

第四章：形态学

中国科学技术大学 电子工程与信息科学系

主讲教师：李厚强 (lihq@ustc.edu.cn)
周文罡 (zhwg@ustc.edu.cn)
李 礼 (li11@ustc.edu.cn)
胡 洋 (eeyhu@ustc.edu.cn)



形态学

□ 形态学

- 二值形态学
 - ✓ 基本定义
 - ✓ 基本运算
 - ✓ 实用算法

二值形态学

□ 基本集合定义

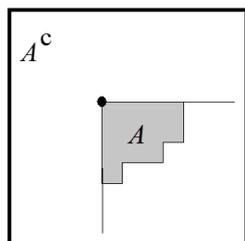
■ 集合：用大写字母表示，空集记为 \emptyset

■ 元素：用小写字母表示

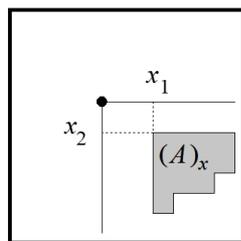
■ 子集：

■ 并集：

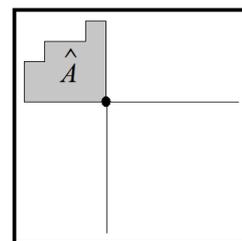
■ 交集：



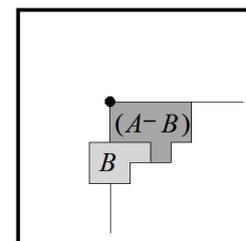
(a)



(b)



(c)



(d)

■ 补集： $A^c = \{x|x \notin A\}$

■ 位移： $(A)_x = \{y|y = a + x, a \in A\}$

■ 映像： $\hat{A} = \{x|x = -a, a \in A\}$

■ 差集： $A - B = \{x|x \in A, x \notin B\} = A \cap B^c$



二值形态学基本运算

□ 集合运算

- A为图象集合，B 为结构元素（集合）
- 数学形态学运算是用 B 对 A 进行操作
- 结构元素要指定1个原点（参考点）

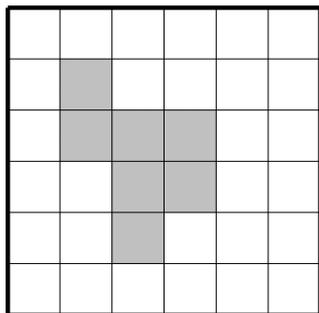
膨胀和腐蚀

□ 膨胀

- 膨胀的算符为 \oplus

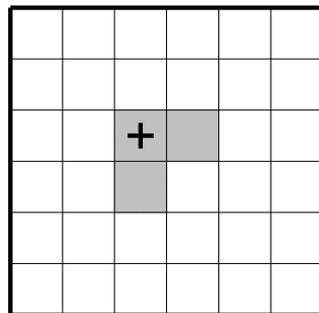
$$A \oplus B = \{x \mid [(\hat{B})_x \cap A] \neq \emptyset\}$$

集合A



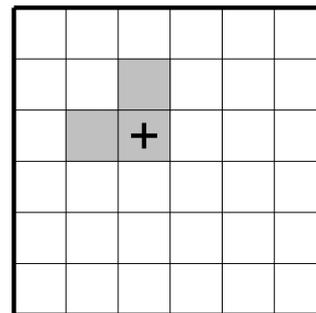
(a)

结构元素B



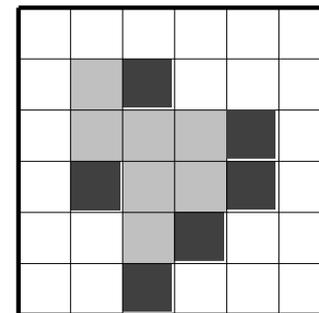
(b)

B的映象



(c)

集合 $A \oplus B$



(d)

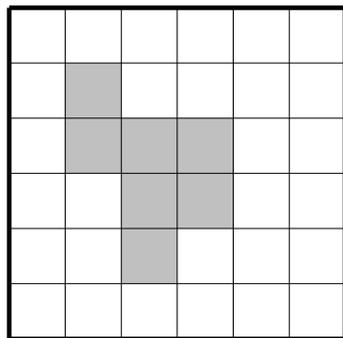
膨胀和腐蚀

□ 腐蚀

- 腐蚀的算符为 \ominus

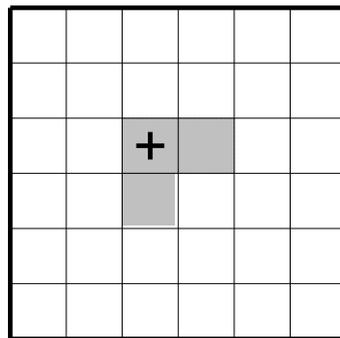
$$A \ominus B = \{x | (B)_x \subseteq A\}$$

集合A



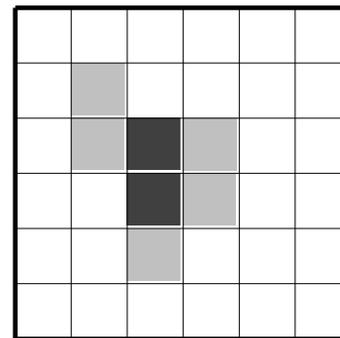
(a)

结构元素B



(b)

集合 $A \ominus B$



(c)



膨胀和腐蚀

□ 原点不包含在结构元素中的膨胀和腐蚀

■ 原点包含在结构元素中

✓ 膨胀运算: $A \subseteq A \oplus B$

✓ 腐蚀运算: $A \ominus B \subseteq A$

■ 原点不包含在结构元素中

✓ 膨胀运算: $A \not\subseteq A \oplus B$

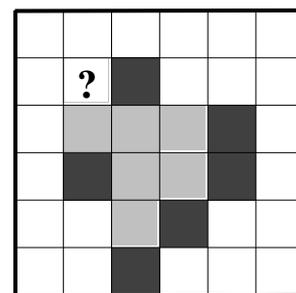
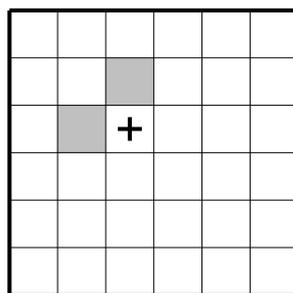
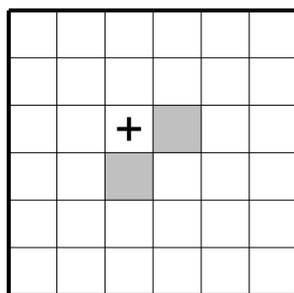
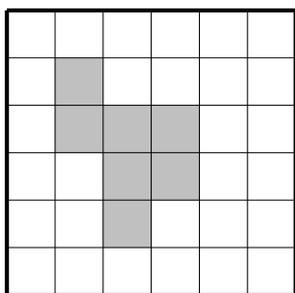
✓ 腐蚀运算: $A \ominus B \subseteq A$, 或 $A \ominus B \not\subseteq A$

