Lecture 25

Frontier-Based Exploration

CS 3630

Revisiting Exploration-Driven SLAM

http://www.cs.washington.edu/ai/Mobile_Robotics/projects/mapping/

Exploration

- **Key question**: Where hasn't robot been?

- **Central concern**: how to explore an unknown area <u>efficiently</u>

- **Possible approaches**:
  - Random walk
  - Avoid areas that have been recently visited
  - Exploit evidential information in the map

Frontier-Based Exploration

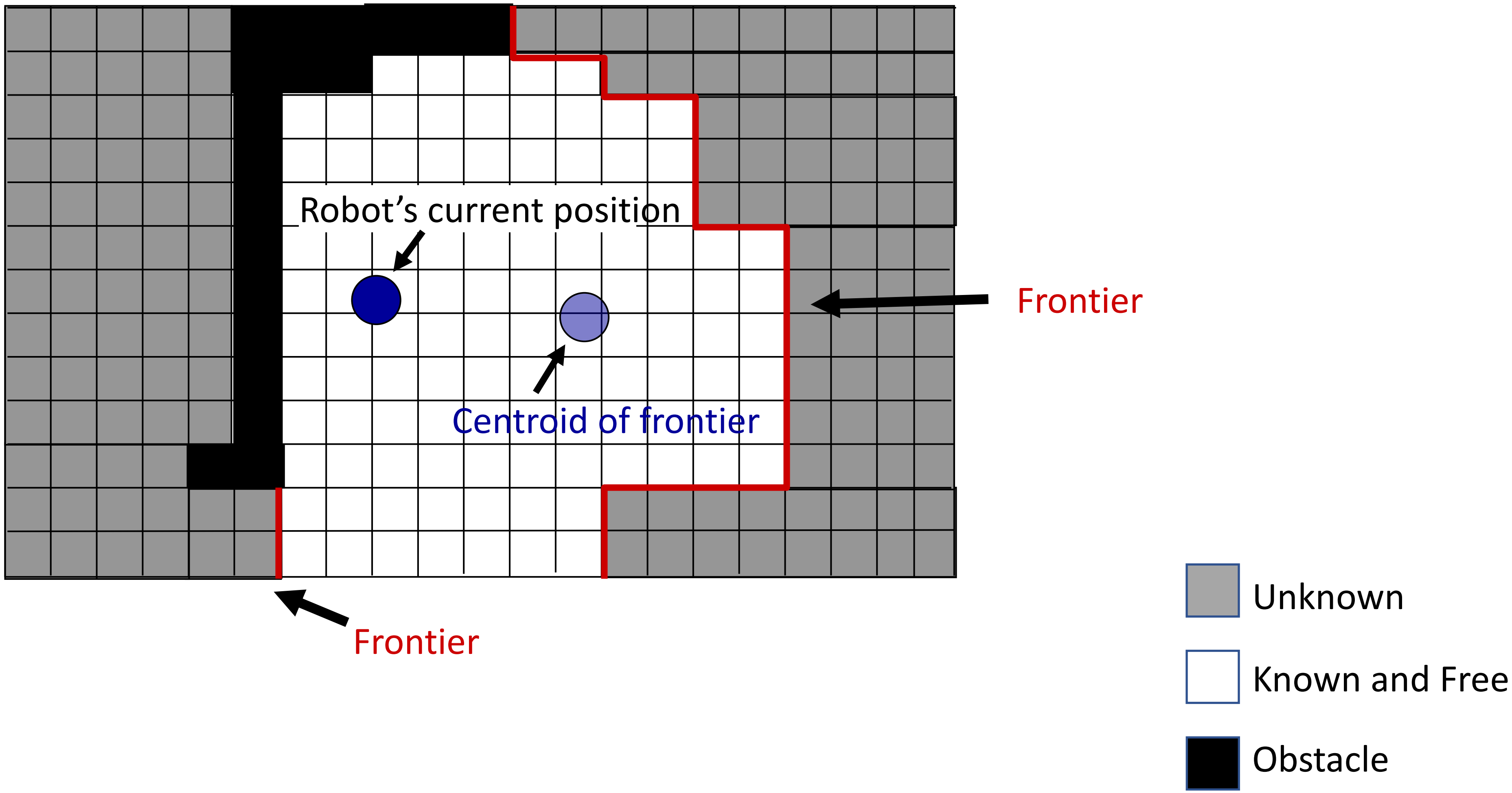
- Assumes robot uses occupancy grid

- When the robot enters new area, find boundary (“frontier”) between sensed (free) and unsensed (unknown) areas

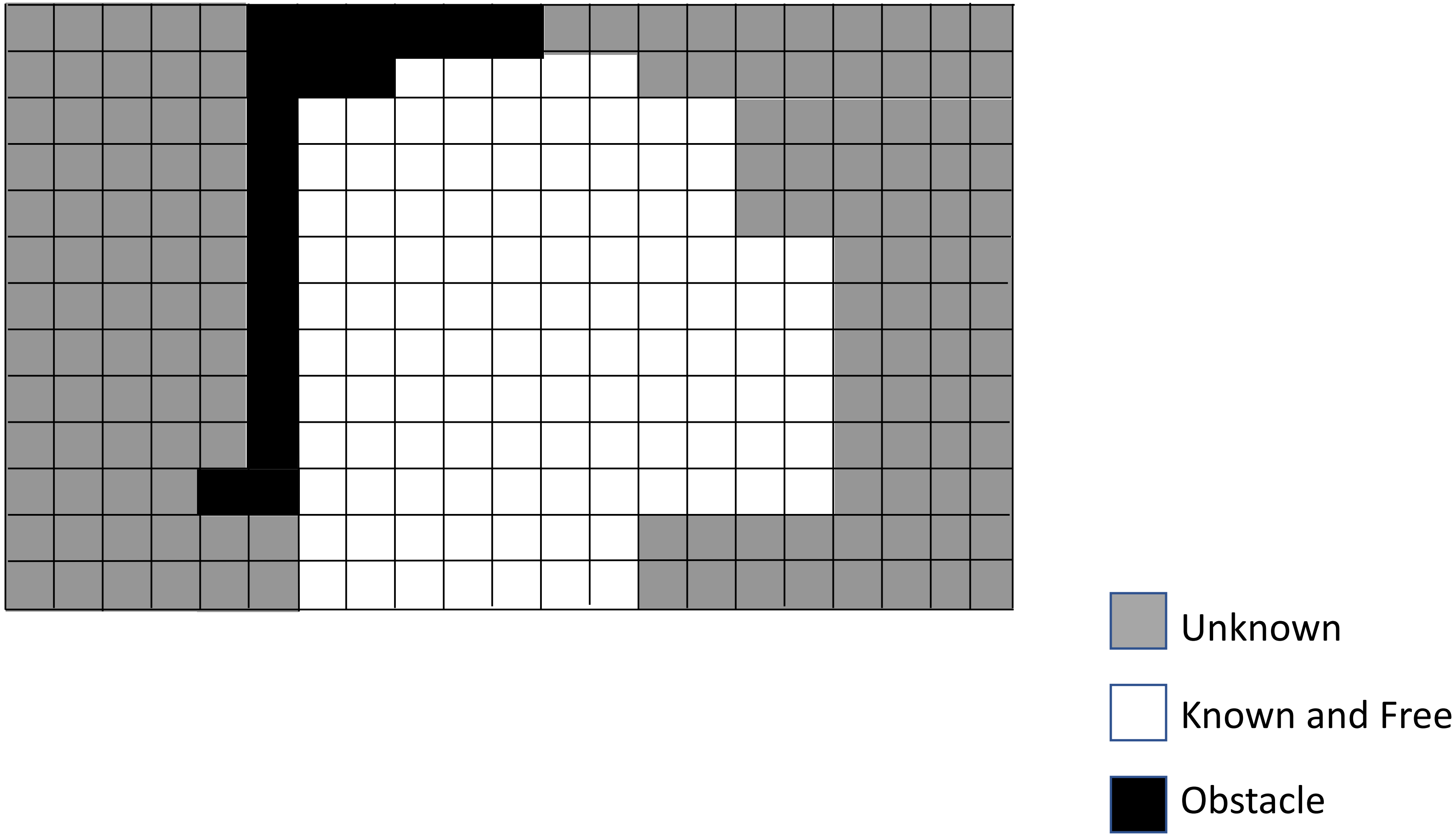
- Navigate to the centroid of the frontier

Yamauchi, 1997.

Frontier-Based Exploration

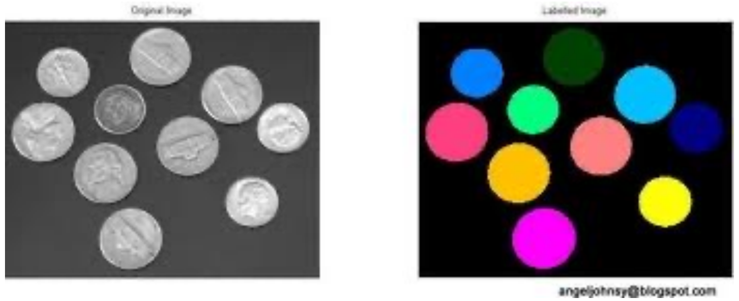


How do we find frontiers?



