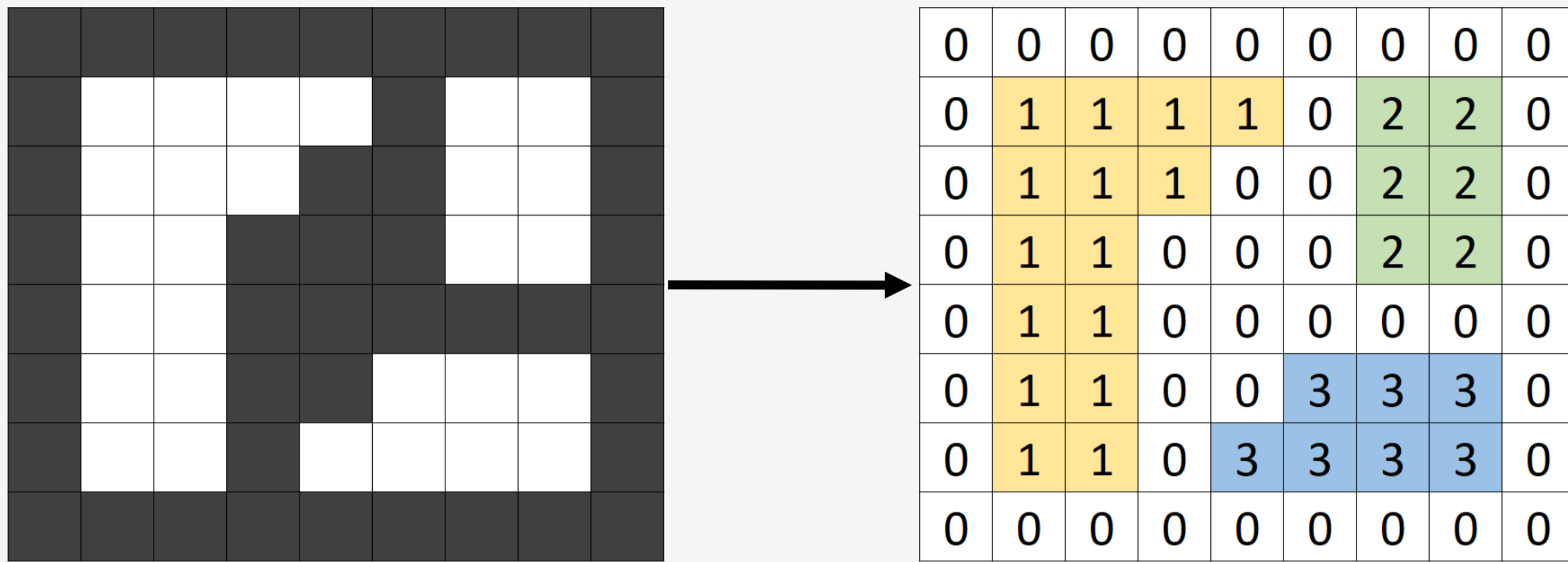


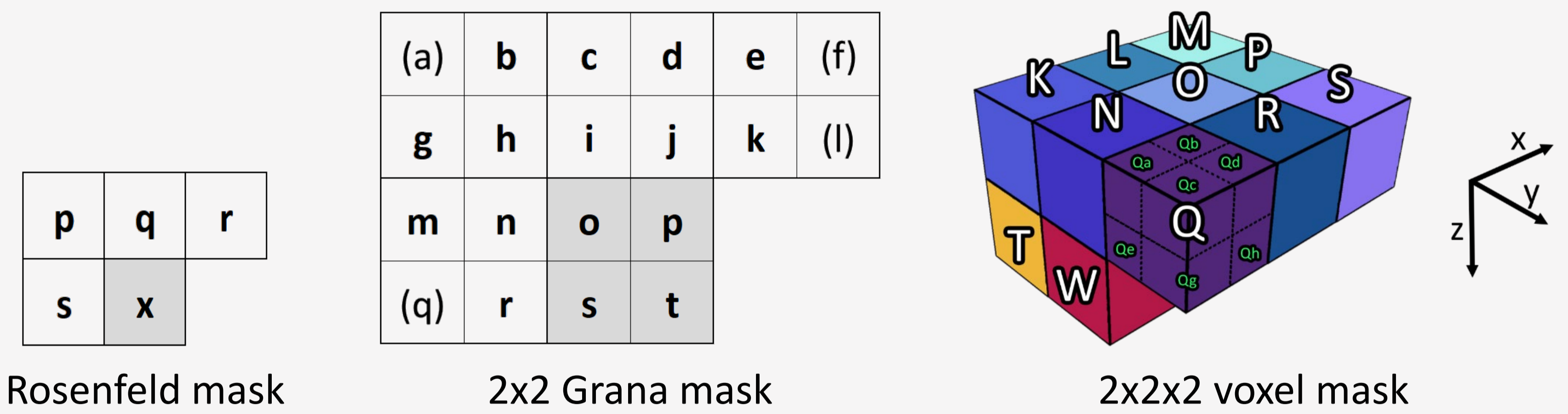
Connected Components Labeling (CCL)

