint f(r) dA_i dA_j$$



$$H_{ij}(\beta) = \iint \exp(-r^2/\beta) dA_i dA_j$$





# Proximity Correction – Matrix approach

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$$H_{ij}(\beta) = (\pi/4) \beta^4 (Q(\gamma_{22}) + Q(\gamma_{11}) - Q(\gamma_{12}) - Q(\gamma_{21}))^* \\ (Q(\delta_{22}) + Q(\delta_{11}) - Q(\delta_{12}) - Q(\delta_{21}))$$

Where  $Q(x) = \text{erfc}(x) + (1/\pi)\exp(-x^2)$

And  $\gamma_{ij} = (x_i - x_j)/\beta$  and  $\delta_{ij} = (y_i - y_j)/\beta$  are the normalized coordinate differences





# Proximity Correction – Matrix approach

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- Set up a very large linear equation

$$Hx = 1$$

This gives each shape the correct total dose





# Proximity Correction – Matrix approach

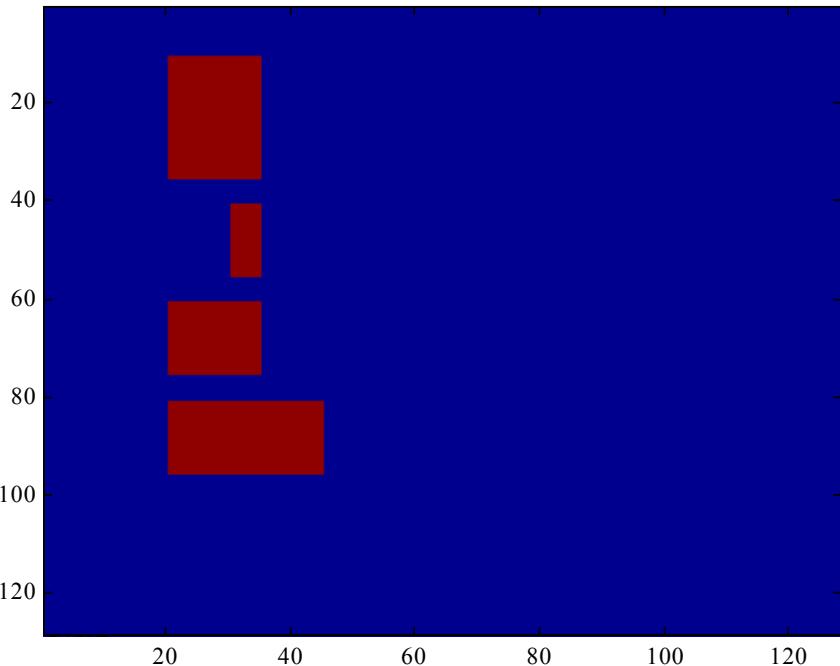
```
tp=p/beta;  
for i=1:n  
    for j=i:n  
        gamma11=(tp(i,1)-tp(j,1));  
        gamma12=(tp(i,1)-tp(j,3));  
        gamma21=(tp(i,3)-tp(j,1));  
        gamma22=(tp(i,3)-tp(j,3));  
        delta11=(tp(i,2)-tp(j,2));  
        delta12=(tp(i,2)-tp(j,4));  
        delta21=(tp(i,4)-tp(j,2));  
        delta22=(tp(i,4)-tp(j,4));  
  
FACTOR=eta*(pi)*(beta^2)*(1/4)*(gcal(gamma22)+gcal(gamma11)-gcal(gamma21)-  
gcal(gamma12))*(gcal(delta22)+gcal(delta11)-gcal(delta21)-gcal(delta12));  
M(i,j)=FACTOR/((p(i,3)-p(i,1))*(p(i,4)-p(i,2)));  
M(j,i)=FACTOR/((p(j,3)-p(j,1))*(p(j,4)-p(j,2)));  
  
gcal=1/sqrt(pi)*x.*erf(x)+(1/pi)*exp(-x.*x);
```