Answer:

- The brute force method (appropriate for our relatively small maps) utilizes connected-component labeling
  - A.k.a. connected-component analysis, blob extraction, region labeling, blob discovery, region extraction, etc…
  - Algorithmic application of graph theory, where subsets of connected components are uniquely labeled



- More efficient techniques have also been published that search for frontiers only in areas recently visited/sensed by the robot

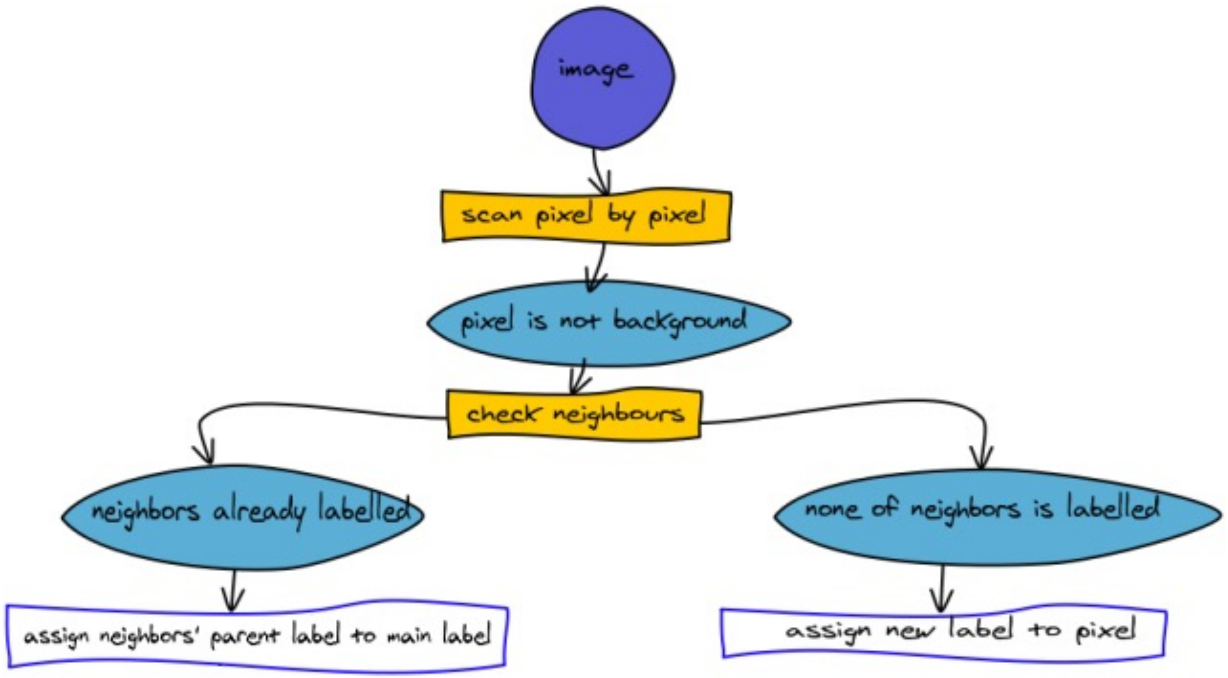
How to do Connected Component Labeling…

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0
0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0
0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0
0	0	1	1	1	1	0	0	0	1	1	1	0	0	1	1	0
0	1	1	1	0	0	1	1	0	0	0	1	1	1	0	0	0
0	0	1	1	0	0	0	0	0	1	1	0	0	0	1	1	0
0	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