- Find all connected, foreground pixel regions within a binary image
- Each pixel region, or **connected component**, receives a unique label
- Fundamental for image segmentation and object recognition
- CCL should be as **fast** as possible



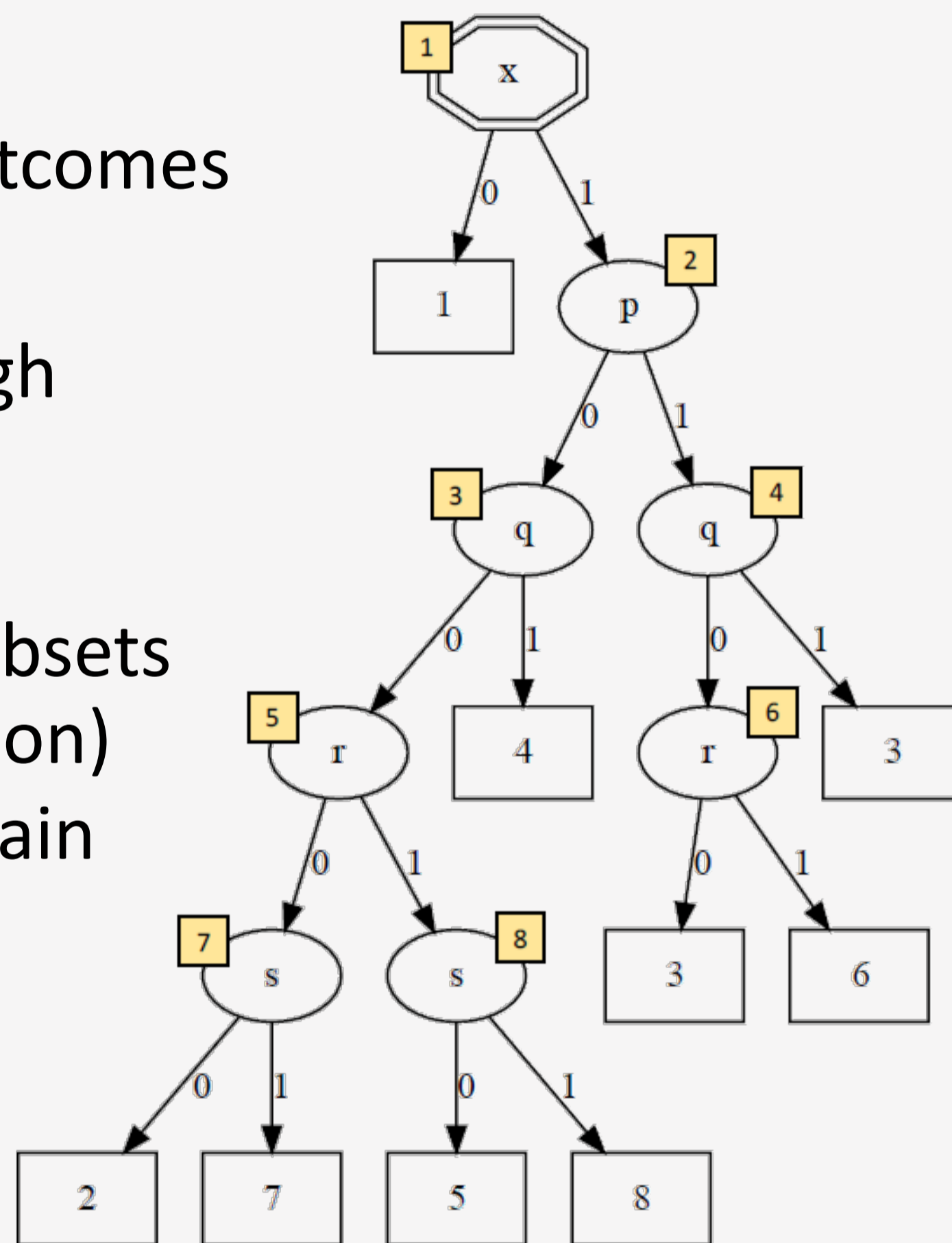
History of CCL Research

- Rosenfeld and Pfaltz invented **two scans** algorithms
- Wu et al. proposed **Optimal Decision Trees (ODTs)**
- Grana et al. proposed **block-based mask**
- What about 3D CCL?**
 - Multiple possible block-based masks: 2x1x1, 2x2x1 and 2x2x2
 - Explosion in complexity makes the ODT generation **infeasible**
 - Existing 3D CCL algorithms **do not employ** block-based masks
 - Goal: generate a near-optimal tree with a heuristic strategy**



Heuristics – Concept

- Shannon Entropy** (information theory)
 - Given a set of events E , with P_i being the probability of an event $i \in E$, the entropy H_E is:
$$H_E = -\sum_i P_i \log P_i$$
 - Entropy describes the uncertainty of outcomes
- Decision Tree Learning**
 - Recursively partition** the dataset through entropy calculation
 - Try *splitting* on every attribute
 - Calculate **Information Gain (IG)** on subsets (IG measures average entropy reduction)
 - Apply *split* with highest information gain



- Entropy Partitioning Decision Tree (EPDT)** for the Rosenfeld mask is **near-optimal**

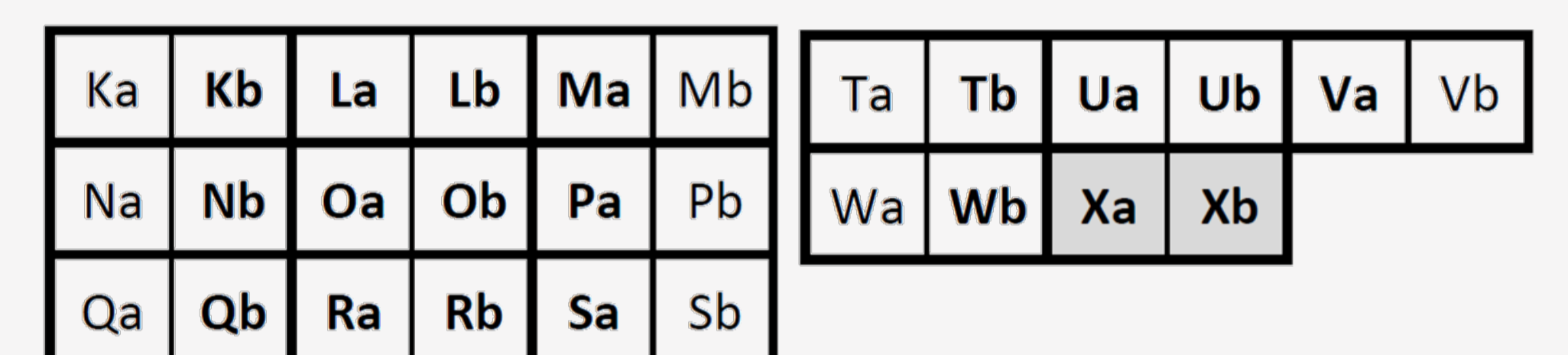
Node	Depth	$H(S)$	p			q			r			s			x		
			H_0	H_1	IG	H_0	H_1	IG	H_0	H_1	IG	H_0	H_1	IG	H_0	H_1	IG
1	0	2.2	2.0	1.4	0.5	2.3	1.5	0.3	1.9	2.1	0.2	2.1	2.1	0.1	0.0	2.4	1.0
2	1	2.4	2.0	0.8	1.0	2.5	1.0	0.7	1.8	2.3	0.4	2.2	2.2	0.2			
3	2	2.0				2.0	0.0	1.0	1.5	1.5	0.5	1.5	1.5	0.5			
4	2	0.8				1.0	0.0	0.3	0.0	1.0	0.3	0.8	0.8	0.0			
5	3	2.0							1.0	1.0	1.0	1.0	1.0	1.0			
6	3	1.0							0.0	0.0	1.0	1.0	1.0	0.0			
7	4	1.0										0.0	0.0	1.0			
8	4	1.0										0.0	0.0	1.0			