# Proximity Correction – Matrix approach

Example 4 rectangles



X1	Y1	X2	Y2
10	20	35	35
40	30	55	35
60	20	75	35
80	20	95	45





# Proximity Correction – Matrix approach

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Forward scatter  $\delta=8\text{nm}$  ( $\eta=1$ ) and backscatter  
 $\beta=30\text{um}$  ( $\eta=.5$ )

Coupling matrix  $M_{ij} =$

1.0524 0.0065 0.0051 0.0010

0.0323 1.0007 0.0241 0.0117

0.0085 0.0080 1.0307 0.0383

0.0010 0.0023 0.0230 1.0524





# Proximity Correction – Matrix approach

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Solution to  $Mx = 1$ :

X = 0.9392

0.9360

0.9207

0.9272





# Proximity Correction – Matrix approach

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Advantages of matrix method

- simple to implement
- works well for short range interactions

Disadvantages

- for  $N$  shapes the matrix is  $N \times N$  – if the interaction is large this can be a **HUGE** matrix
- Not practical at High-Voltage ( $N \approx \rho \beta^2$ ) ( $N \times N \approx \rho^2 \beta^4$ )





# Proximity Correction – Ghost

## God Help Our System Throughput

$f(r)$  is “forward” scattering function

$s(r)$  is longer range “back” scattering

$$h(r) = f(r) + \eta s(r)$$

$B(r)$  = blurring function (perhaps from defocus)

Two pass process

$$p1 = p \otimes (f(r) + \eta s(r)) = p \otimes f + \eta p \otimes s$$

$$p2 = \eta(1-p) \otimes B(r) \otimes (f(r) + \eta s(r)) = \eta(1-p) \otimes B(r) \otimes f(r) + \eta^2(1-p) \otimes B(r) \otimes s(r)$$

*G. Owen and P. Rissman, "Proximity effect correction for electron beam lithography by equalization of background dose," J. Appl. Phys. 54 (6), 3573-3581 (1983).*





# Proximity Correction – Ghost

$$p1 = p \otimes (f(r) + \eta s(r)) = p \otimes f + \eta p \otimes s$$

$$p2 = \eta(1-p) \otimes B \otimes (f(r) + \eta s(r)) = \eta(1-p) \otimes B \otimes f + \eta^2(1-p) \otimes B \otimes s$$

Adding the two exposures

$$p1 + p2 = p \otimes f + (\eta p \otimes s - \eta p \otimes B \otimes f) + \eta^2(-p) \otimes B \otimes s + (\eta + \eta^2)$$