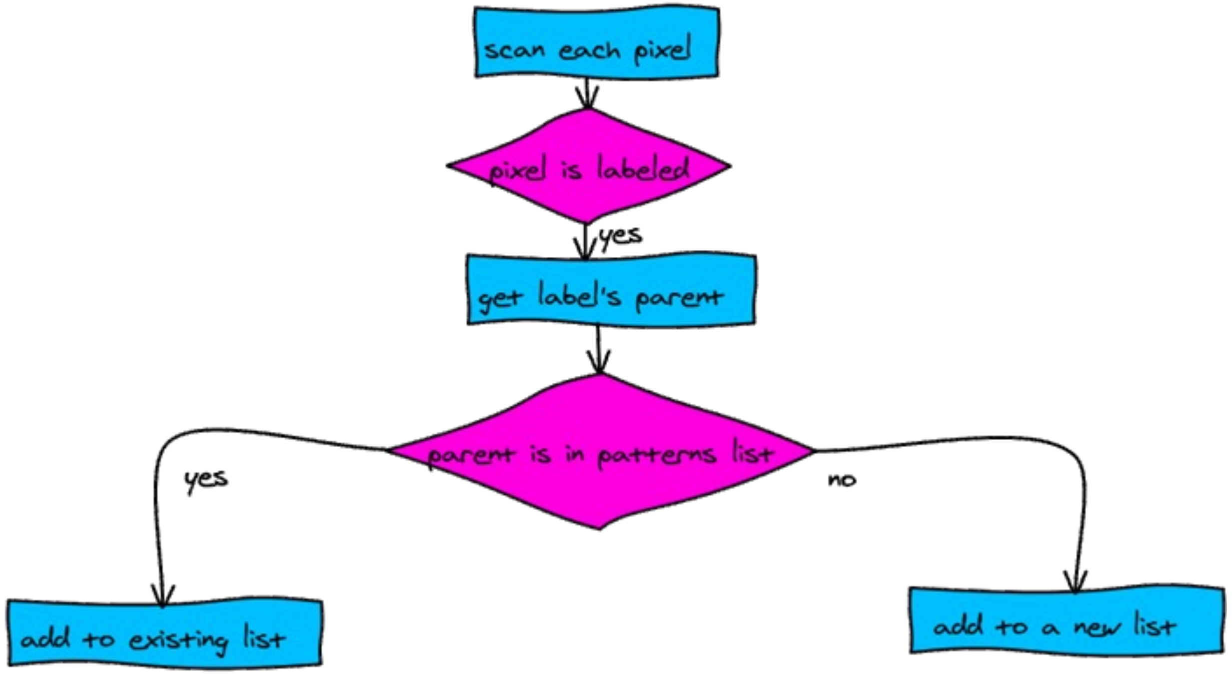
Pixel info:(X, Y) Intensity

Two-Pass Algorithm

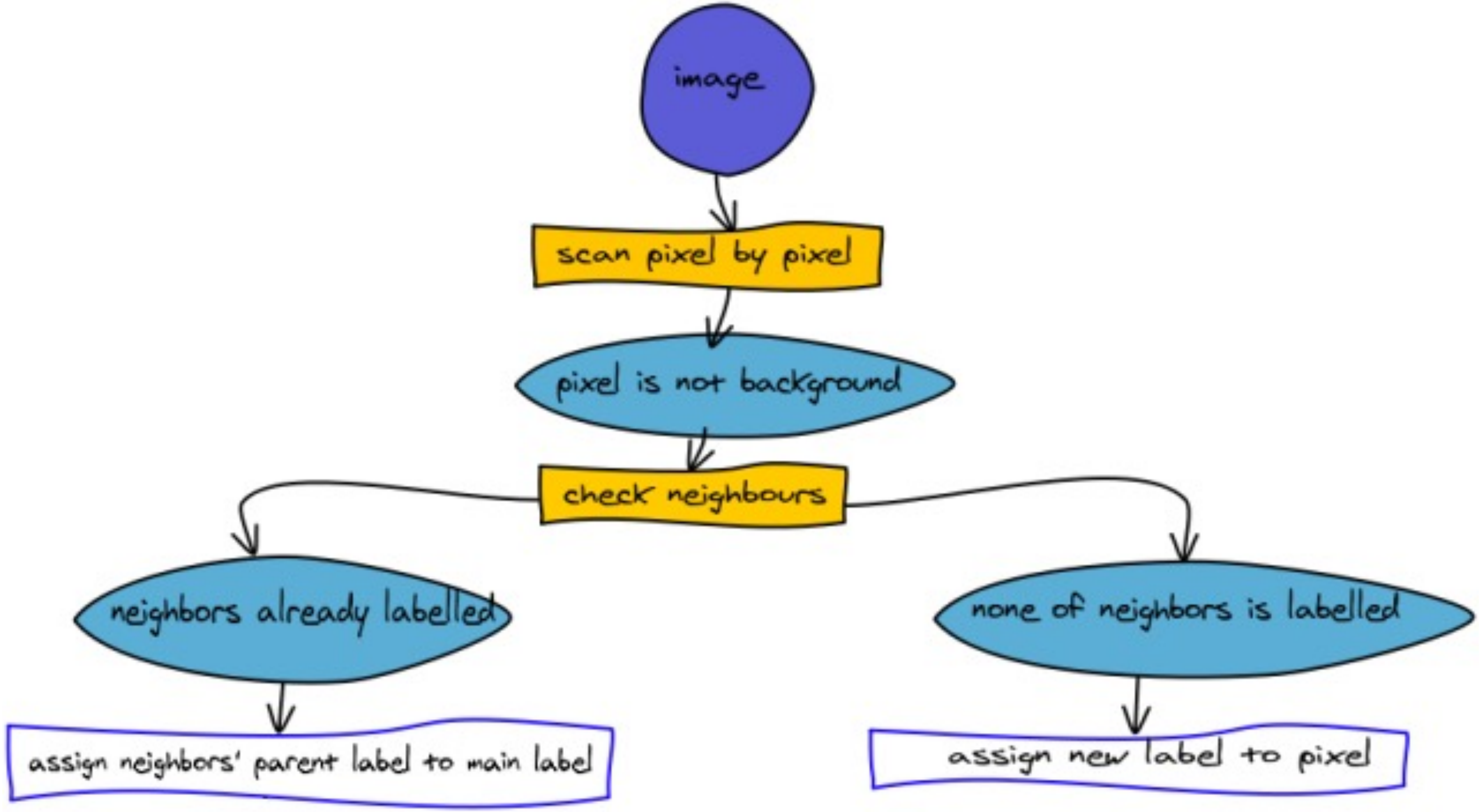
Pass 1

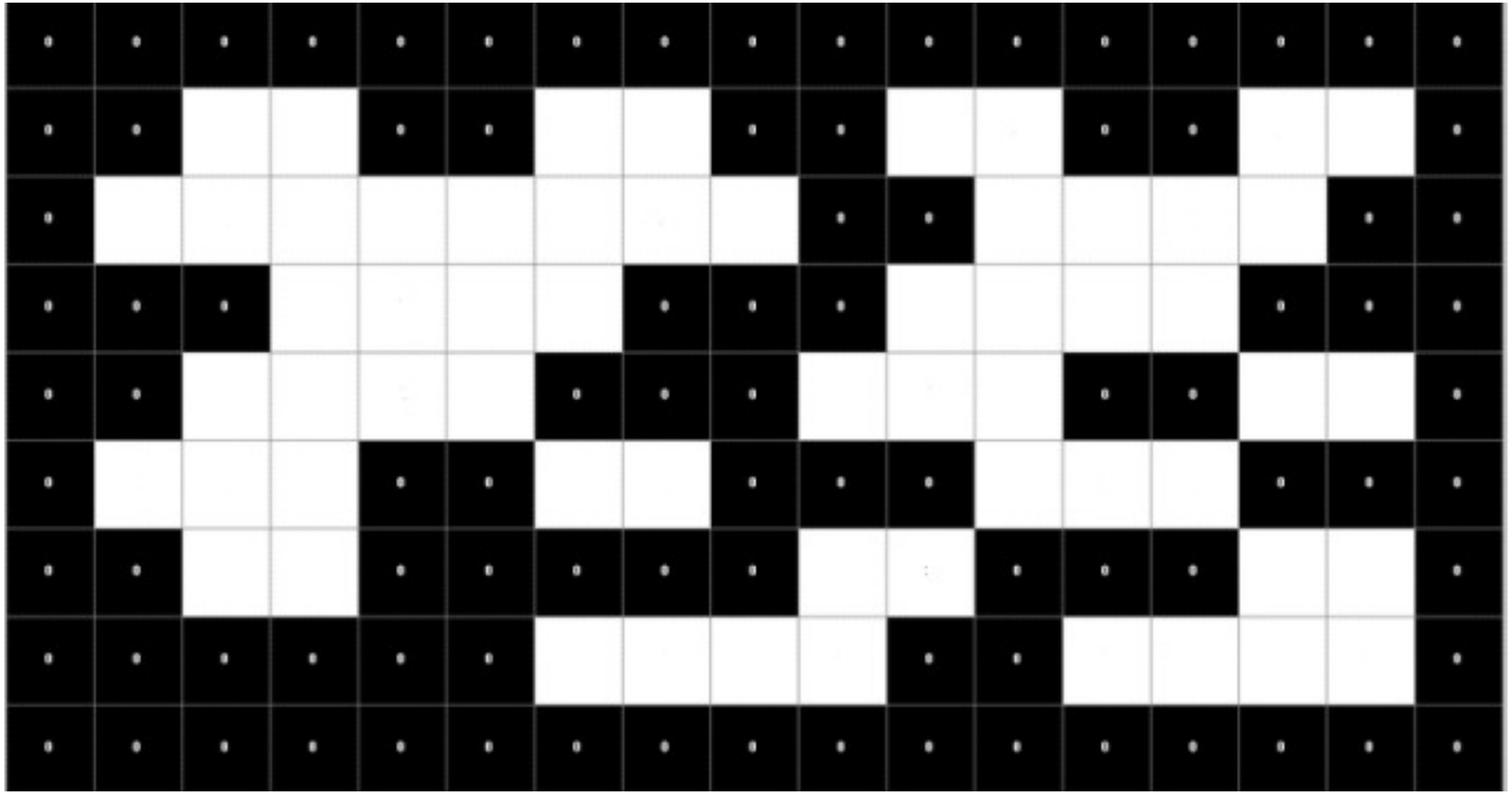


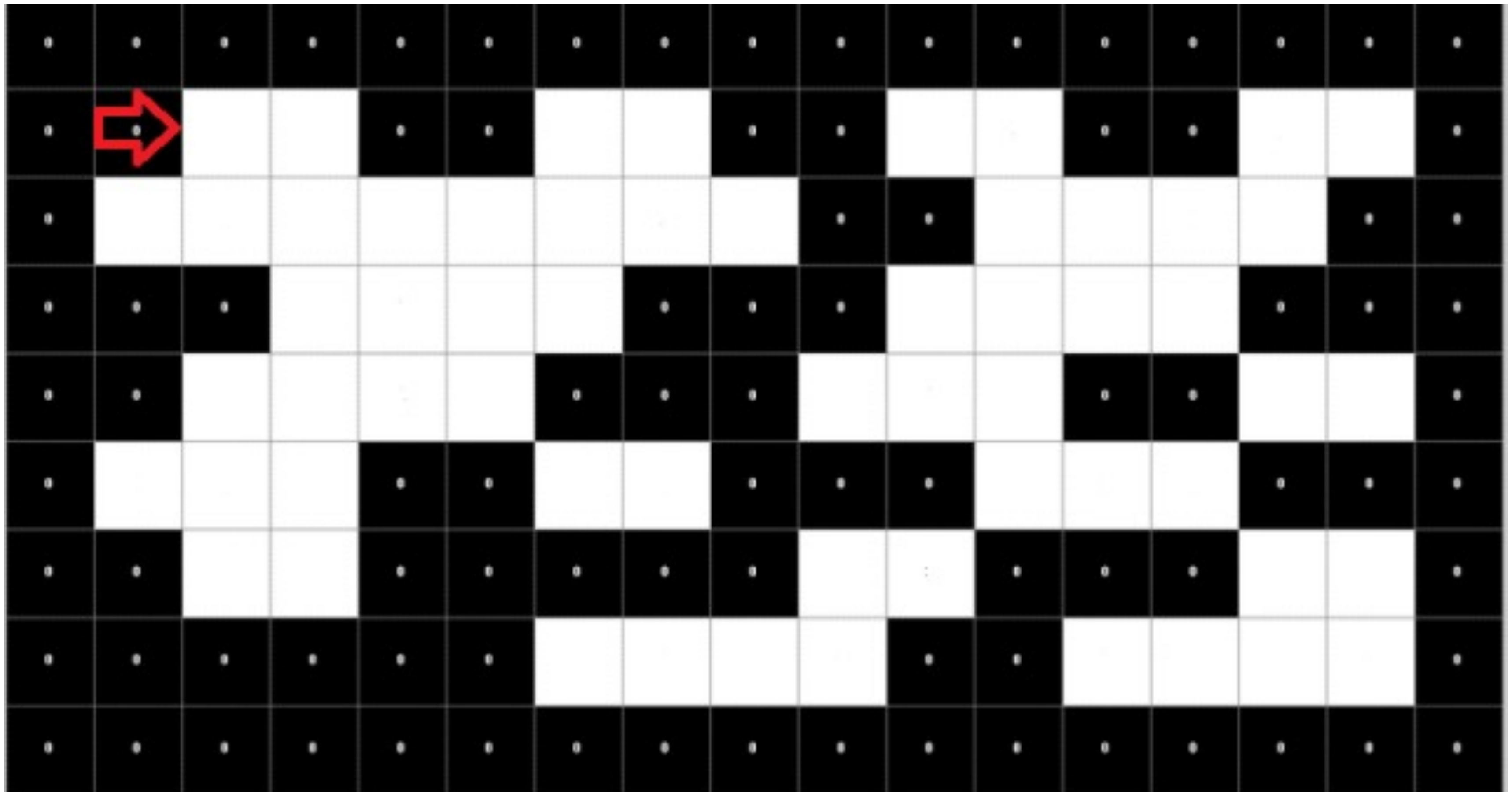