Applying Decision Tree Learning to 3D CCL

- New 3D EPDT CCL algorithms
- Varying block size and number of pixels

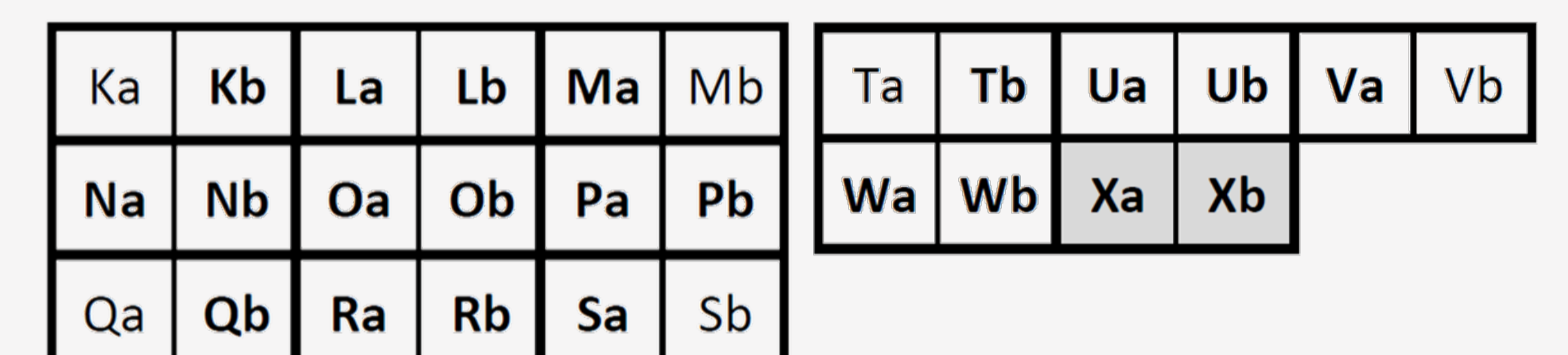
EPDT_19c

- Block size 2x1x1
- Smallest 3D block-based mask



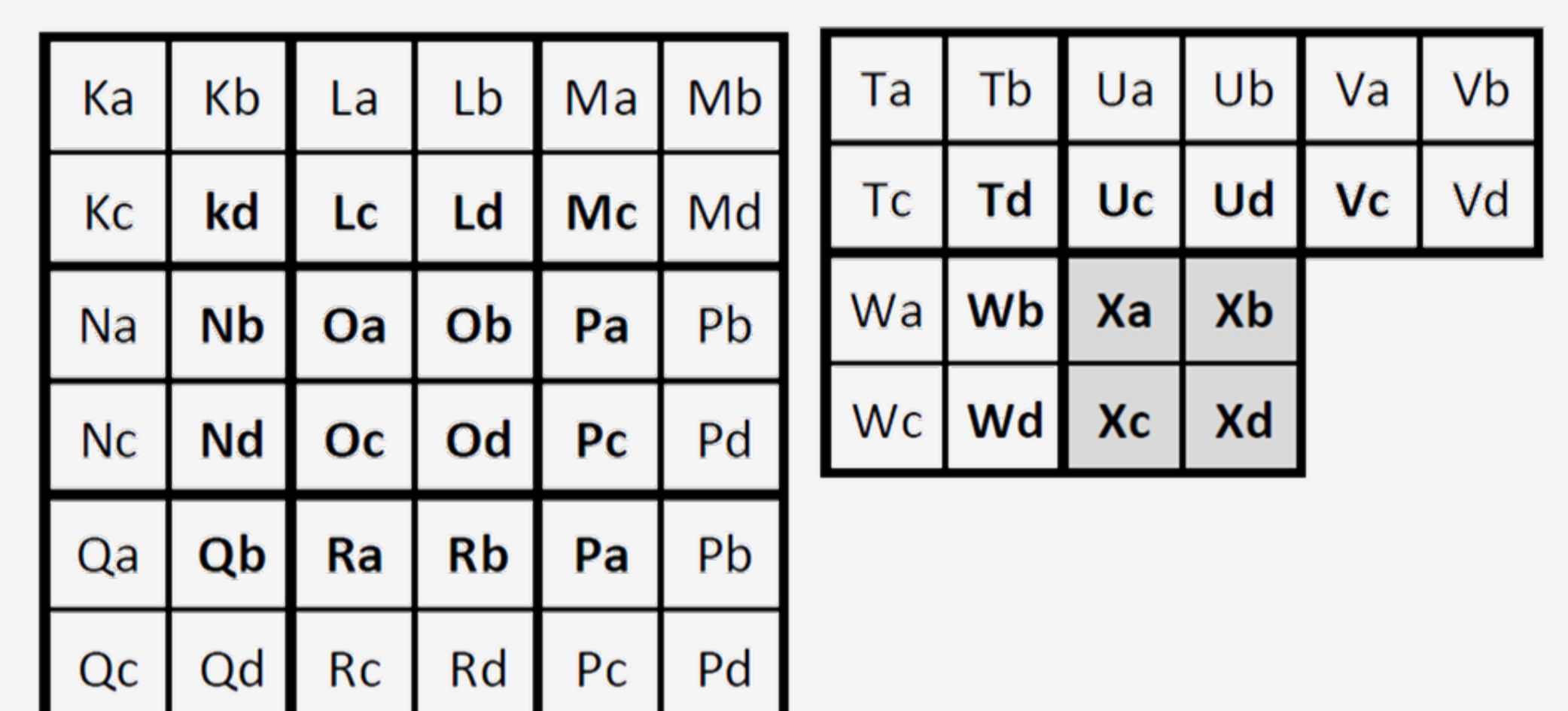
EPDT_22c

- Block size 2x1x1
- Add border pixels, for more efficient actions

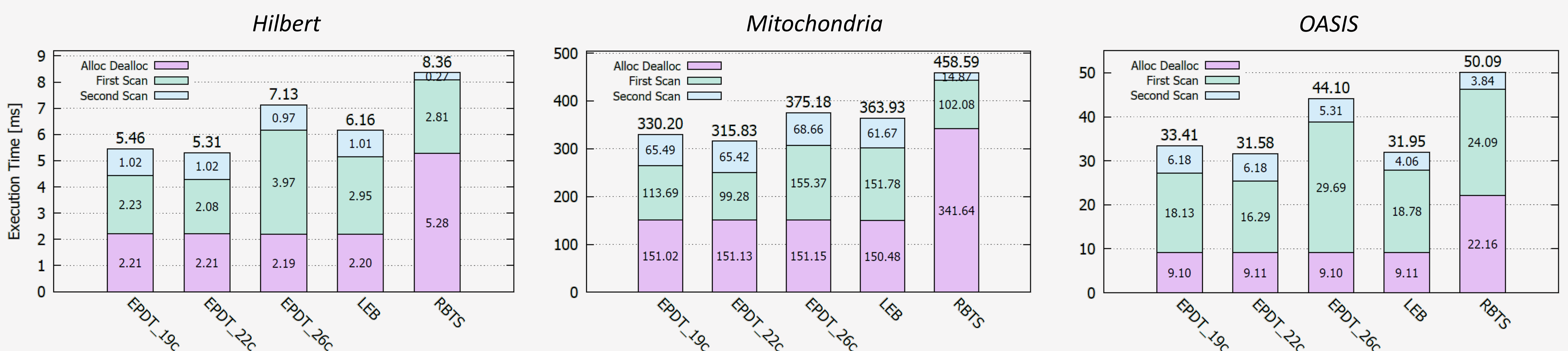


EPDT_26c

- Block size 2x2x1
- Largest tree that compilers can handle



Experimental Results



- EPDT algorithms improve the performance of the first scan by saving many **memory accesses**
- EPDT_26c has a very large decision tree → **bad impact** on instruction cache
- EPDT_22c **improves** current state-of-the-art¹

Average number of load/store operations on the OASIS dataset, expressed in millions.

Algorithm	Binary Image	Labels Image	Equivalences Vector	Total
LEB	11.461	27.182	9.851	48.494
EPDT_19c	14.917	17.760	1.169	33.846
EPDT_22c	14.057	17.753	1.145	32.955
EPDT_26c	13.695	13.145	0.728	27.568

¹L. He, Y. Chao, and K. Suzuki, "Two Efficient Label-Equivalence-Based Connected-Component Labeling Algorithms for 3-D Binary Images," *IEEE Transactions on Image Processing*, vol. 20, no. 8, pp. 2122–2134, 2011.