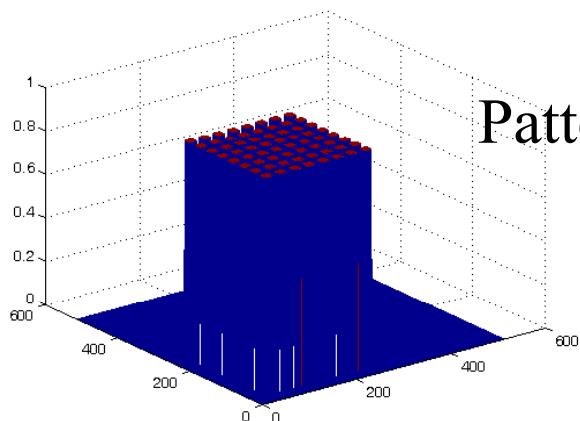
Pattern

Choose  $B(r)$  so that  
these (almost)  
canceled out

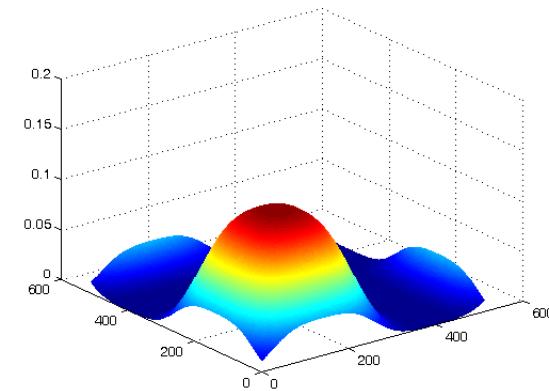
Second order  
term

Contrast pattern

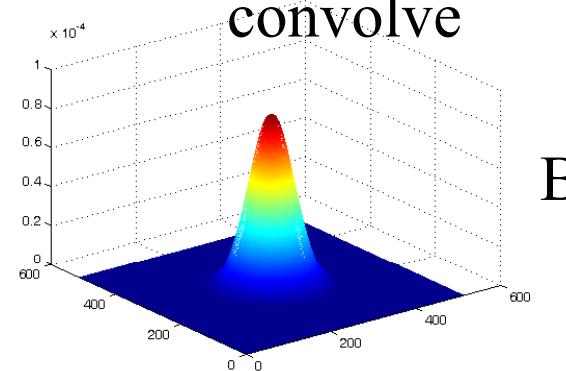




Pattern

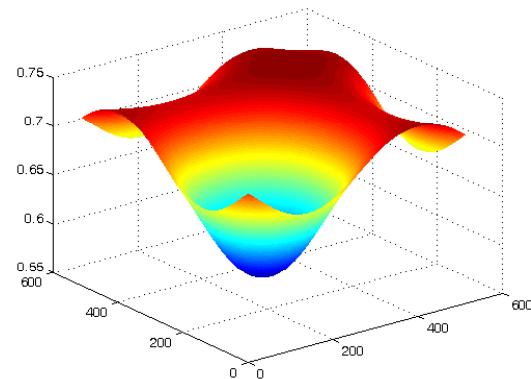


Resulting Background dose



Invert and  
convolve

$B(r)$



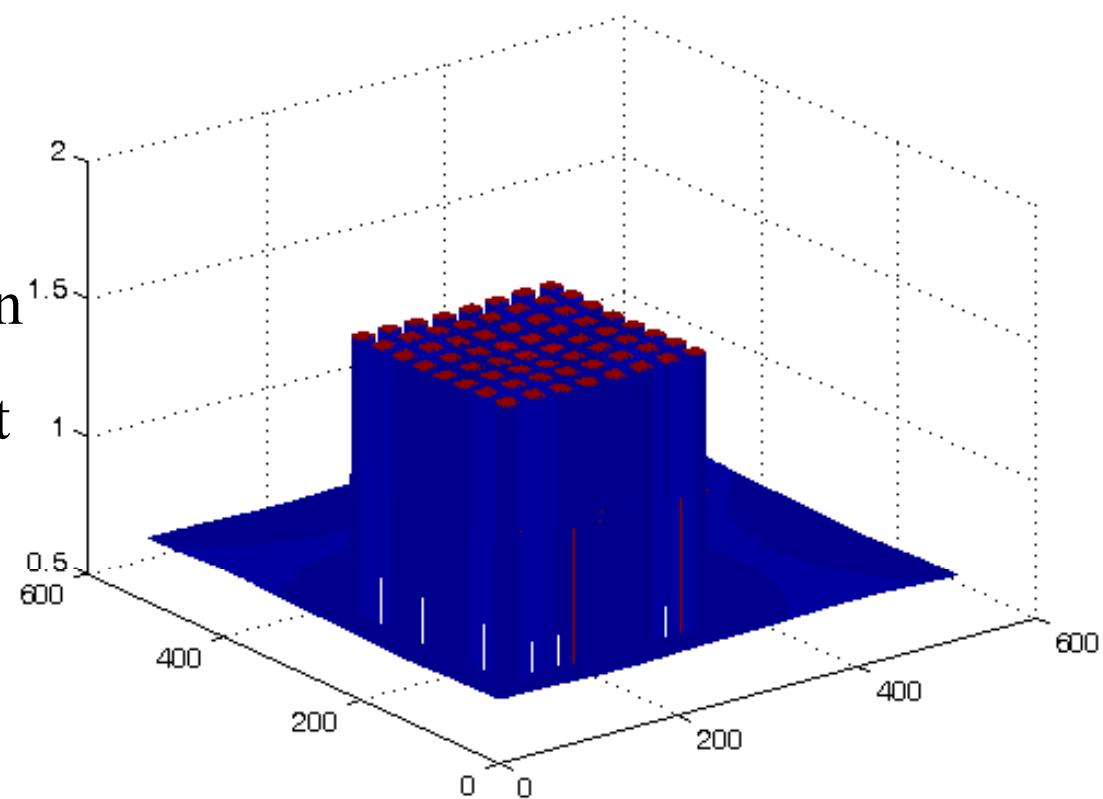
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Lecture 6 Proximity Correction