Pass 2

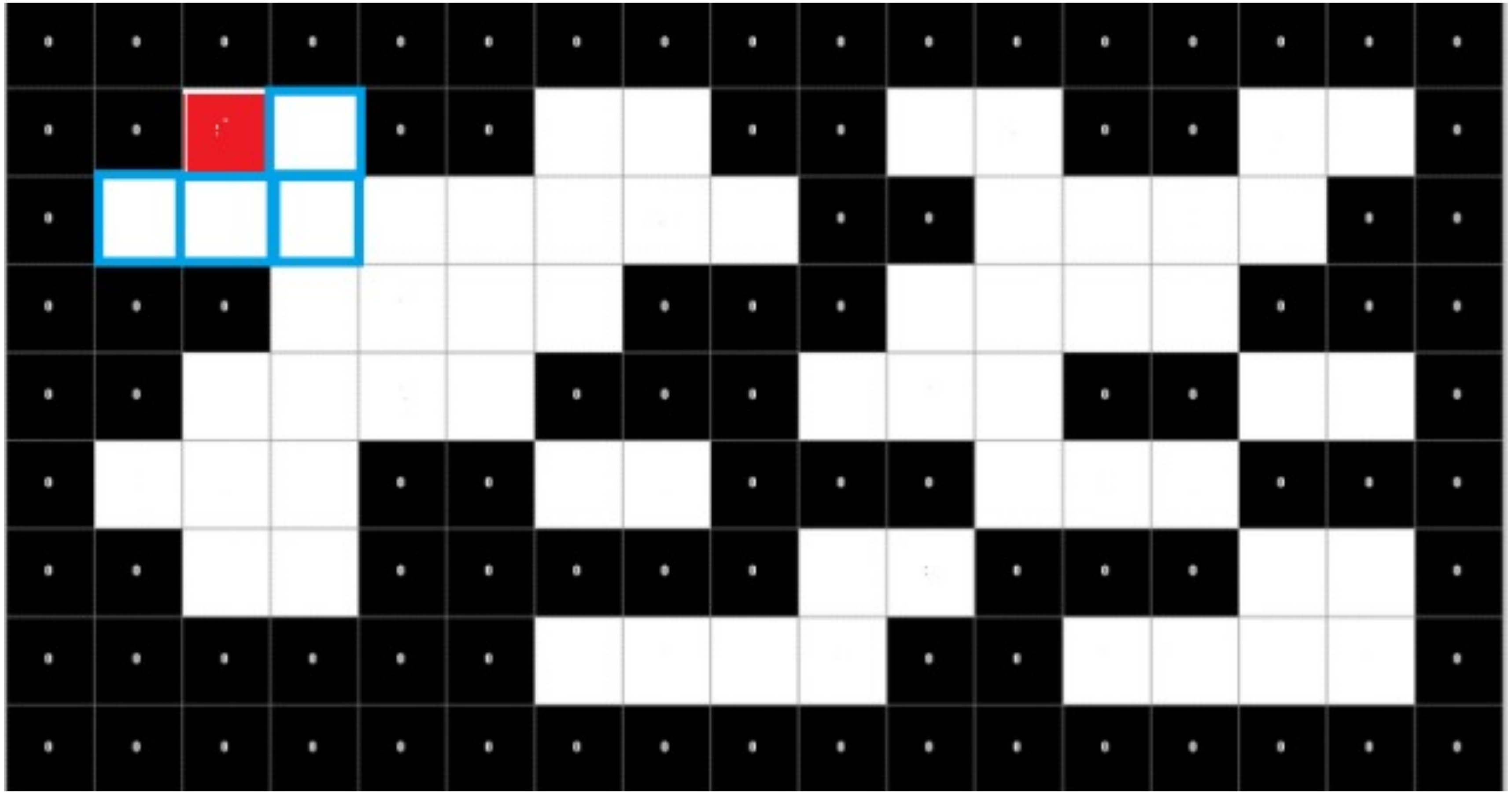


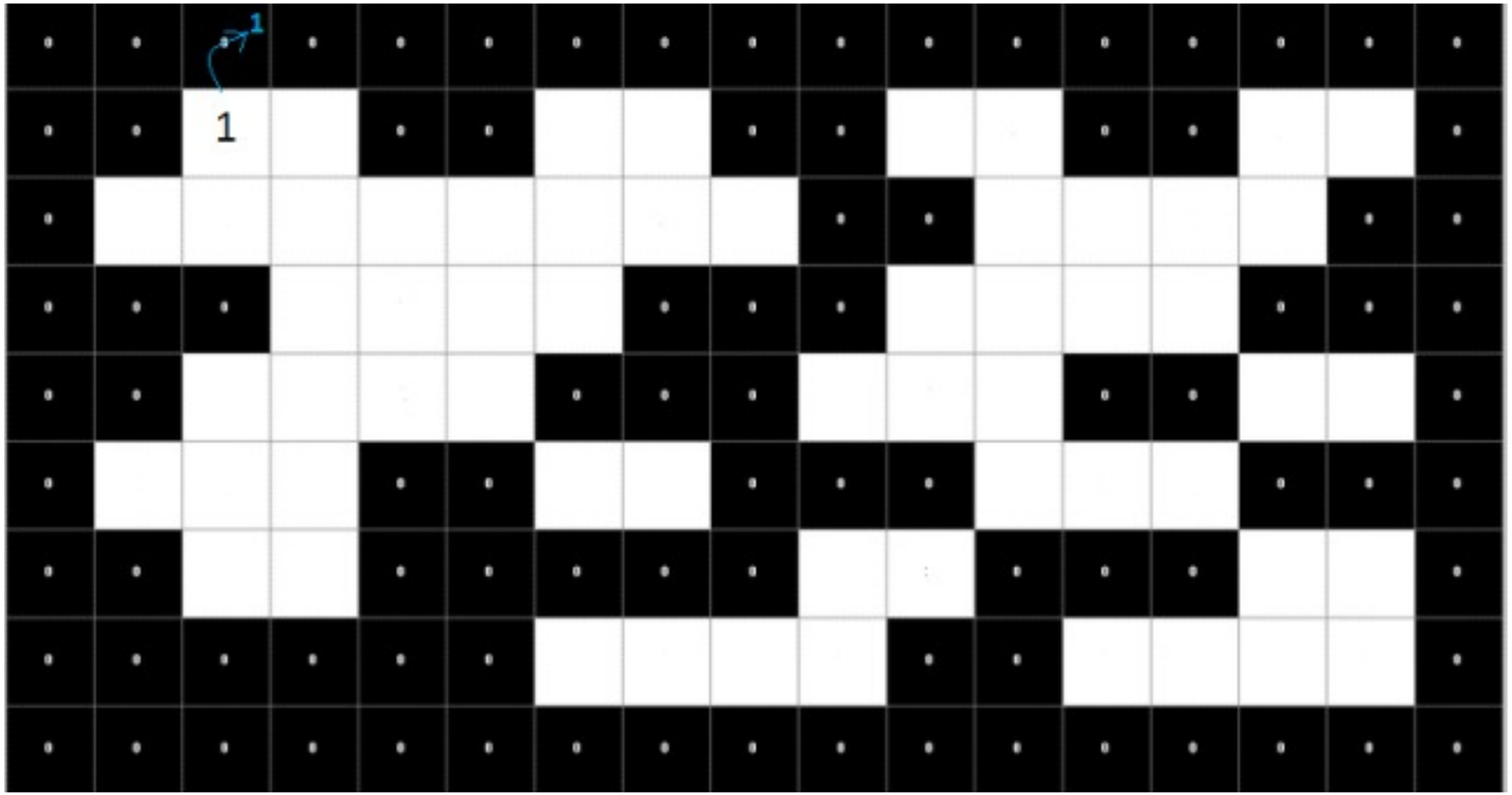
Two-Pass Algorithm – Pass 1

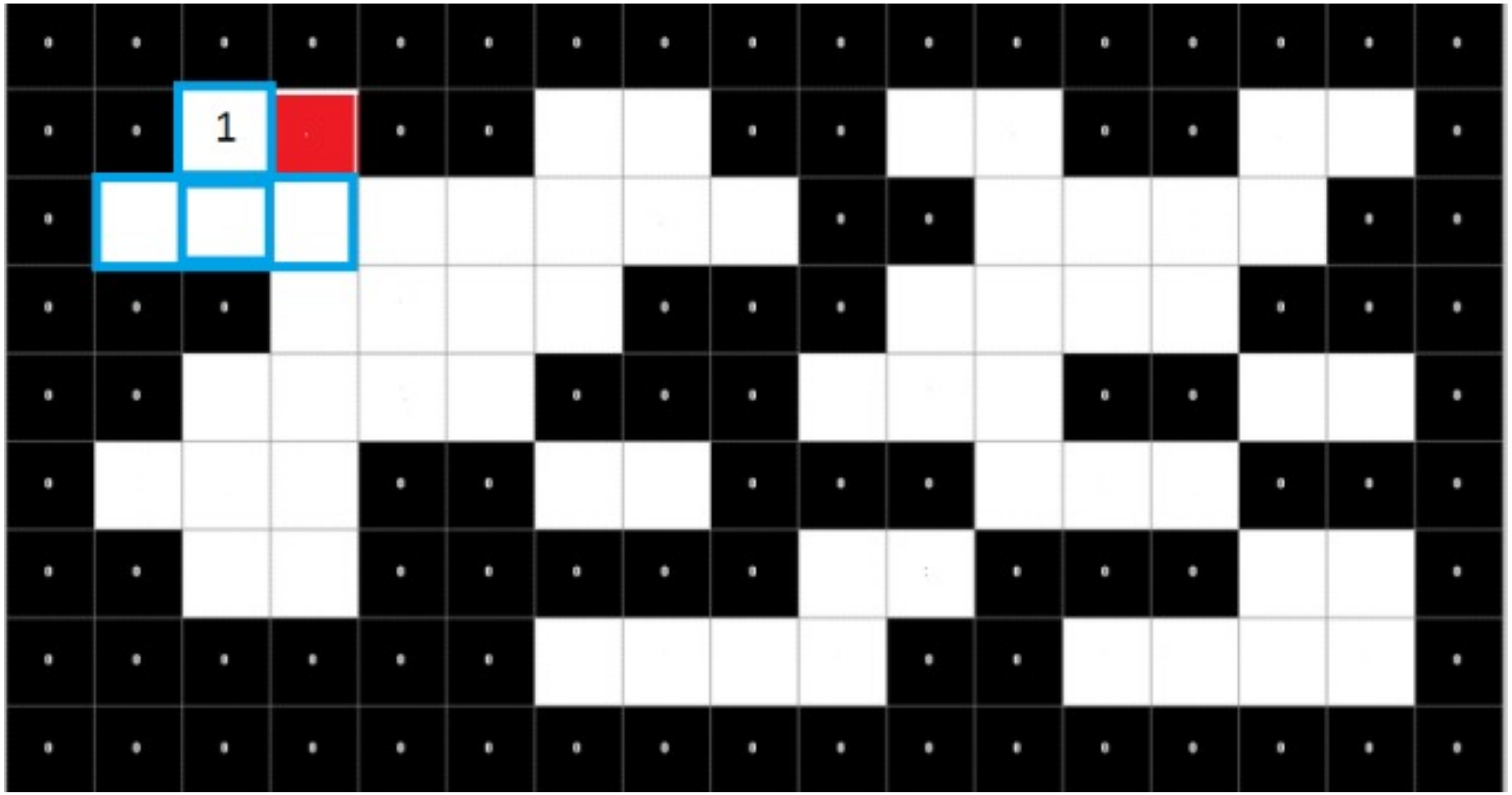


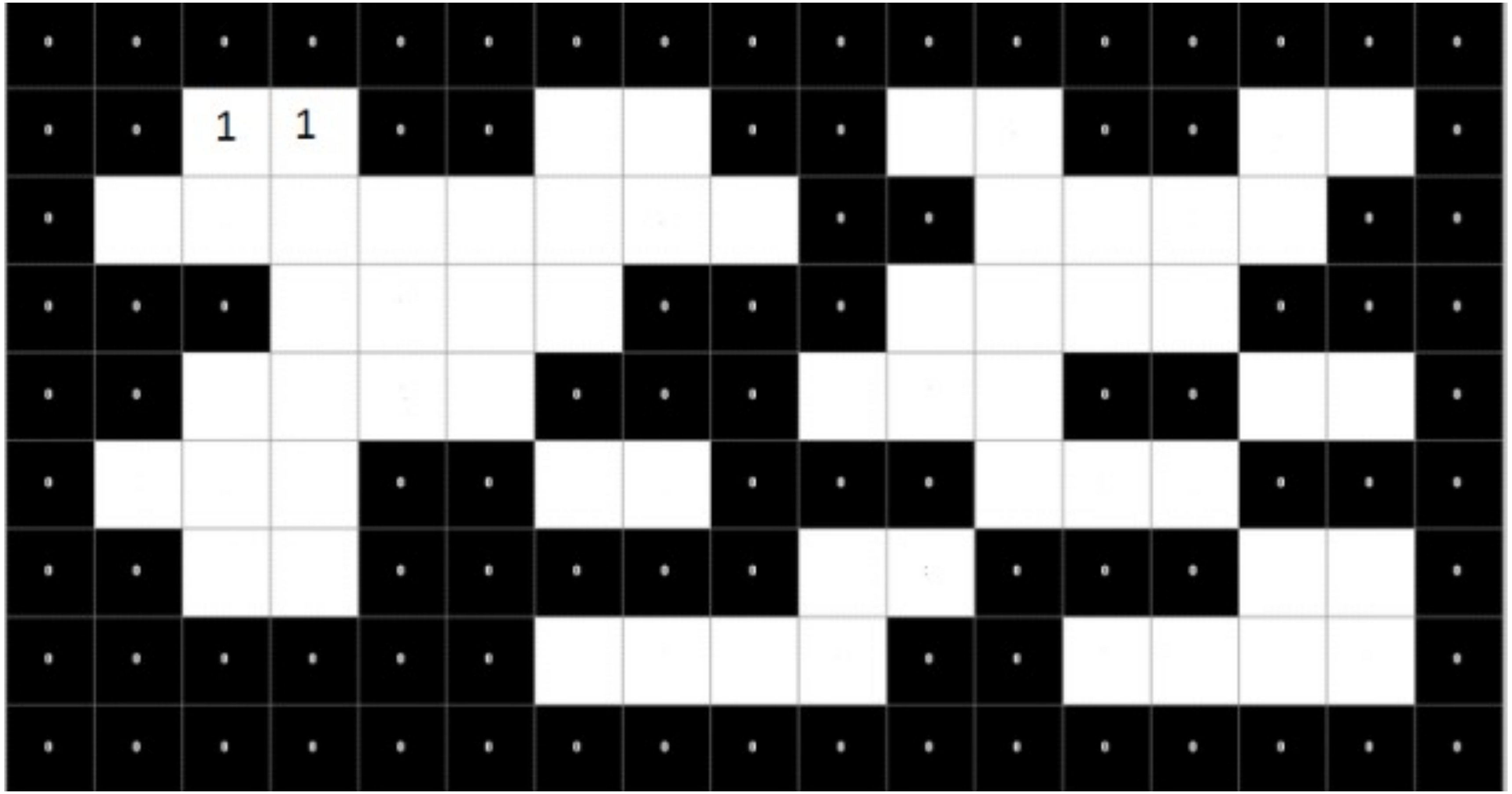