膨胀和腐蚀

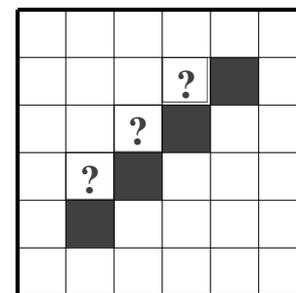
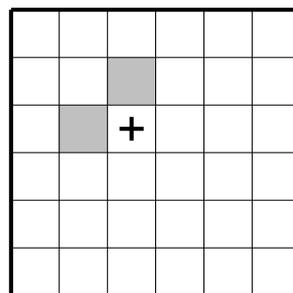
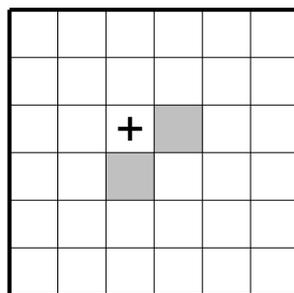
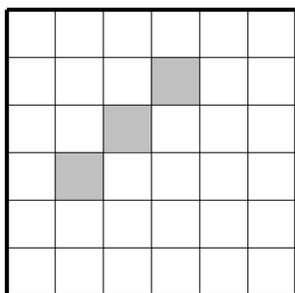
□ 原点不包含在结构元素中的时的膨胀运算

$$A \not\subset A \oplus B$$

$$A \oplus B = \{x \mid [(\hat{B})_x \cap A] \neq \emptyset\}$$



A在膨胀中自身完全消失了

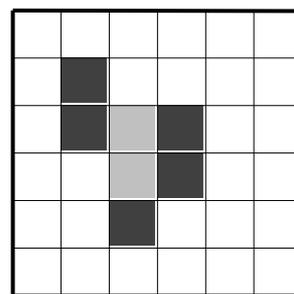
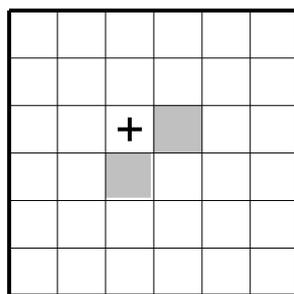
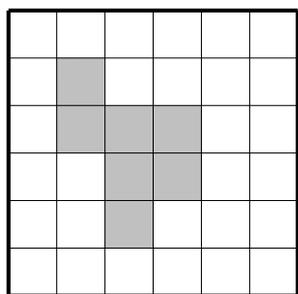


膨胀和腐蚀

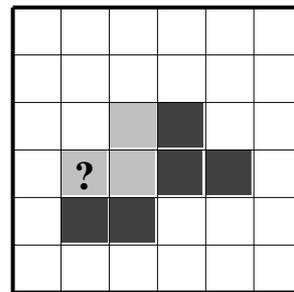
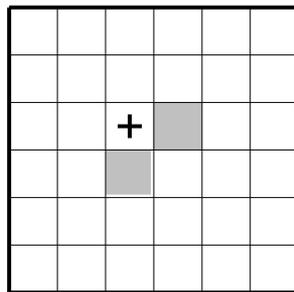
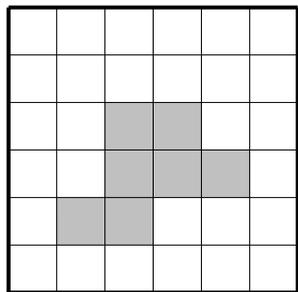
□ 原点不包含在结构元素中的时的腐蚀运算

$$A \ominus B \subseteq A$$

$$A \ominus B = \{x | (B)_x \subseteq A\}$$



$$A \ominus B \not\subseteq A$$



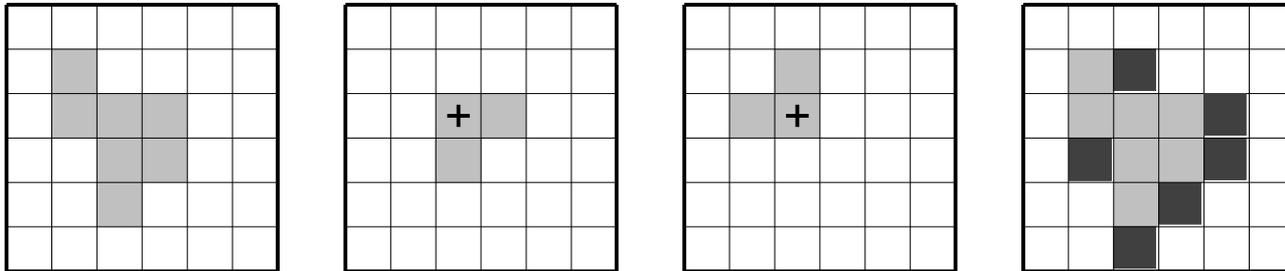
膨胀和腐蚀

□ 用向量运算实现膨胀和腐蚀

$$A \oplus B = \{x | x = a + b, \text{ 对于任意 } a \in A \text{ 和 } b \in B\}$$

$$A = \{(1, 1), (1, 2), (2, 2), (3, 2), (2, 3), (3, 3), (2, 4)\}$$

$$B = \{(0, 0), (1, 0), (0, 1)\}$$



$$A \oplus B = \{(1, 1), (2, 1), (1, 2), (2, 2), (3, 2), (4, 2), \\ (1, 3), (2, 3), (3, 3), (4, 3), (2, 4), (3, 4), (2, 5)\}$$

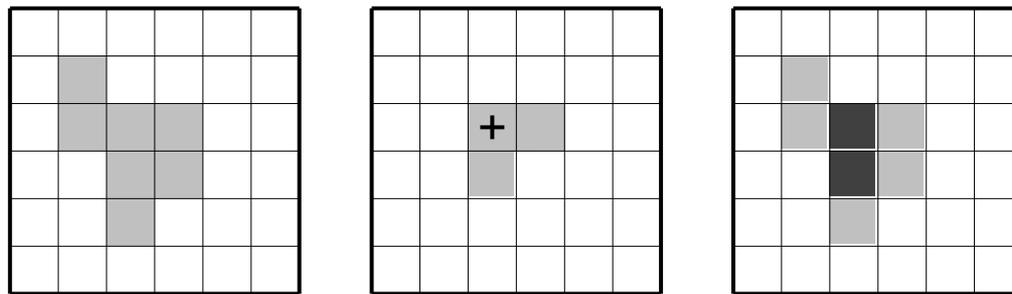
膨胀和腐蚀

□ 用向量运算实现膨胀和腐蚀

$$A \ominus B = \{x | (x + b) \in A \text{ 对每一个 } b \in B\}$$

$$A = \{(1, 1), (1, 2), (2, 2), (3, 2), (2, 3), (3, 3), (2, 4)\}$$

$$B = \{(0, 0), (1, 0), (0, 1)\}$$



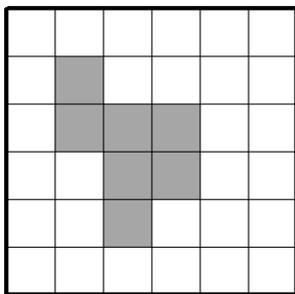
$$A \ominus B = \{(2, 2), (2, 3)\}$$

膨胀和腐蚀

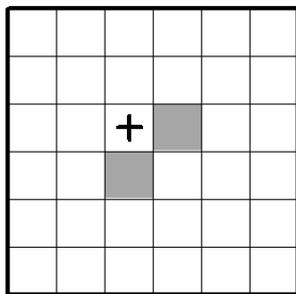
□ 用位移运算实现膨胀和腐蚀

按每个 b 来位移 A 并把结果或 (OR) 起来

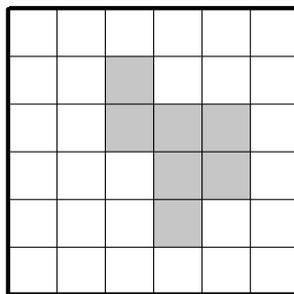
$$A \oplus B = \bigcup_{b \in B} (A)_b$$