## Resulting Pattern

- Flat with offset





# Proximity Correction – Ghost

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Trick to using Ghost:

- Use a defocused beam to approximate the scattering function and then expose the complement of the pattern
- Ghost (almost) cancels out backscatter variation
- Well suited for gaussian raster tools, complement of the pattern is obtained with inverting the blanker signal





# Proximity Correction – Convolution Iteration

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Let  $w$  be the dose distribution that produces the “best” proximity correction in the following sense:

$$w \otimes (1 + \eta h) = 1 \text{ when the pattern is 1}$$

$$\text{And } W = 0 \text{ when the pattern is 0}$$

This can be written in the following way:

$$w \otimes (1 + \eta h) = p + (1-p) \otimes (\eta w \otimes h)$$

Expanding

$$p(x,y) * (1 - \eta h \otimes w(x,y)) = w(x,y)$$





# Proximity Correction – Convolution Iteration

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$$\int p(x,y) * (1 - \eta h \otimes w(x,y)) = \int w(x,y)$$

$p \Rightarrow P$  and  $w \Rightarrow W$  “Local density values”

Calculate  $P$  from the pattern  $p$  on a suitable grid which is large compared to the smallest feature sizes but small compared to the backscatter range,  $\beta$ .

The equation to solve is then:

$$P(x,y) * (1 - \eta h \otimes W(x,y)) = W(x,y)$$





# Proximity Correction – Convolution Iteration

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- Calculate  $P$  from the pattern  $p$
- guess a trial solution  $W$ ,  $W=P$
- Put it into the left hand side of the equation and calculate using FFTs for the convolution.
- Use the right hand side of the equation as the next starting point
- Iterate until solution converges