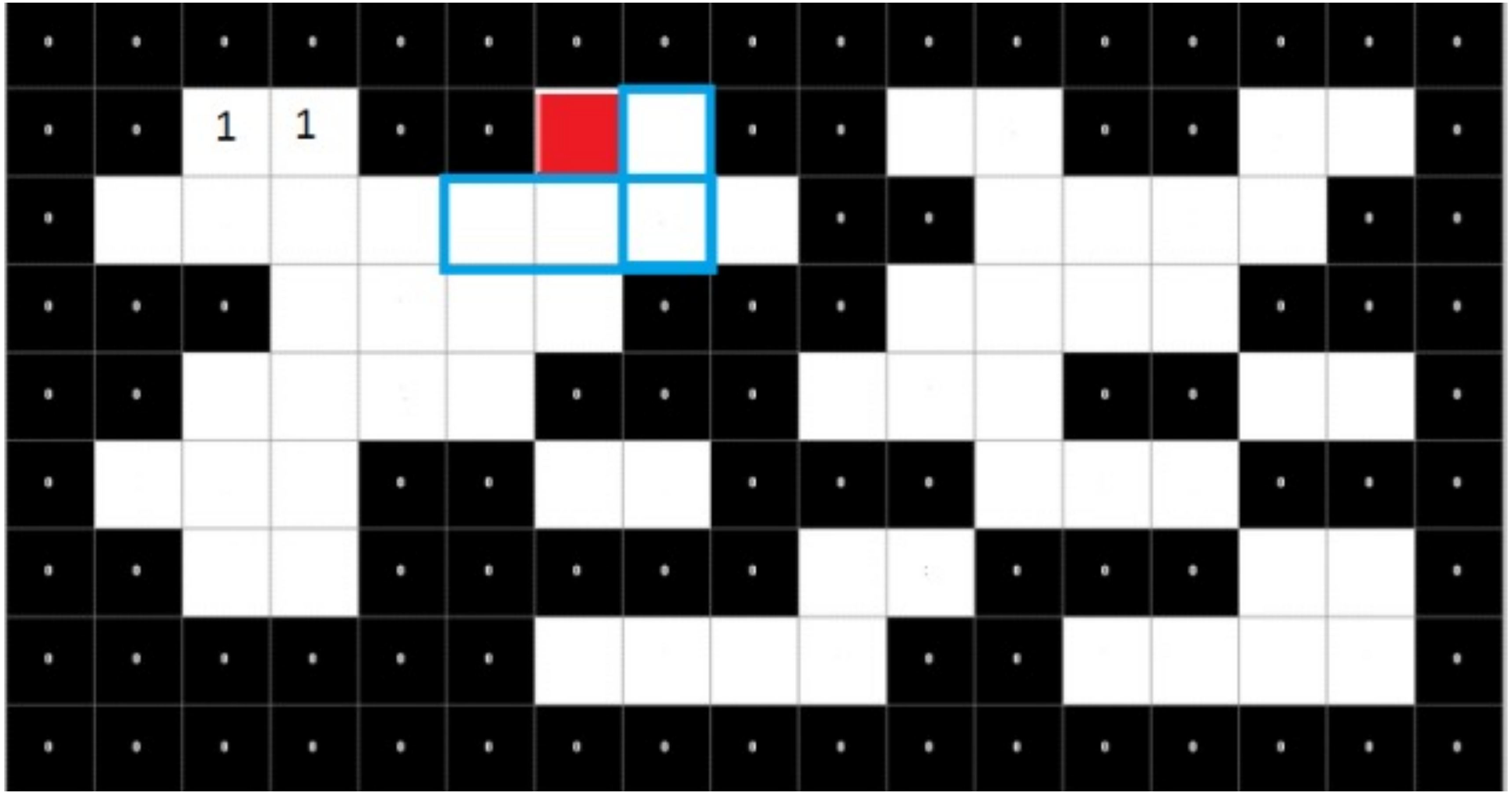


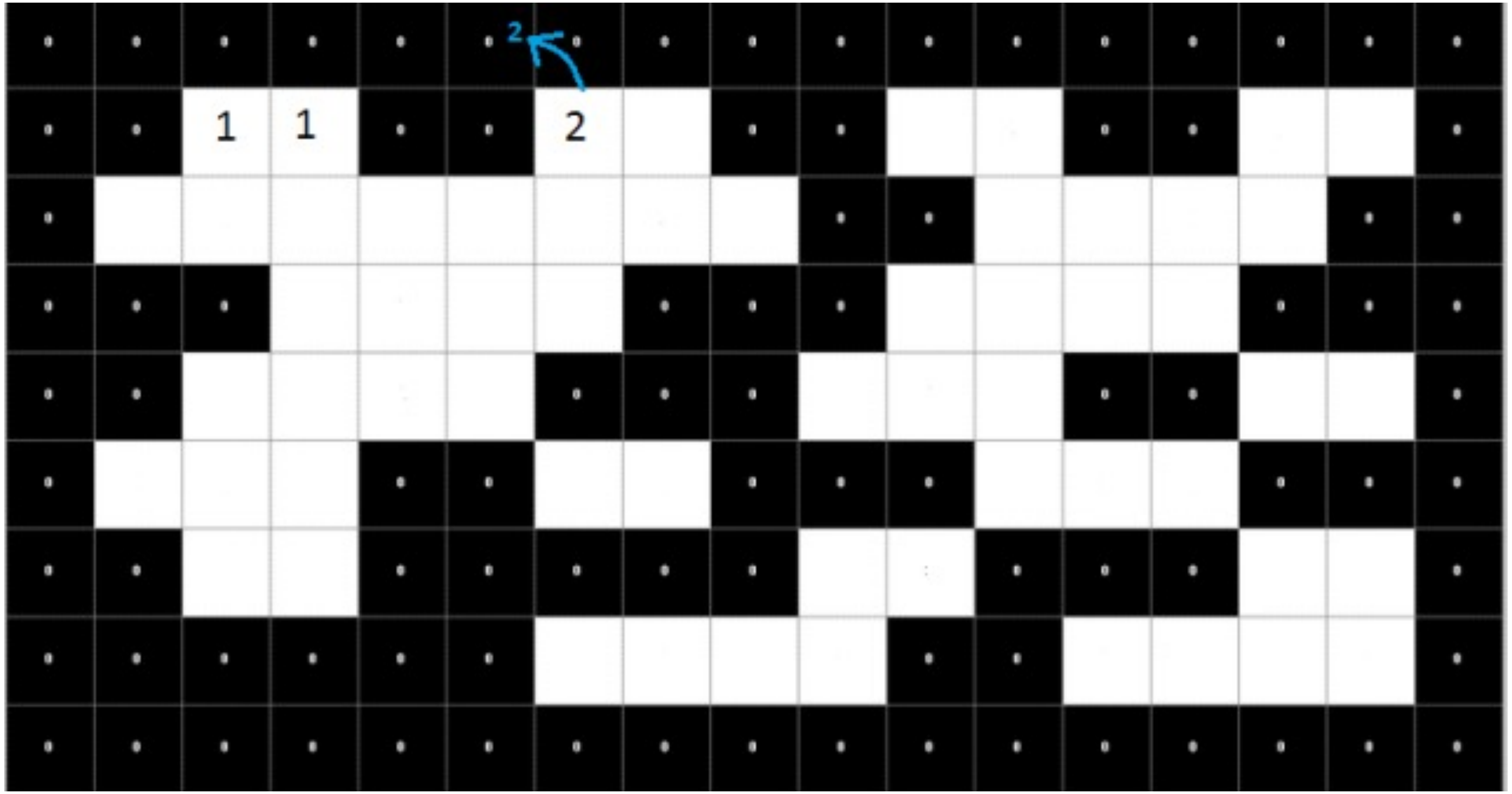


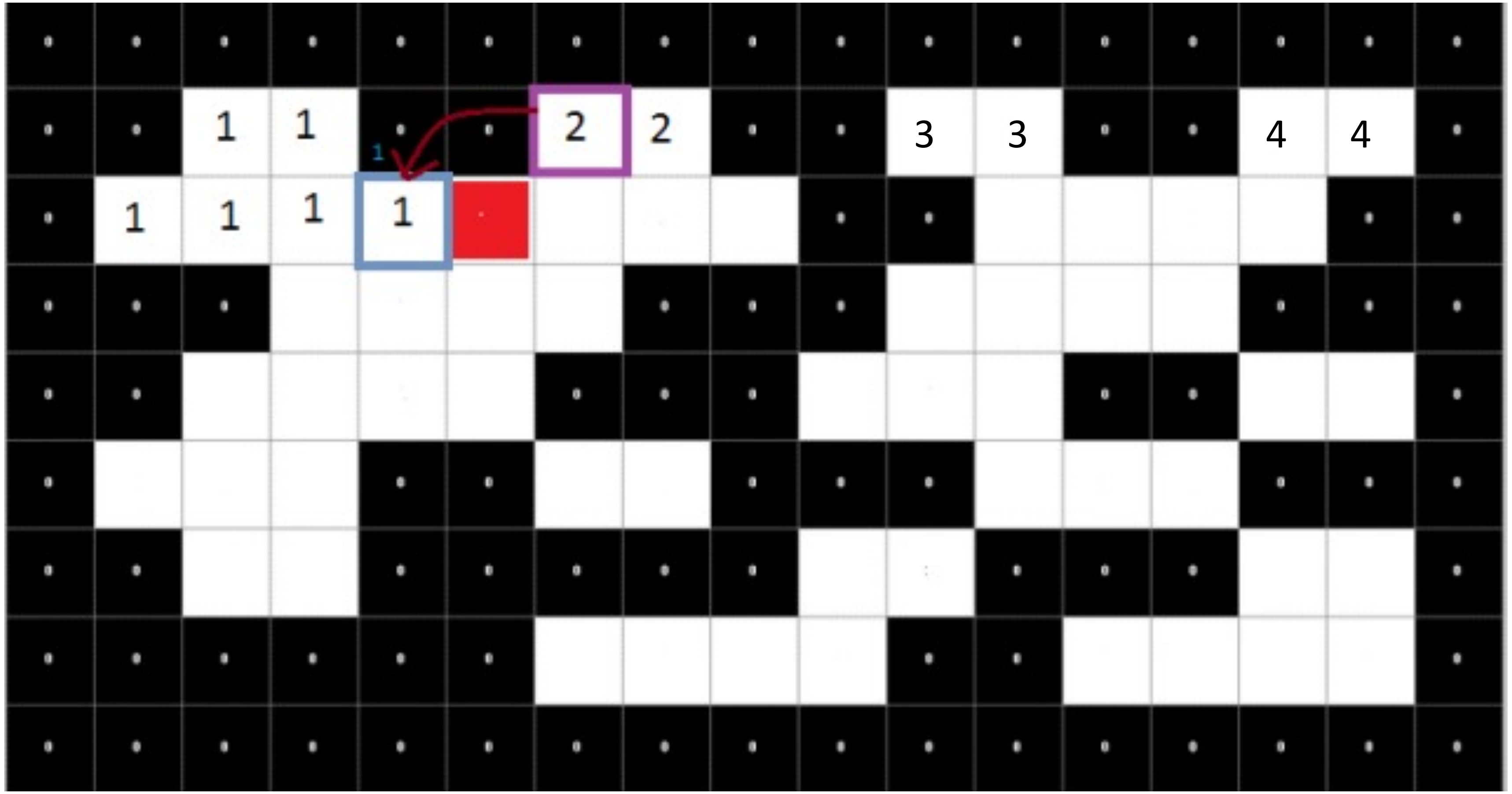

1
1


1

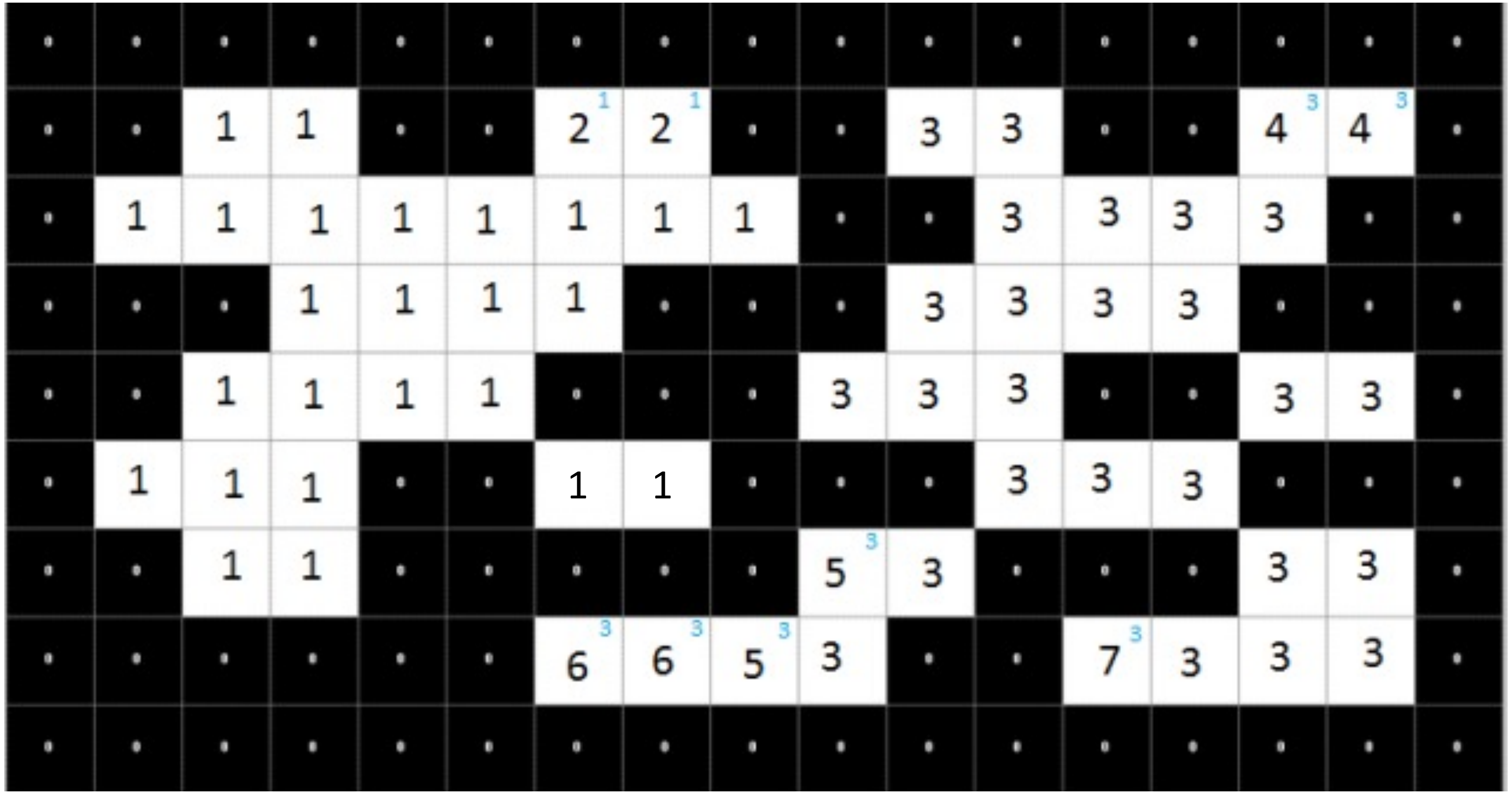



1
1