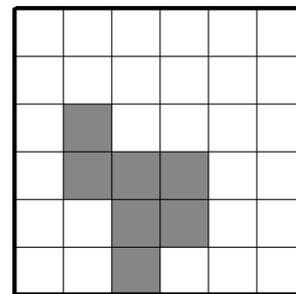
(a)



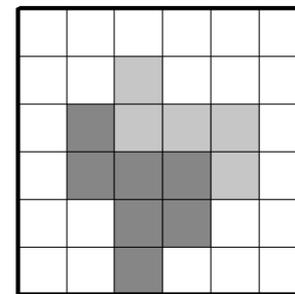
(b)



(c)



(d)



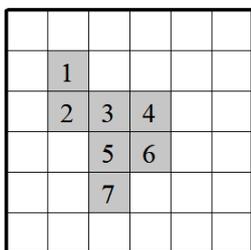
(e)

膨胀和腐蚀

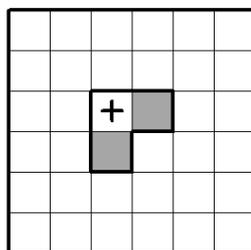
□ 用位移运算实现膨胀和腐蚀

按每个a来位移B并把结果或（OR）起来

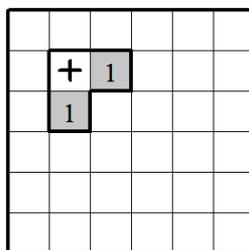
$$A \oplus B = \bigcup_{a \in A} (B)_a$$



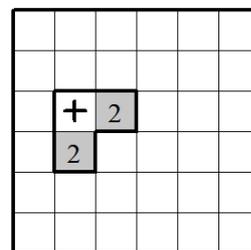
(a)



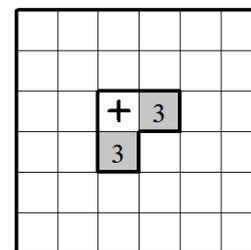
(b)



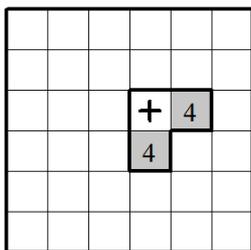
(c)



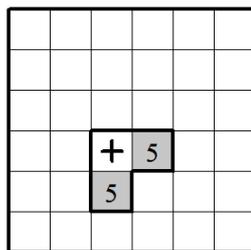
(d)



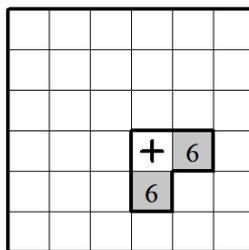
(e)



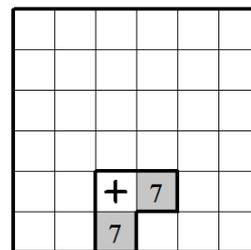
(f)



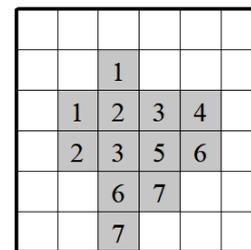
(g)



(h)



(i)



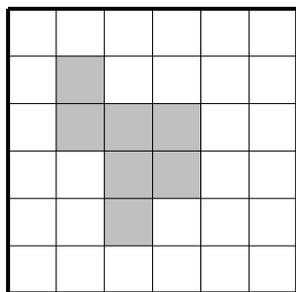
(j)

膨胀和腐蚀

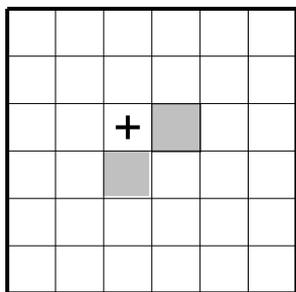
□ 用位移运算实现膨胀和腐蚀

按每个b来负位移A并把结果交（AND）起来

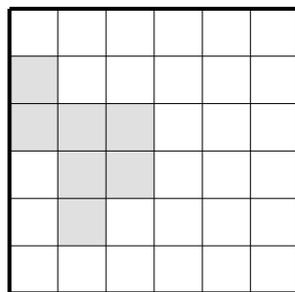
$$A \ominus B = \bigcap_{b \in B} (A)_{-b}$$



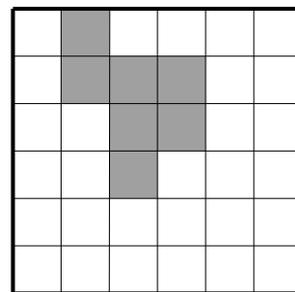
(a)



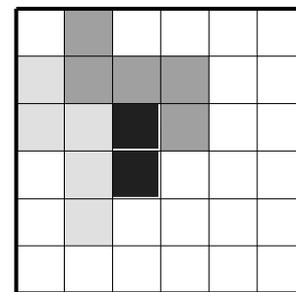
(b)



(c)



(d)

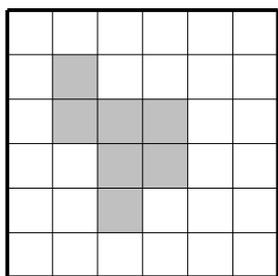


(e)

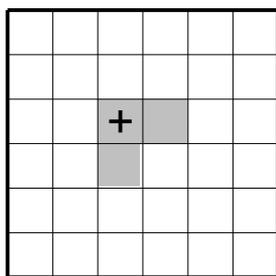
膨胀和腐蚀

□ 膨胀和腐蚀的对偶性

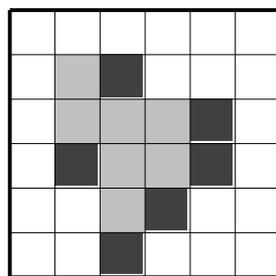
$$(A \oplus B)^c = A^c \ominus \hat{B} \quad (A \ominus B)^c = A^c \oplus \hat{B}$$



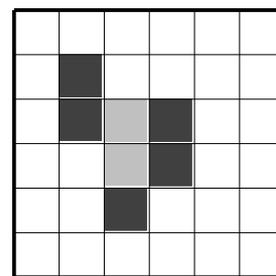
(a)



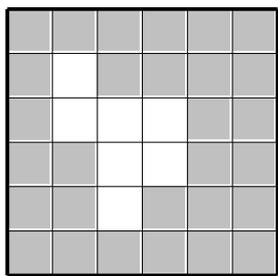
(b)



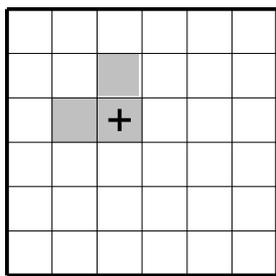
(c)



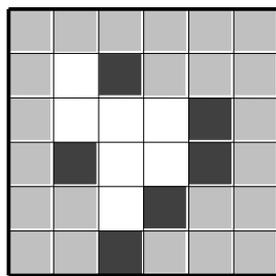
(d)



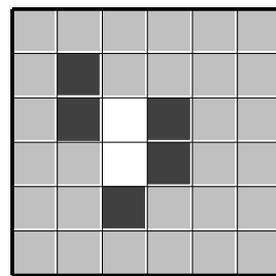
(e)



(f)



(g)



(h)

