Cell Segmentation and Tracking in Phase Contrast Images using Graph Cut with Asymmetric Boundary Costs

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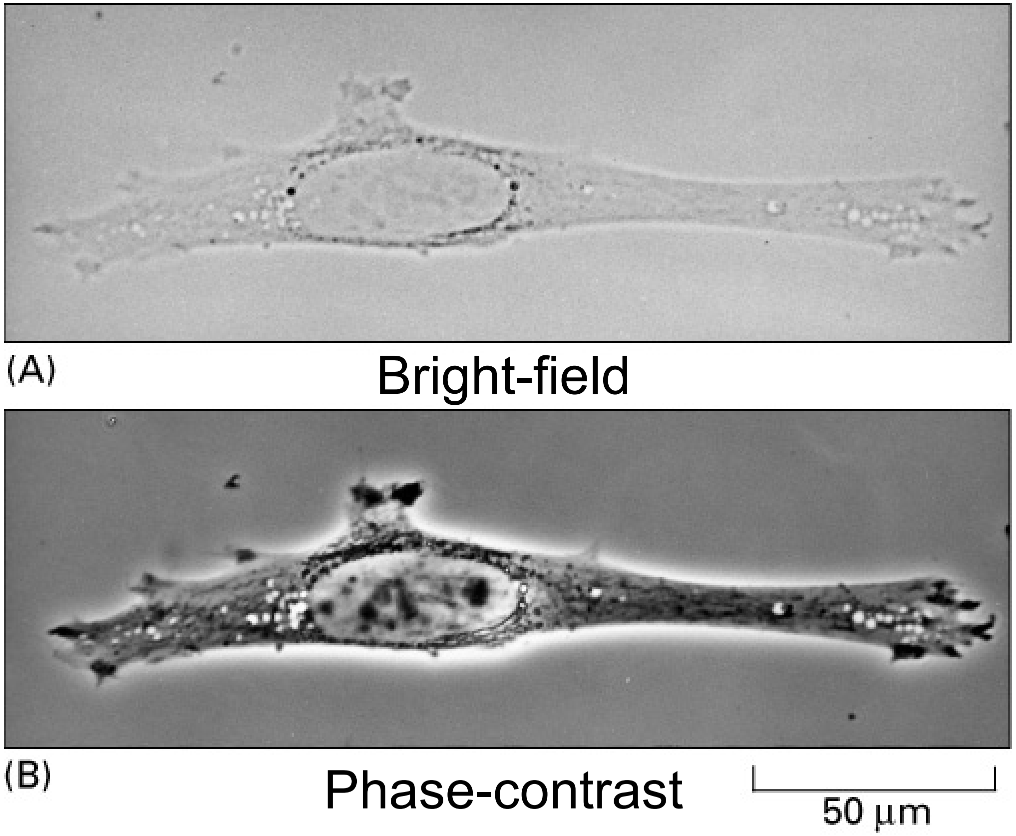
Outline

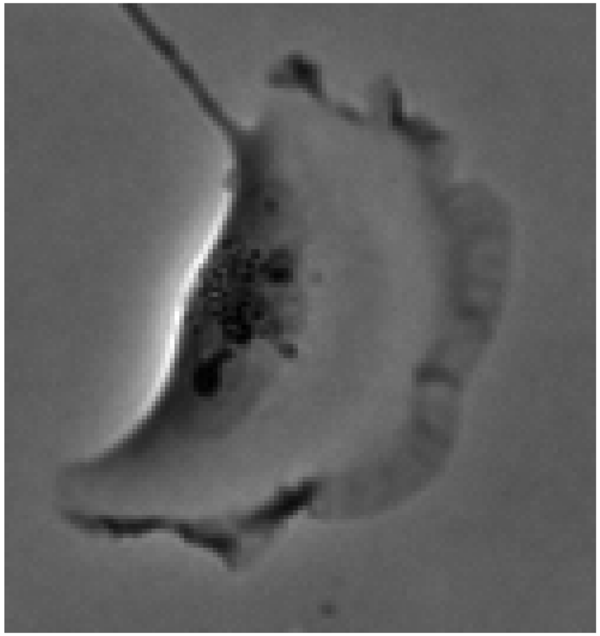
- Introduction
- Method
  - Segmentation
  - Tracking
- Experiments & Results
- Conclusion