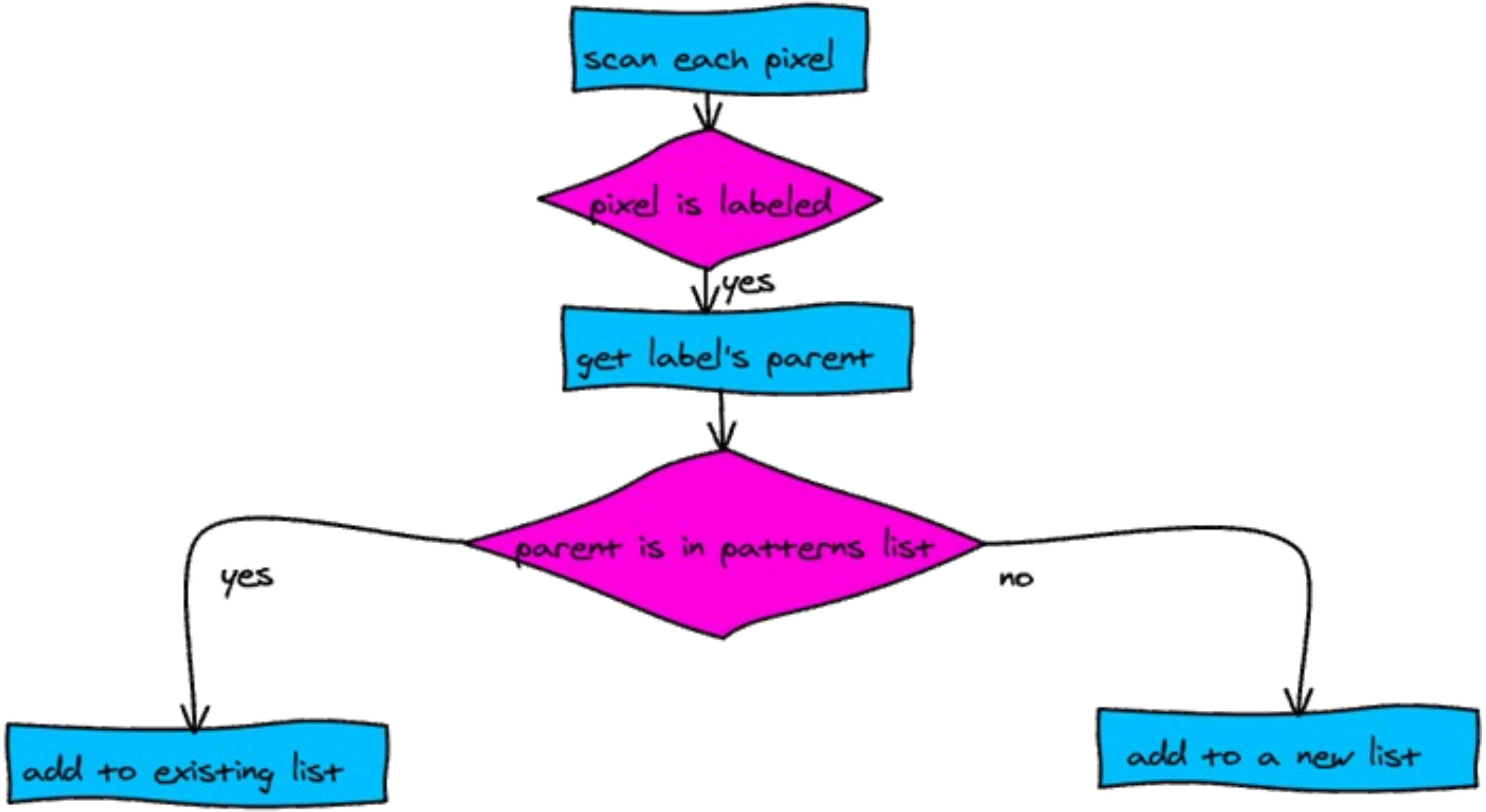

2
1
1
2



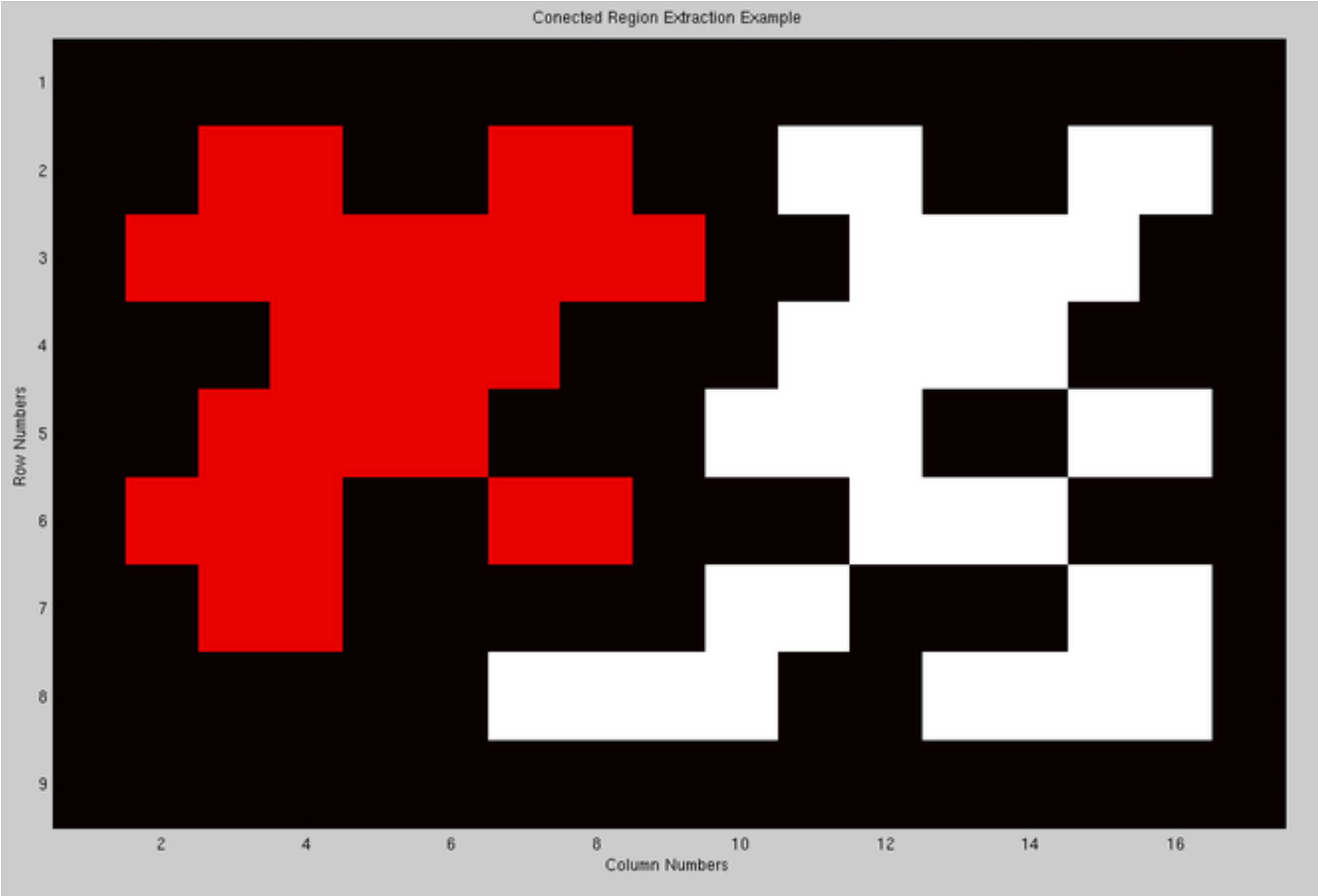
1 1 2 2 3 3 4 4
1
1 1 1 1


1 1 2^1 2^1 3 3 4^3 4^3
1 1 1 1 1 1 1 1 3 3 3 3
1 1 1 1 3 3 3 3
1 1 1 1 3 3 3 3 3
1 1 1 1 1 3 3 3
1 1 5^3 3 3 3