膨胀和腐蚀

□ 膨胀和腐蚀的对偶性

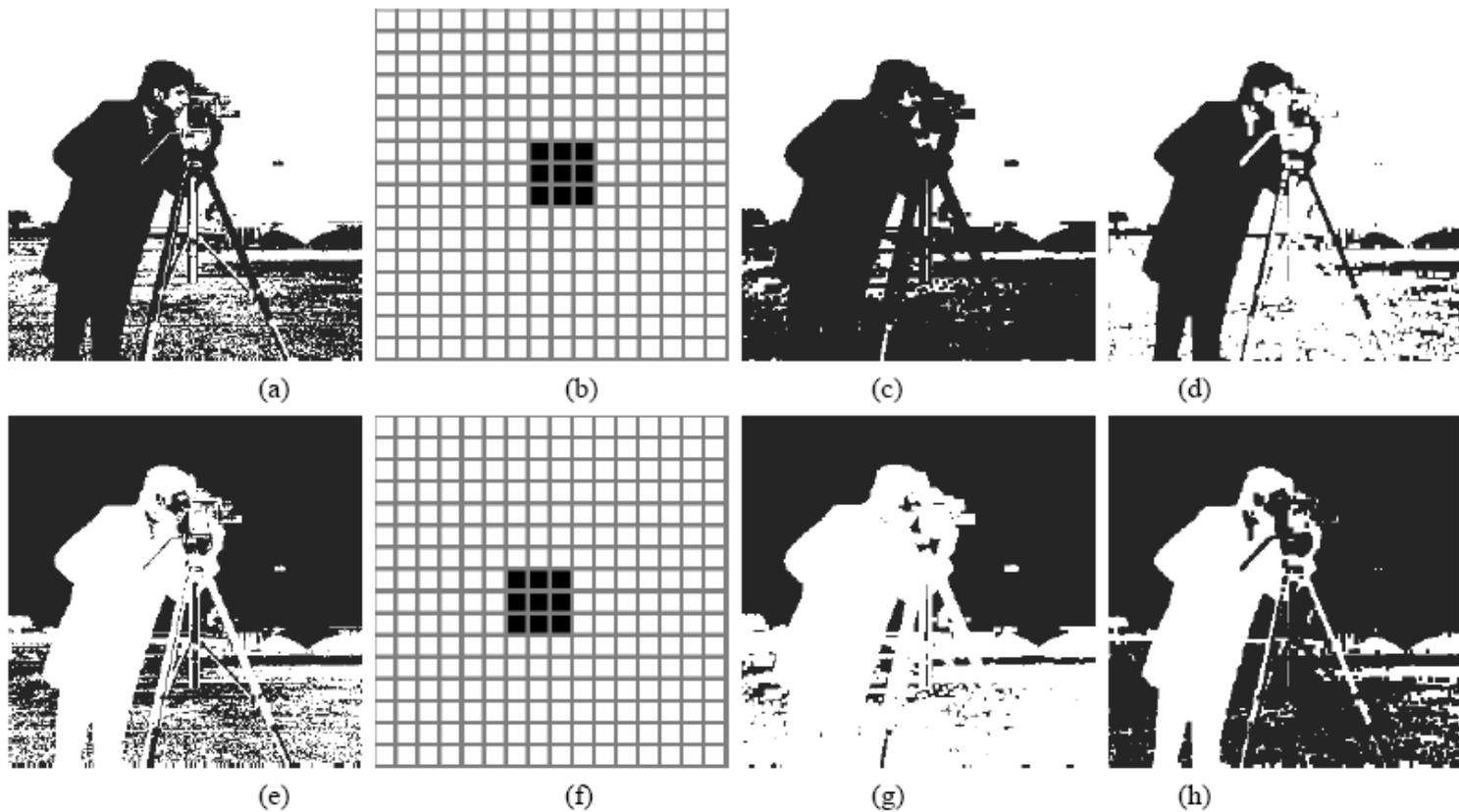


图 14.2.12 膨胀和腐蚀的对偶性验证实例



开启和闭合

□ 开启和闭合定义

- 膨胀和腐蚀并不互为逆运算
- 它们可以级连结合使用
- 开启：先对图象进行腐蚀然后膨胀其结果

$$A \circ B = (A \ominus B) \oplus B$$

- 闭合：先对图象进行膨胀然后腐蚀其结果

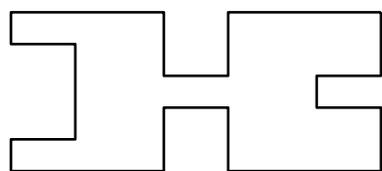
$$A \cdot B = (A \oplus B) \ominus B$$

- 开启和闭合不受原点是否在结构元素之中的影响

开启和闭合

□ 开启和闭合定义

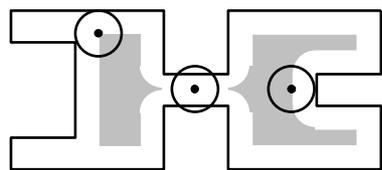
- 开启运算可以把比结构元素小的突刺滤掉
- 闭合运算可以把比结构元素小的缺口或孔填充上



(a)



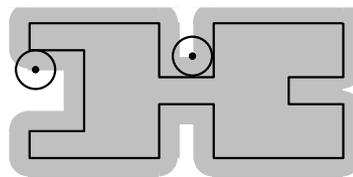
(b)



(c)



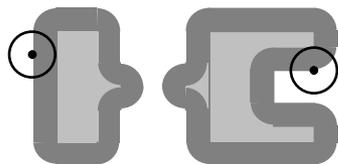
(d)



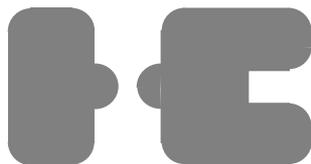
(e)



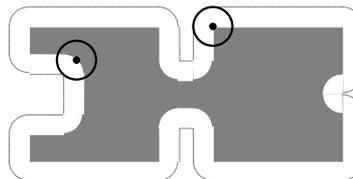
(f)



(g)



(h)



(i)



(j)

开启

闭合

开启和闭合

□ 开启和闭合定义



原图



(a)



(b)

图 14.2.14 开启和闭合实例



开启和闭合

- 开启和闭合的对偶性
 - 开启和闭合也具有对偶性

$$(A \circ B)^c = A^c \cdot \hat{B}$$

$$(A \cdot B)^c = A^c \circ \hat{B}$$

$$(A \circ B)^c = [(A \ominus B) \oplus B]^c = (A \ominus B)^c \ominus \hat{B} = A^c \oplus \hat{B} \ominus \hat{B} = A^c \cdot \hat{B}$$

$$(A \cdot B)^c = [(A \oplus B) \ominus B]^c = (A \oplus B)^c \oplus \hat{B} = A^c \ominus \hat{B} \oplus \hat{B} = A^c \circ \hat{B}$$



开启和闭合

□ 开启和闭合与集合的关系

操作	并集	交集
开启	$\left(\bigcup_{i=1}^n A_i\right) \circ B \supseteq \bigcup_{i=1}^n (A_i \circ B)$	$\left(\bigcap_{i=1}^n A_i\right) \circ B \subseteq \bigcap_{i=1}^n (A_i \circ B)$
闭合	$\left(\bigcup_{i=1}^n A_i\right) \cdot B \supseteq \bigcup_{i=1}^n (A_i \cdot B)$	$\left(\bigcap_{i=1}^n A_i\right) \cdot B \subseteq \bigcap_{i=1}^n (A_i \cdot B)$