Phase contrast microscopy



Bright-field

Phase-contrast

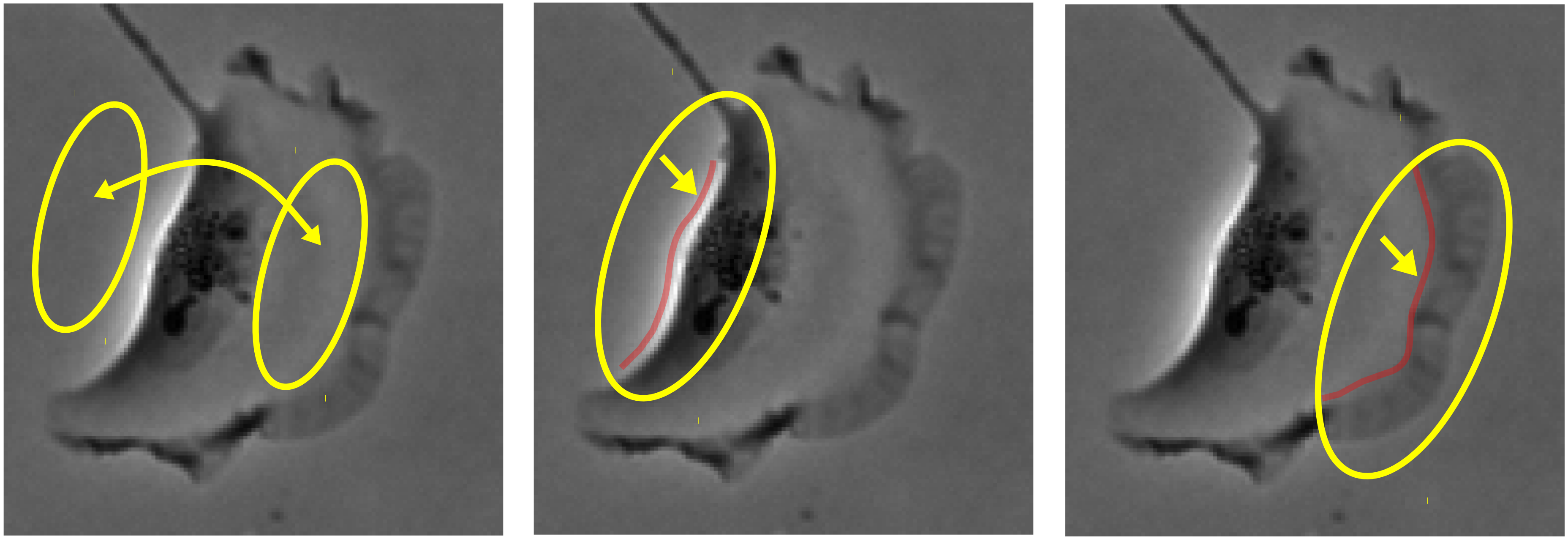


Phase-contrast

Figure: B. Alberts et al., Molecular Biology of the Cell, 4th Edition, 2002.