6^3 6^3 5^3 3 7^3 3 3 3

Two-Pass Algorithm - Pass 2

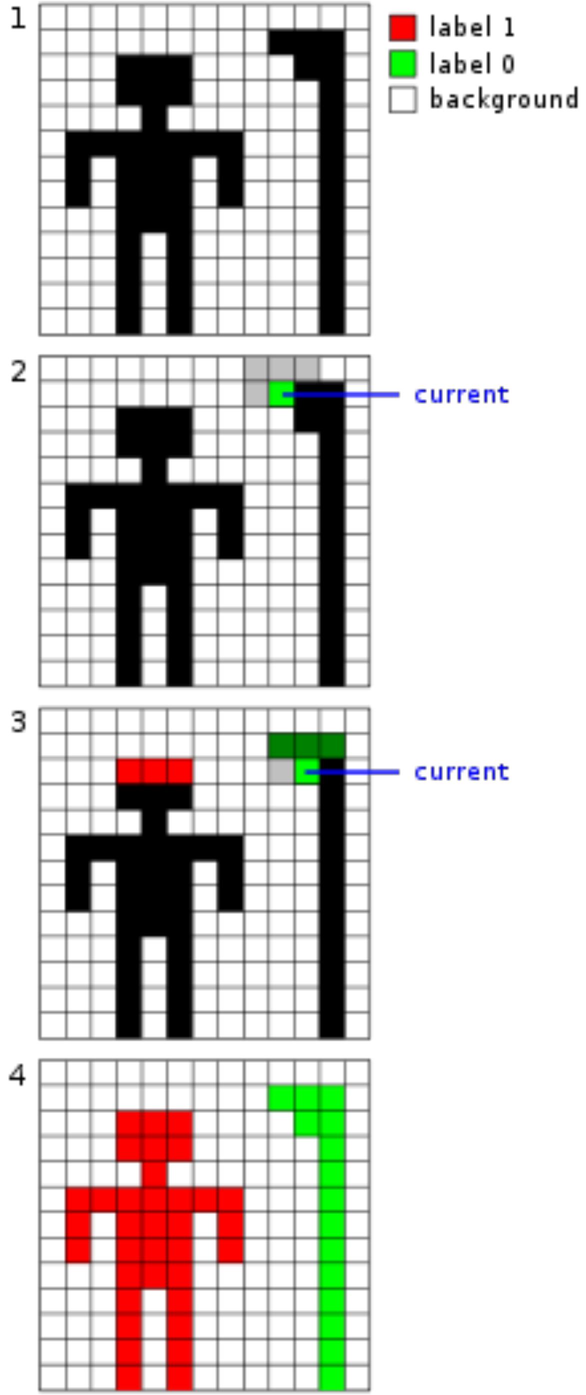


Set ID	Equivalent Labels / Pattern List
1	1,2
2	1,2
3	3,4,5,6,7
4	3,4,5,6,7
5	3,4,5,6,7
6	3,4,5,6,7
7	3,4,5,6,7