开启和闭合

□ 开启和闭合的几何解释

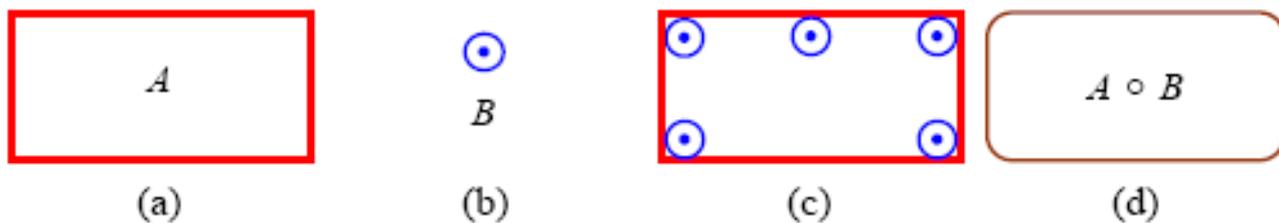


图 14.2.15 开启的填充特性

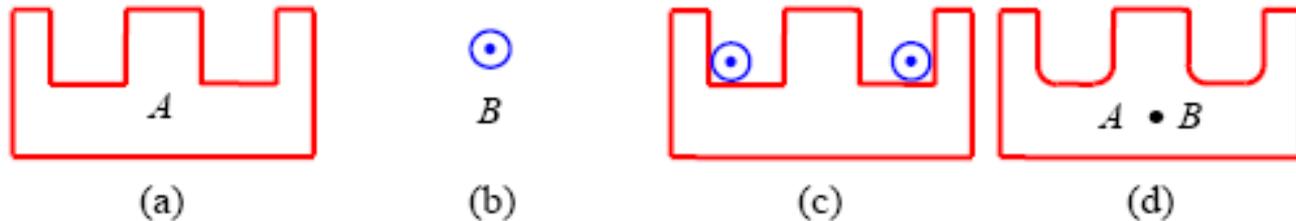


图 14.2.16 闭合的几何解释



击中-击不中变换

□ 击中-击不中变换

- 形状检测的一种基本工具
- 对应两个操作，所以用到两个结构元素
- 设A为原始图象，E和F为一对不重合的集合

$$A \uparrow (E, F) = (A \ominus E) \cap (A^c \ominus F) = (A \ominus E) \cap (A \oplus F)^c$$

E : 击中结构元素

F : 击不中结构元素

击中-击不中变换

□ 击中-击不中变换

$$A \uparrow (E, F) = (A \ominus E) \cap (A^c \ominus F) = (A \ominus E) \cap (A \oplus F)^c$$

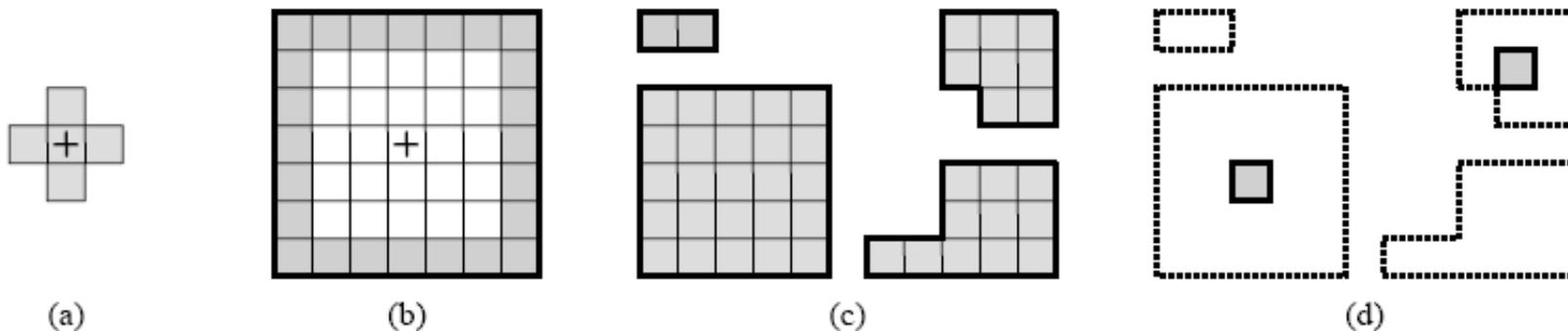


图 14.3.1 击中-击不中变换示例

- (a): 击中结构元素 (b): 击不中结构元素
(c): 原始图像 (d): 变换结果

击中-击不中变换

□ 击中-击不中变换 ((e)和(f)来自于别的变换)

击中变换: $[1 \ 1 \ 1]$

击不中变换: $\begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix}$

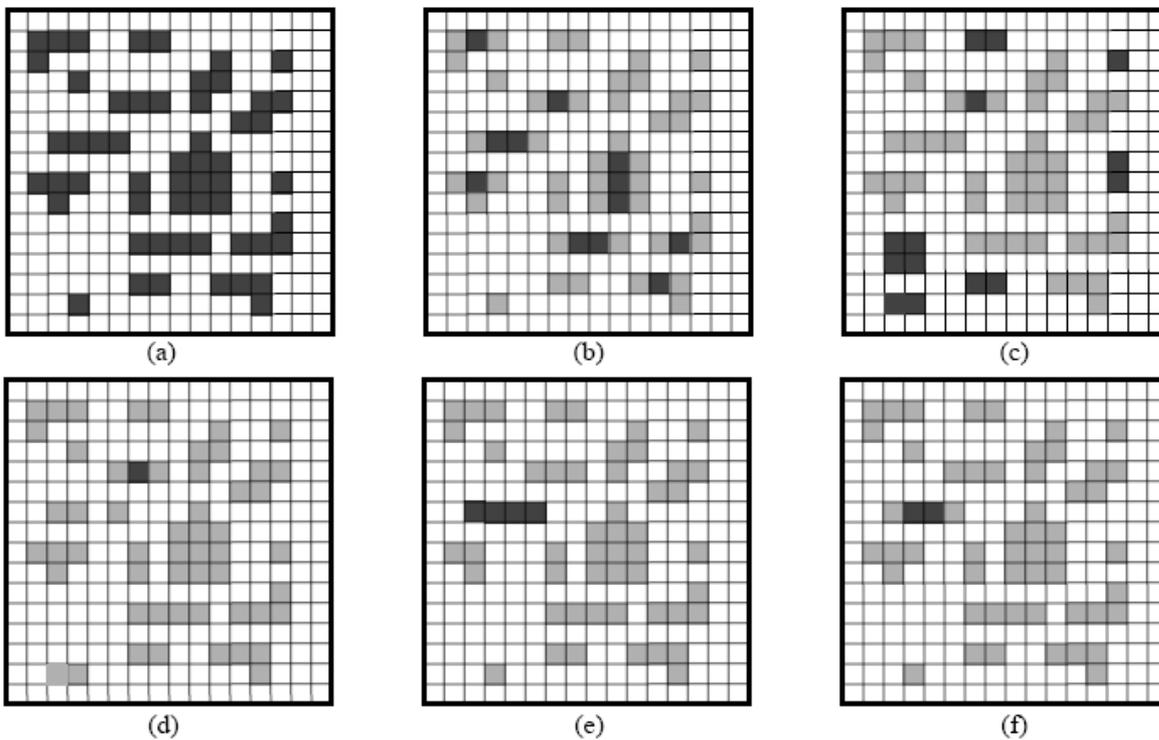
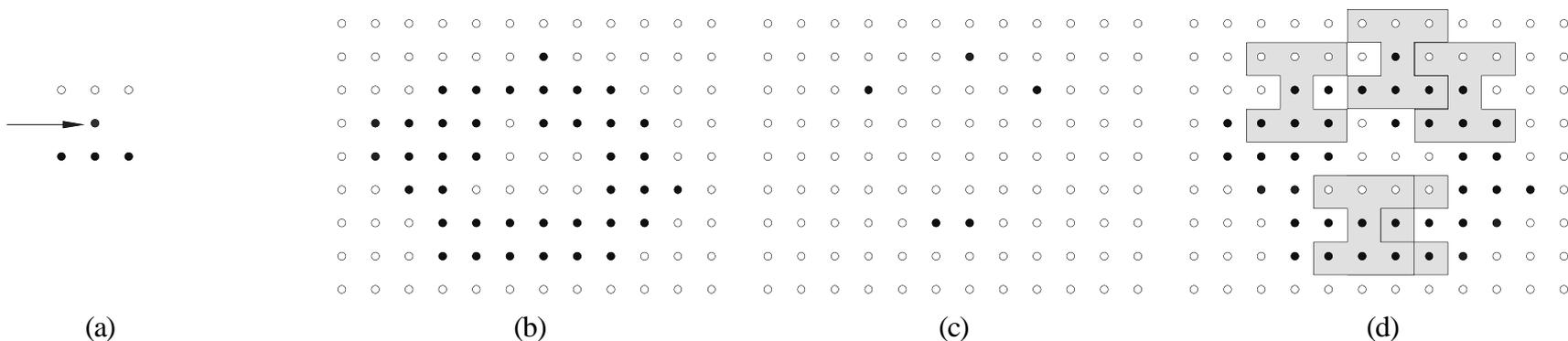