- **Visualize transparent objects** with high contrast at cell borders

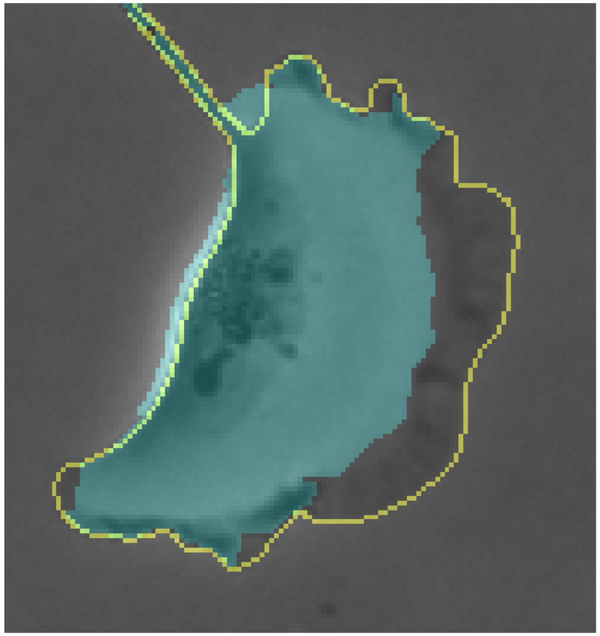
Phase contrast microscopy



Shade-off | Halo pattern | Strong edges inside and outside the cell

- Drawback: **Artifacts**

Standard segmentation algorithms

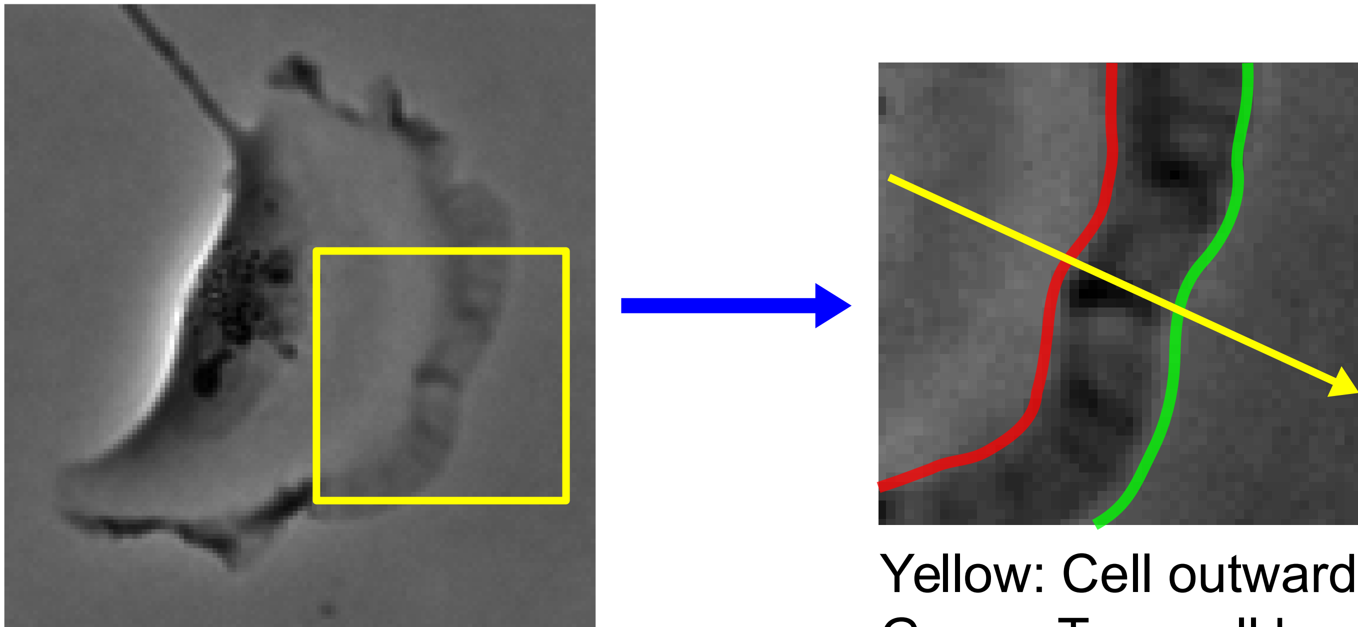


Cyan: Graph cut segmentation result
Yellow: Our manual ground truth

- Standard edge-based segmentation algorithms fail
- Traditional graph cut with **symmetric boundary costs**.

Our approach

- True cell borders appear as **dark-to-bright** transition*



Yellow: Cell outwards direction
Green: True cell border
Red: Wrong cell border

(*positive phase contrast microscopy)

- Search for segmentation mask that favors dark-to-bright transitions at its boundary
- Graph cut with **asymmetric boundary costs**

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Segmentation energy functional

- Cost function (Region & boundary term)

$$E(M) = \lambda \cdot R(M) + \boxed{B(M)}$$

Mask $M : \Omega \to \{0, 1\}$,
$\Omega \subset \mathbb{R}^2$

- Boundary term

$$B(M) = \int_\Omega C_{\text{edge}} \big(\underbrace{\langle \nabla M(\mathbf{x}), -\nabla I(\mathbf{x}) \rangle}_{\substack{\text{intensity derivative } d \\ \text{(perpendicular to mask boundary)}}} \big) \, d\mathbf{x}$$