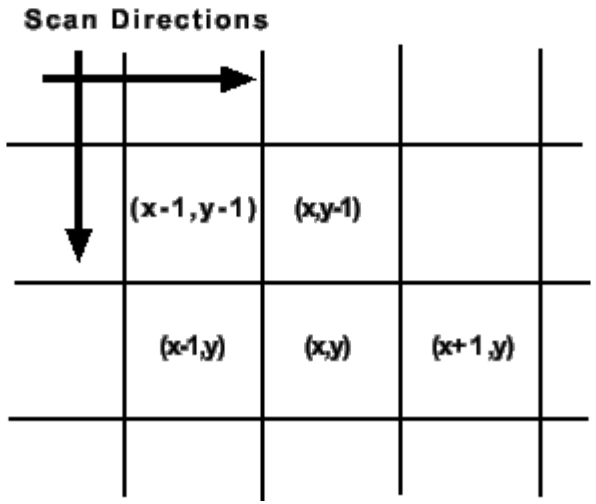


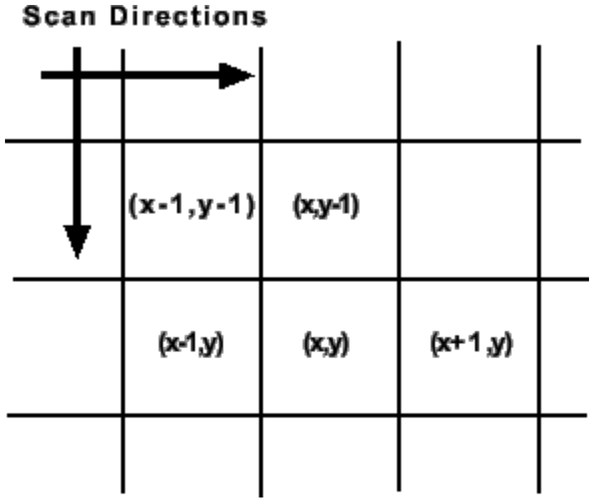
Final

Sample graphical output from running the two-pass algorithm on a binary image. The first image is unprocessed, while the last one has been recolored with label information. Darker hues indicate the neighbors of the pixel being processed.



There is also a single-pass variant…





Algorithm 6 Connected Component Labelling

Input: Labelling a particular pixel (x, y)

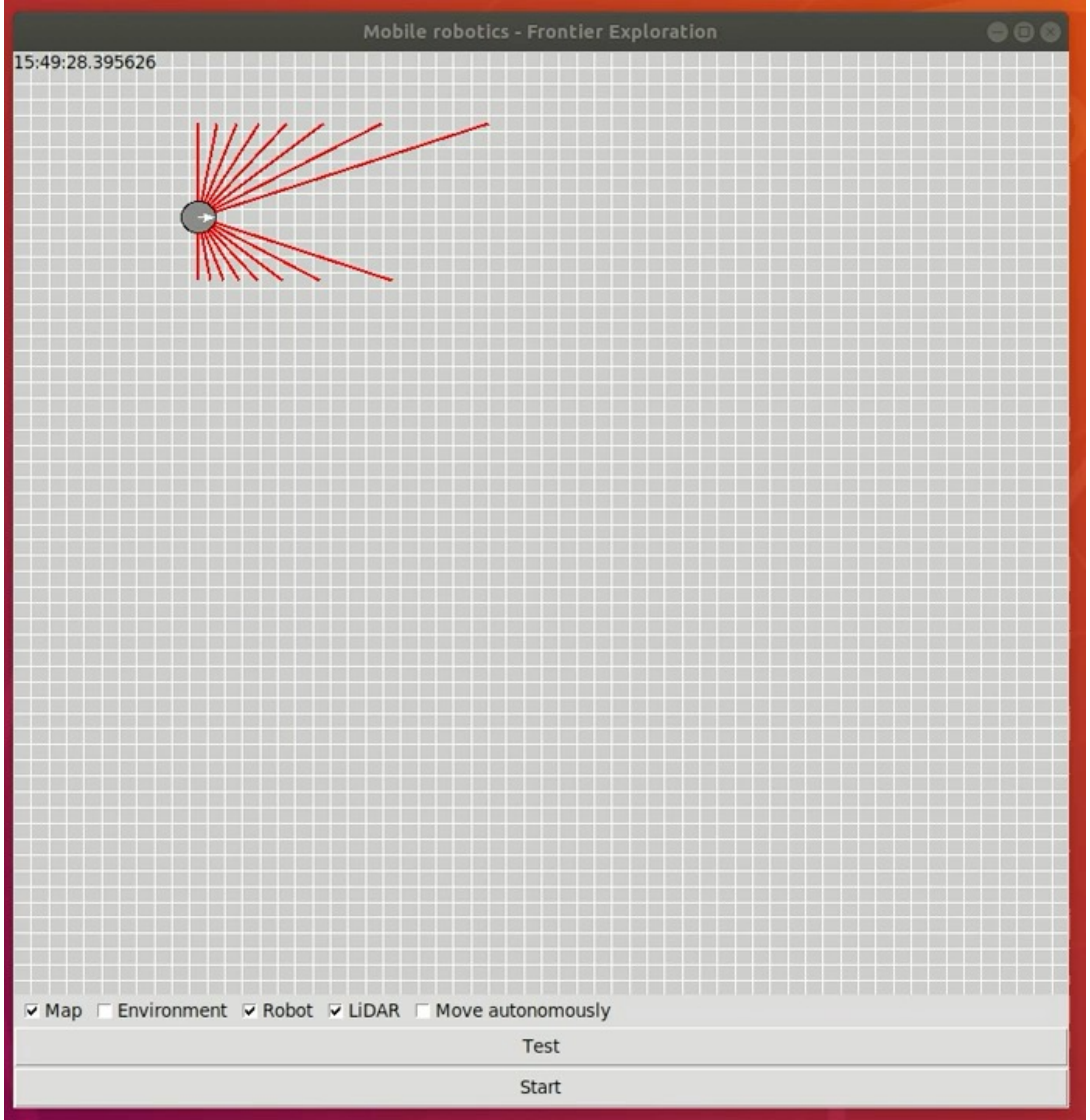
if the pixel (x, y) has '0' **then**
    Do nothing and proceed to next pixel $(x + 1, y)$
else if the pixel $(x - 1, y - 1)$ has a label **then**
    Assign the label to the pixel (x, y).
else if neither pixels $(x - 1, y)$ or $(x, y - 1)$ is not labelled **then**
    Increment label numbering and assign the latest label to pixel (x, y)
else if pixels $(x - 1, y)$ XOR $(x, y - 1)$ is labelled **then**
    Assign the label to the pixel (x, y)
else if both pixels $(x - 1, y)$ and $(x, y - 1)$ are labelled **then**
    Assign the label of pixel $(x - 1, y)$ to the pixel (x, y)
    Record the equivalence if labels of pixels $(x-1, y)$ and $(x, y-1)$ are not identical.
end if

Merges labels in single pass

Back to exploration…

Motion Control Based on Frontier Exploration

- Robot calculates centroid
- Robot navigates using path planning and obstacle avoidance
- Robot updates the map with new observations as it drives
- Once robot reaches frontier, frontiers are recalculated for the updated map
- Continue until no new frontiers remaining



https://www.youtube.com/watch?v=B-dSyKx4Fsc

Rating Frontiers

- How does the robot pick which frontier to go to?
  - Rate the utility of exploring a given frontier:
    - How close is it? How many steps needed to reach it?
    - How big/long is it?
    - Variant 1:

$$util = \alpha_1 distance + \alpha_2 length$$

    - Variant 2:

$$util = \frac{length}{distance}$$

Stopping criteria

- Why does the robot in the video stop even though there are still frontiers (red lines) that have been identified?
  - Most likely because the path planner determines that they are unreachable.

- In general, exploration terminates when all reachable frontiers larger than some minimal size are explored.

- Some approaches place the navigation target <u>on the frontier</u>, at the closest point to the centroid
  - Helps to eliminate navigation to unreachable frontiers

Can also be applied in 3D!

https://www.youtube.com/watch?v=tH2VkVony38

Anna Dai, Sotiris Papatheodorou, Nils Funk, Dimos Tzoumanikas, and Stefan Leutenegger. “Fast Frontier-based Information-driven Autonomous Exploration with an MAV”. ICRA 2020.