图 14.3.2 利用击中-击不中算子以提取包含水平方向上有连续 3 个像素的线段

击中-击不中变换

- 击中-击不中算子中的击中模板与击不中模板不重合，可以被结合成一个结构元素，1对应击中模板，0对应击不中模板，X表示不关心的像素
- 击中-击不中变换中的结构元素
 - $A \uparrow B$ 的结果中仍保留的目标象素对应应在A中其邻域与结构元素B对应的象素

$$A \uparrow B = (A \ominus B_o) \cap (A^c \ominus B_b)$$





组合运算-I

□ 区域凸包

- 令 $B_i (i = 1, 2, 3, 4)$ 代表4个结构元素, $X_i^0 = A$ 构造:

$$X_i^k = (X_i^{k-1} \uparrow B_i) \cup A \quad i = 1, 2, 3, 4 \text{ 和 } k = 1, 2, \dots$$

- 令 $D_i = X_i^{conv}$, 上标“conv”表示在 $X_i^k = X_i^{k-1}$ 意义下收敛, A 的凸包可表示为:

$$C(A) = \bigcup_{i=1}^4 D_i$$

组合运算-I

□ 区域凸包 (X表示其值可为任意)

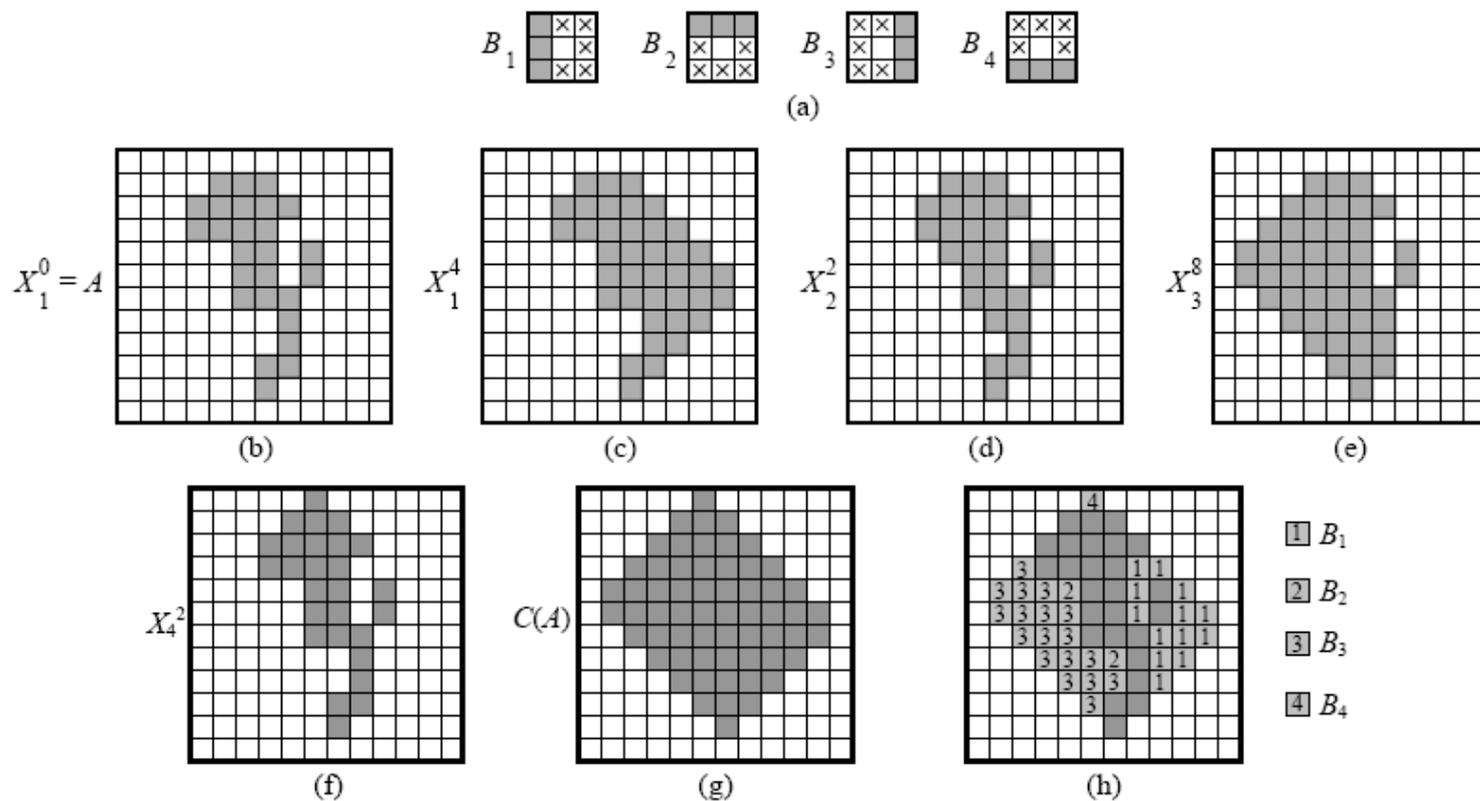


图 14.3.5 构造凸包的示例



组合运算-II

□ 细化

- 用结构元素B细化集合A记作 $A \otimes B$
- 借助击中-击不中变换定义

$$A \otimes B = A - (A \uparrow B) = A \cap (A \uparrow B)^c$$

- 定义一个结构元素系列

$$\{B\} = \{B_1, B_2, \dots, B_n\}$$

$$A \otimes \{B\} = A - ((\dots ((A \otimes B_1) \otimes B_2) \dots) \otimes B_n)$$