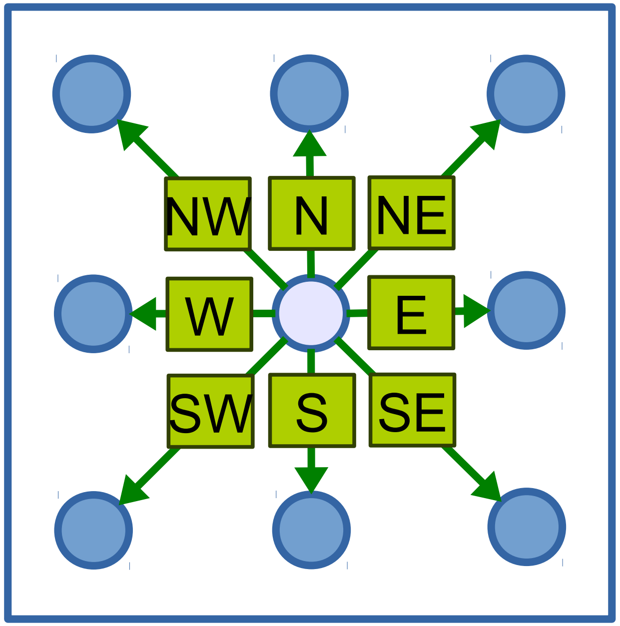
Image I
∇M unit normal vector on mask boundary, and $\mathbf{0}$ elsewhere

- **Asymmetric** boundary penalties **(dark-to-bright)**

$$C_{\text{edge}}(d) = \begin{cases} \exp\left(-\frac{d^2}{2\sigma^2}\right) & \text{if } \boxed{d > 0} \\ 1 & \text{else.} \end{cases}$$

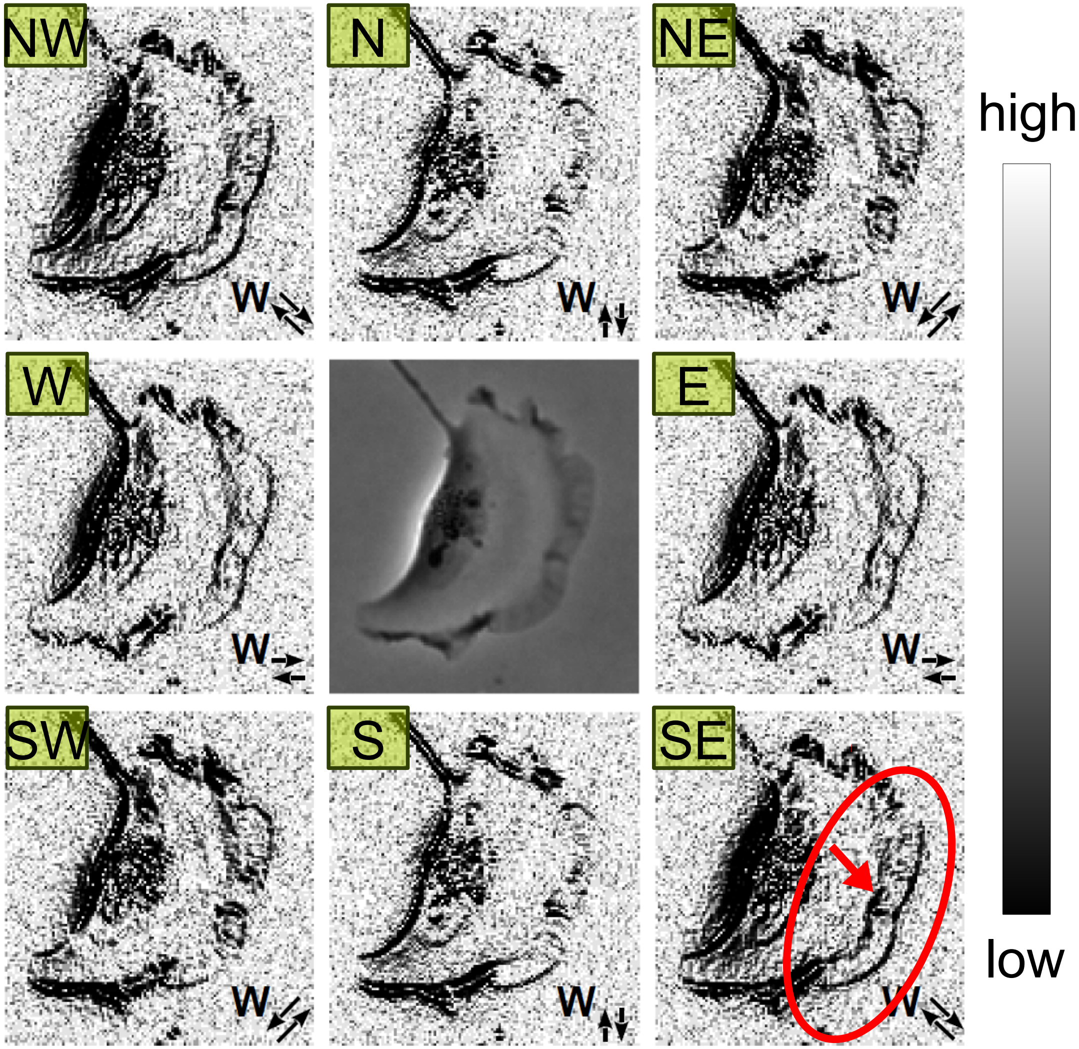
→ **directed graph** with asymmetric edge weights