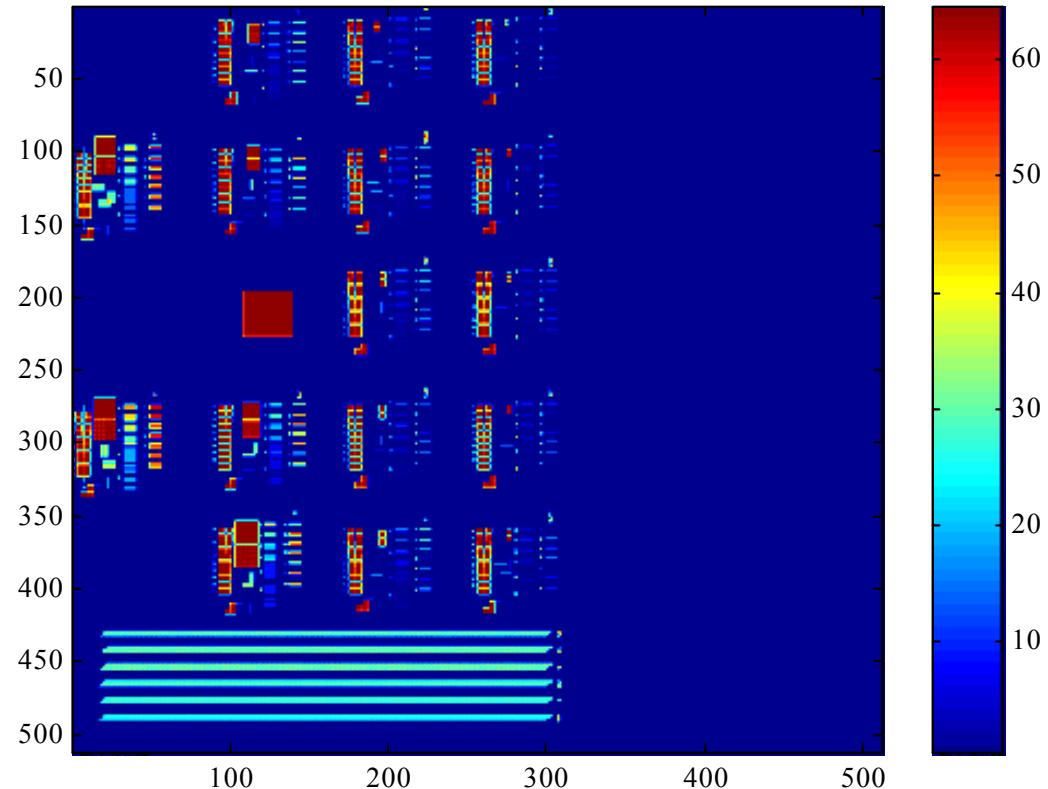
# Proximity Correction – Convolution Iteration

```
function Z = STEP(n,p,np,eta,H,k)
%t=clock;
eps=1e-6*ones(n,n);
zero=zeros(n);
one=ones(n);
HH=eta*H;
Z=np;
w=con2d(H,p);
for i=1:k
q=con2d(H,Z+con2d(HH,Z).*p);
Z=Z.* (w./(q+eps));
Z1=p.*min(one,max(zero,real(1-fftshift(ifft2(HH.*fft2(Z))))));
Z2=p.*min(one,max(zero,real(1-fftshift(ifft2(HH.*fft2(Z1))))));
Z=(0.2*Z1+ 0.8*Z2);
end
Z=real(Z);
```