组合运算-II

□ 细化

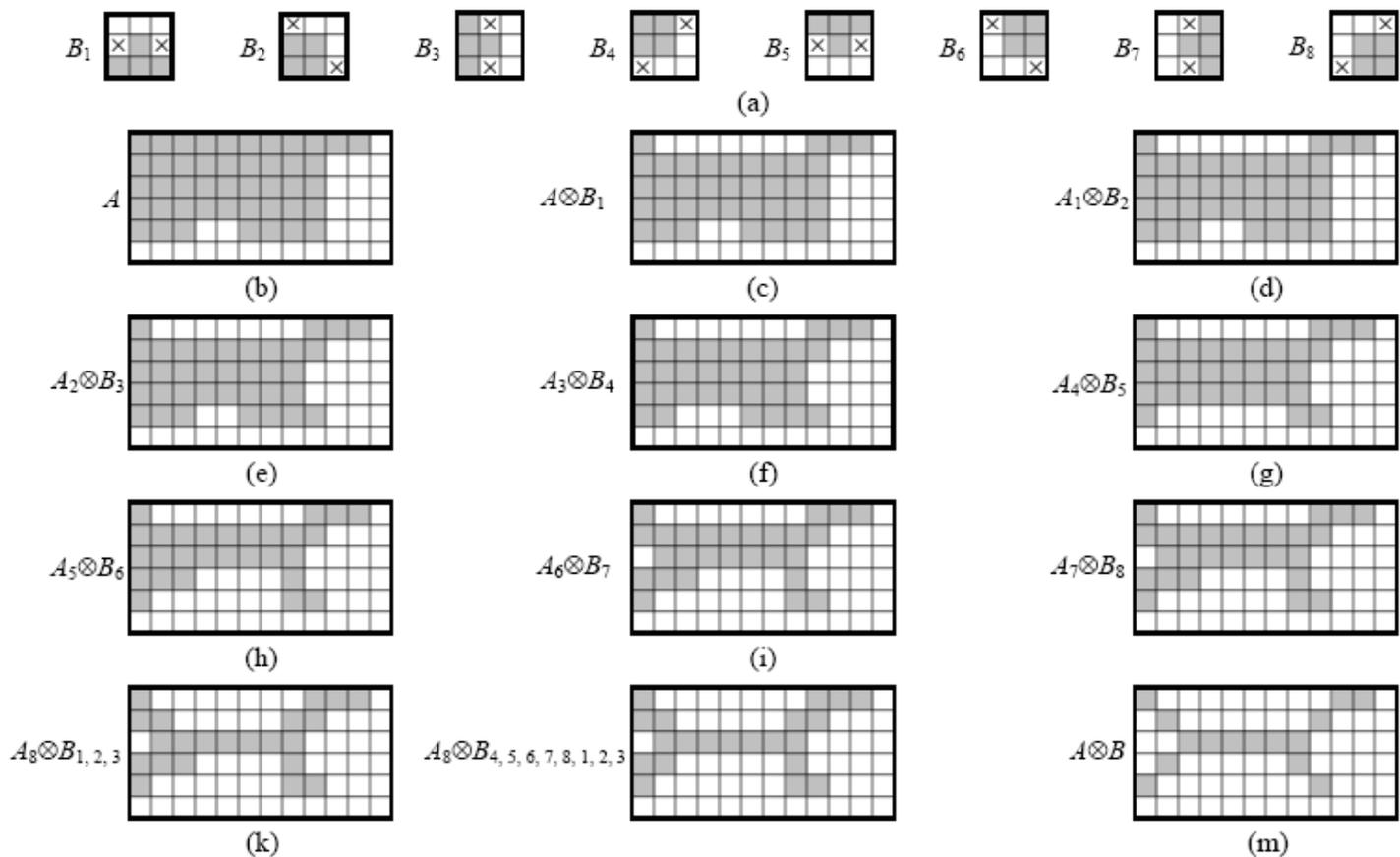


图 14.3.6 细化示例



组合运算-III

□ 粗化

- 用结构元素B粗化集合A记作 $A \oplus B$

$$A \oplus B = A \cup (A \uparrow B)$$

- 定义为一系列操作

$$A \oplus \{B\} = (((\dots((A \oplus B_1) \oplus B_2) \dots) \oplus B_n)$$

粗化从形态学角度来说与细化是对应的，实际中可先细化背景然后求补以得到粗化的结果。换句话说，如果要粗化集合A，可先构造 $C = A^c$ ，然后细化C，最后求 C^c 。

组合运算-III

□ 粗化

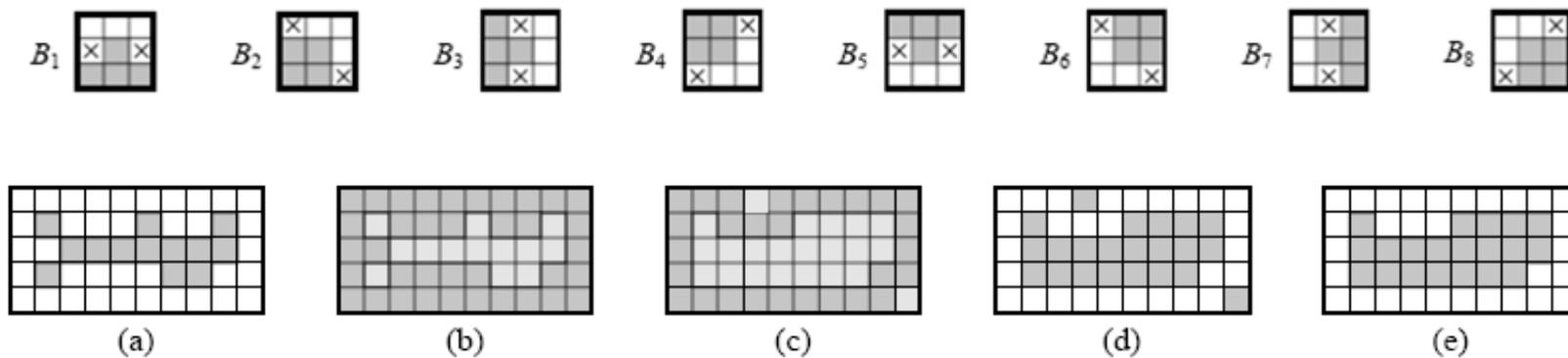


图 14.3.7 利用细化进行粗化



二值形态学实用算法

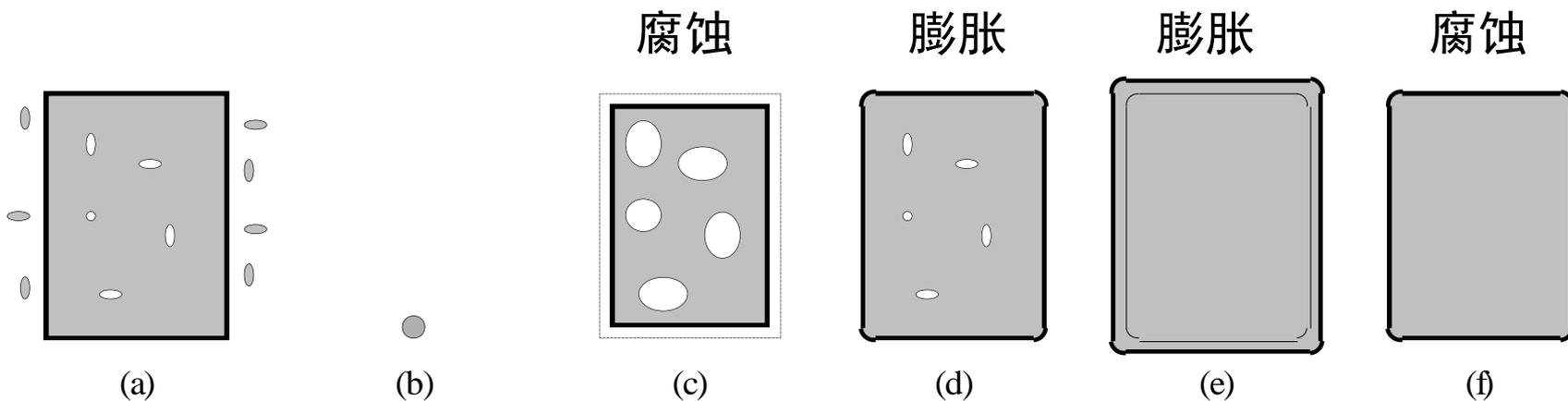
- 噪声滤除
- 目标检测
- 边界提取
- 区域填充
- 连通组元提取
- 区域骨架提取