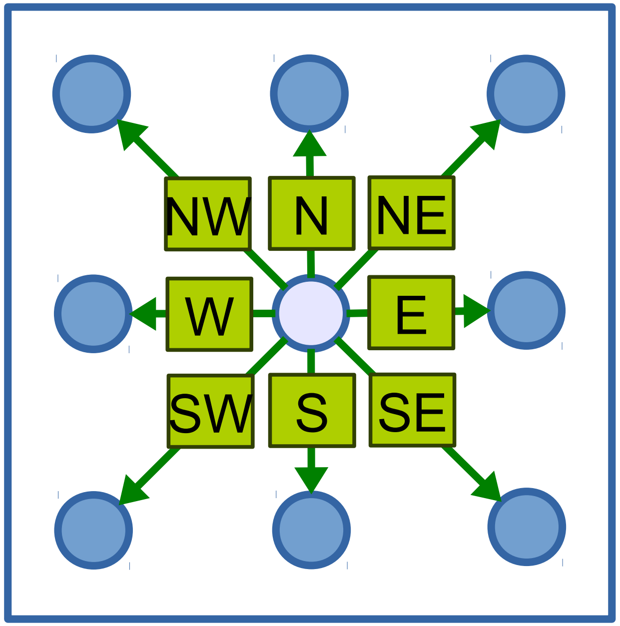
Symmetric boundary penalties



3x3 pixel neighborhood,
Edges and weights (only outwards edges shown)