# Pattern Density

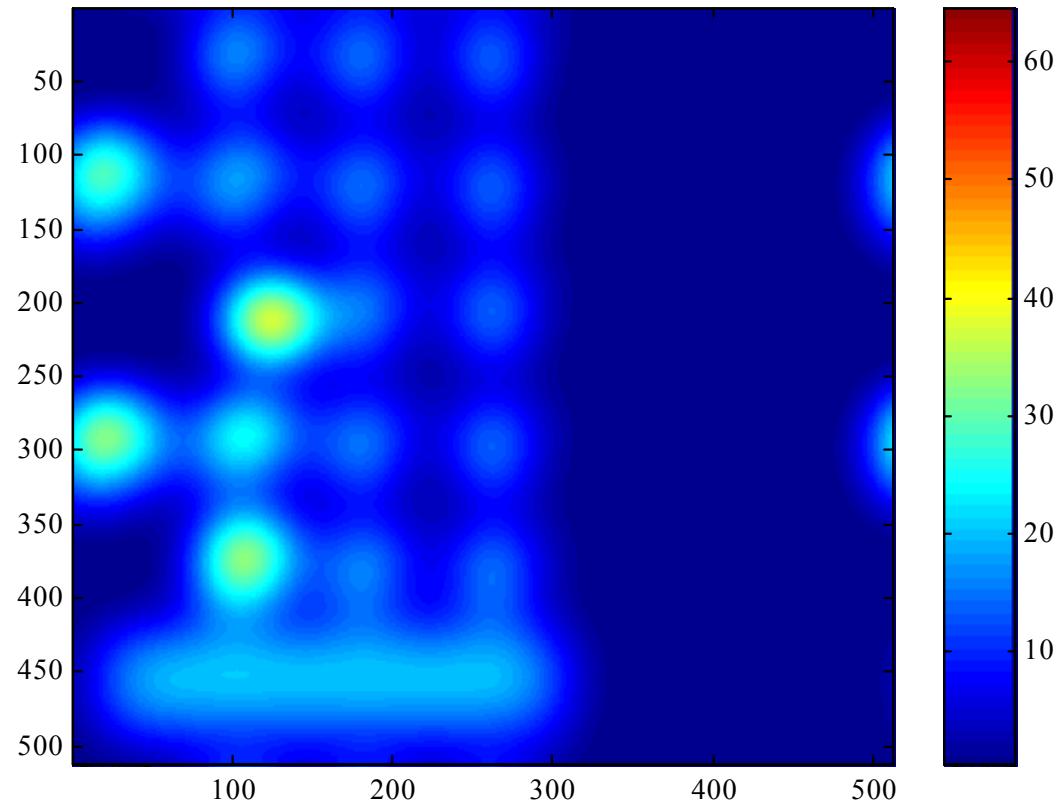


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Lecture 6 Proximity Correction



## Resulting background dose

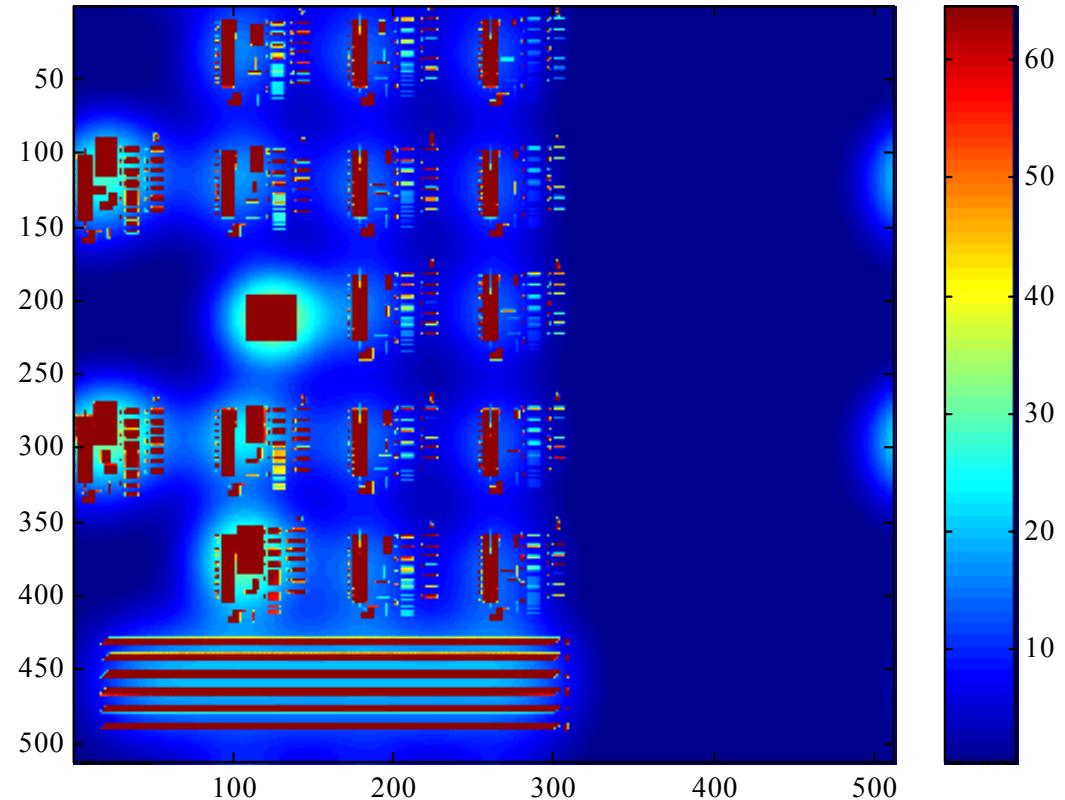


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Corrected  
pattern



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Lecture 6 Proximity Correction