二值形态学实用算法-I

□ 噪声滤除

- 先开启后闭合

$$\{[(A \ominus B) \oplus B] \oplus B\} \ominus B = (A \circ B) \cdot B$$



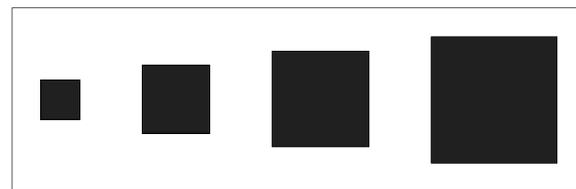
二值形态学实用算法-II

□ 目标检测（击中击不中变换）

- 3×3 , 5×5 , 7×7 和 9×9 的实心正方形

3×3 实心正方形

9×9 方框



(a)

(b) : E

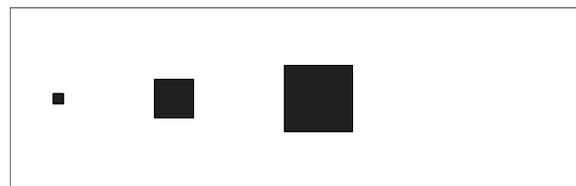
(c) : F



(b)



(c)



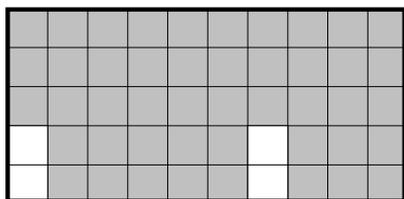
(d)

二值形态学实用算法-III

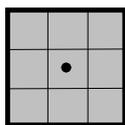
□ 边界提取

- 先用1个结构元素B腐蚀 A，再求取腐蚀结果和A的差集就可得到边界 $\beta(A)$

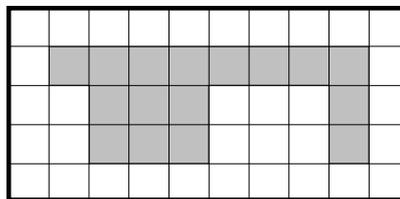
$$\beta(A) = A - (A \ominus B)$$



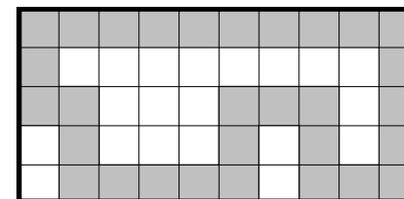
(a)



(b)



(c)



(d)

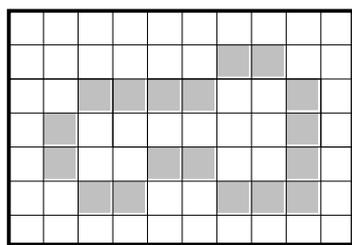
结构元素是8-连通的，而所得到的边界是4-连通的

二值形态学实用算法-IV

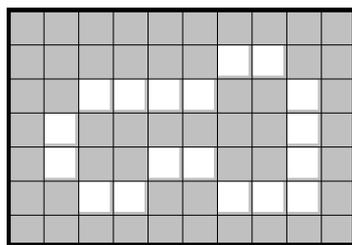
□ 区域填充

$$X_k = (X_{k-1} \oplus B) \cap A^c \quad k = 1, 2, 3, \dots$$

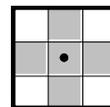
取内部一个点，按照模板膨胀，取交集，迭代多次；最后与 (a) 取并集



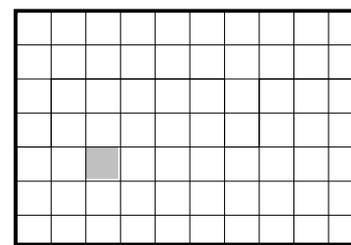
(a)



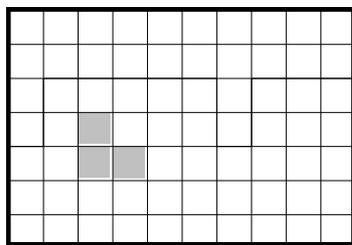
(b)



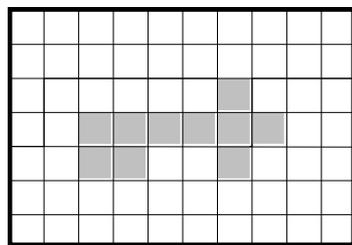
(c)



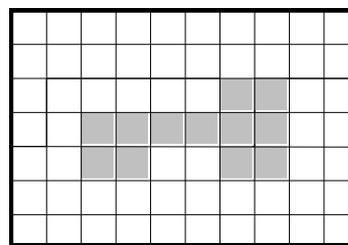
(d)



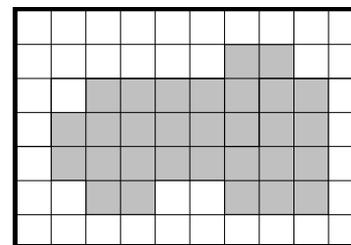
(e)



(f)



(g)



(h)

结构元素是4-连通的，而原填充的边界是8-连通的

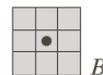
二值形态学实用算法-V

□ 连通组元提取

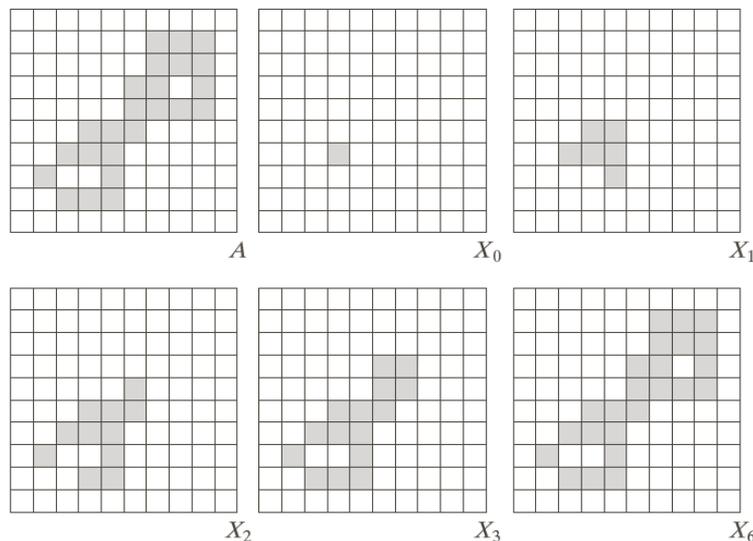
- 设 Y 为集合 A 中的一个连通组元，已知 Y 上的一个点记为阵列 X_0 。如下迭代过程可完成这一目的：

$$X_k = (X_{k-1} \oplus B \cap A) \quad k = 1, 2, 3, \dots$$

- 当 $X_k = X_{k-1}$ 时，迭代过程结束， X_k 包含输入图像中的所有连通分量。



右图说明了此机理， $k=6$ 时即可收敛。注意，所用结构元的形状在像素间是基于8连通的





二值形态学实用算法-VI

□ 区域骨架提取

$$S(A) = \bigcup_{k=0}^K S_k(A) \quad S_k(A) = (A \ominus kB) - [(A \ominus kB) \circ B]$$

$$(A \ominus kB) = ((\dots (A \ominus B) \ominus B) \ominus \dots) \ominus B$$

$$K = \max\{k | (A \ominus kB) \neq \emptyset\}$$

□ 也可以用骨架重构A

$$A = \bigcup_{k=0}^K (S_k(A) \oplus kB)$$