Symmetric boundary penalties

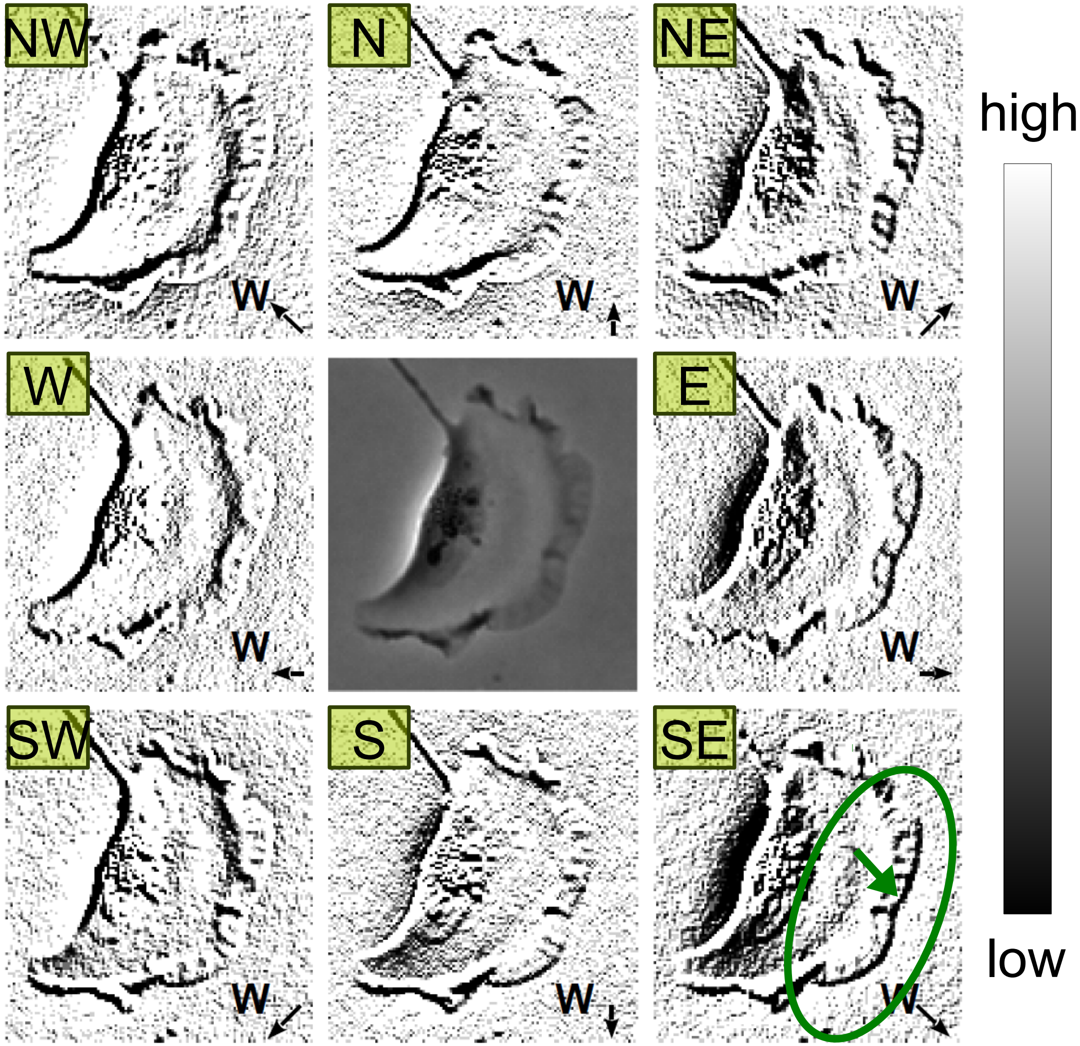


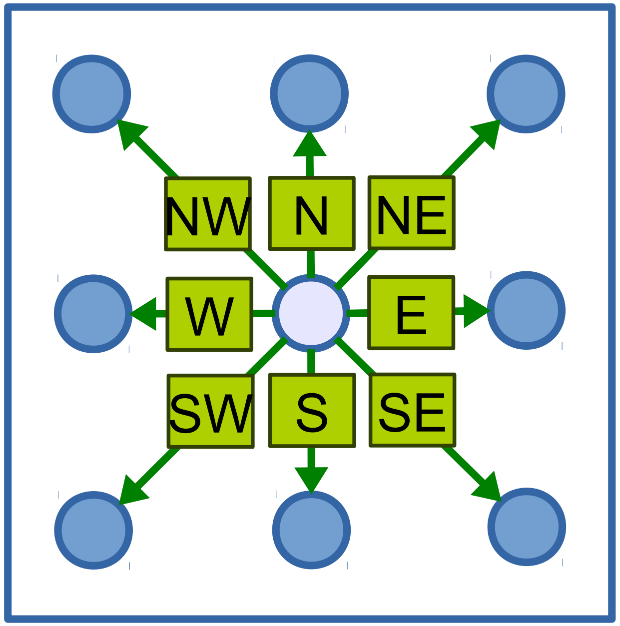


3x3 pixel neighborhood, **Edges and weights** (only outwards edges shown)

- Low costs at **wrong cell borders** (bright-to-dark transitions)

Asymmetric boundary penalties

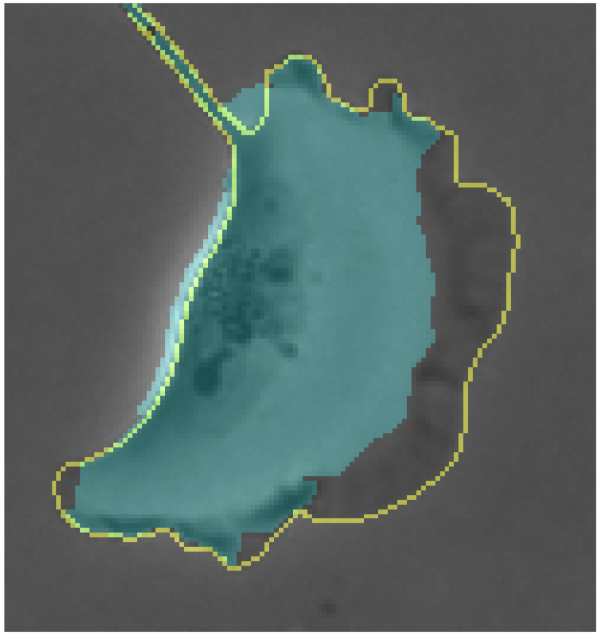




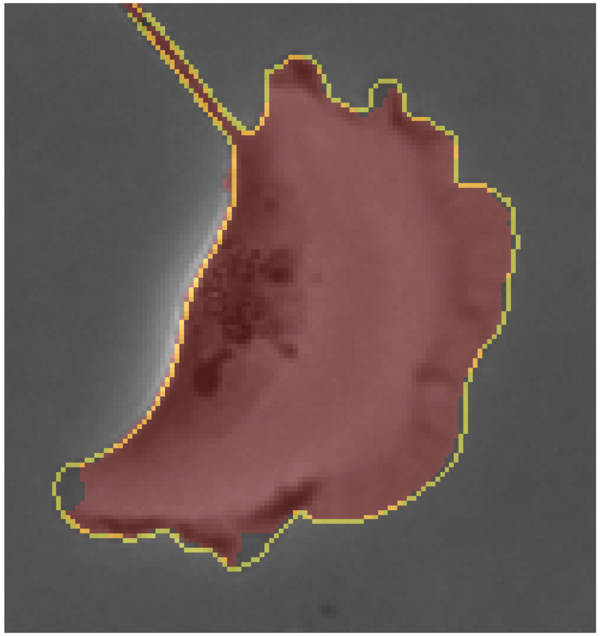
3x3 pixel neighborhood, **Edges and weights** (only outwards edges shown)

- Low costs at **correct cell borders** (dark-to-bright transitions)

Asymmetric boundary penalties



Cyan mask: Segmentation result of graph cut with **symmetric costs**
Yellow: Our manual ground truth



Red mask: Segmentation result of **proposed method**
Yellow: Our manual ground truth

Regional penalties

- Standard graph cut

$$R(A) = \sum_{p \in \mathcal{P}} R_p(A_p) \quad \text{(regional term)}$$

$$R_p(\text{"obj"}) = -\ln \Pr(I_p | \text{"obj"}) \quad \text{(object penalty)}$$

$$R_p(\text{"bkg"}) = -\ln \Pr(I_p | \text{"bkg"}) \quad \text{(background penalty)}$$

$\rightarrow$ **hard constraint**

- In our approach

$$R(M) = \int_\Omega M(\mathbf{x}) \cdot C_{\text{obj}}(I(\mathbf{x})) d\mathbf{x} \quad \text{(regional term)}$$

$$C_{\text{obj}}(v) = \frac{P(v|\mathcal{B}) - P(v|\mathcal{O})}{P(v|\mathcal{O}) + P(v|\mathcal{B})} \quad \text{(data costs)}$$

Intensity v

$P(v|\mathcal{O})$ and $P(v|\mathcal{B})$

from fore-/background

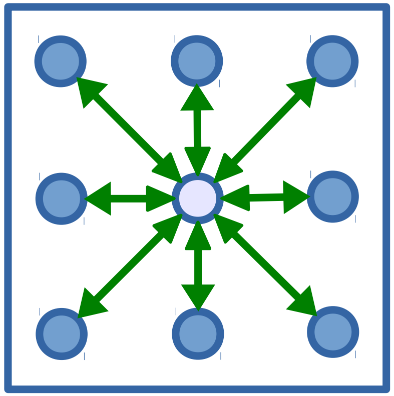
intensity histograms

$\rightarrow$ **soft constraint**

Optimization

$$E(M) = \lambda \int_\Omega M(\mathbf{x}) \cdot C_{\mathrm{obj}}(I(\mathbf{x}))d\mathbf{x} + \int_\Omega C_{\mathrm{edge}}\left(\langle \nabla M(\mathbf{x}), -\nabla I(\mathbf{x})\rangle\right) d\mathbf{x}$$

- Enery minimization problem
- Discretize edge term into 8 directions
  → combinatorial optimization problem
- Solve efficiently by a **min-cut approach**



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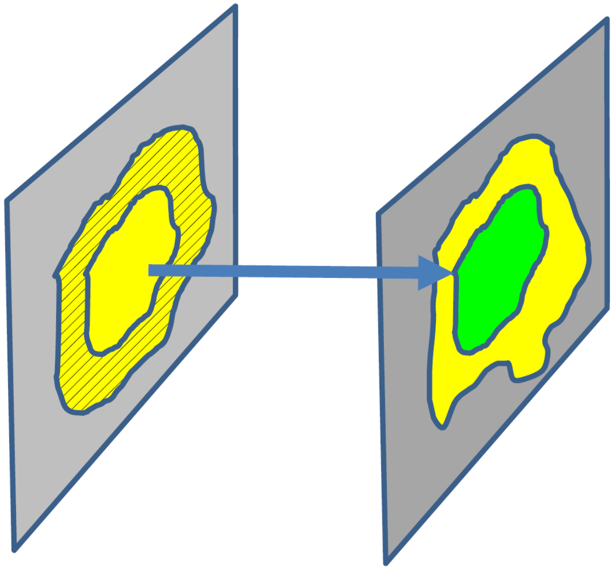
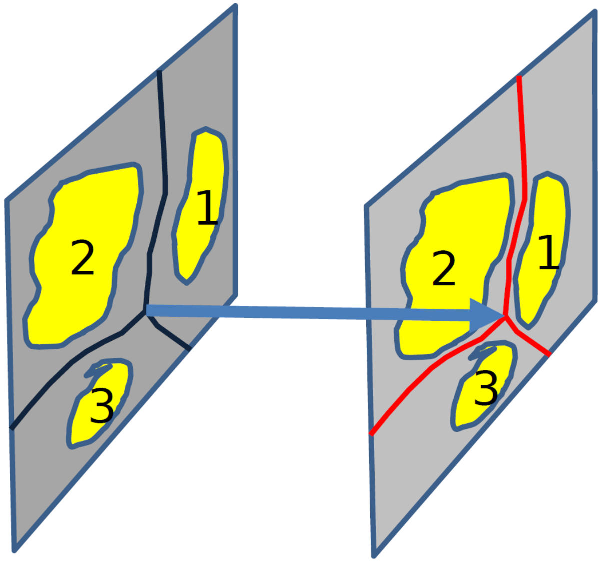
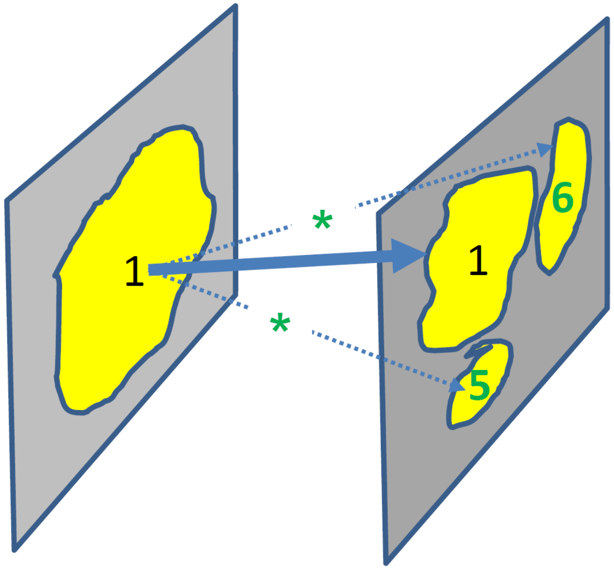
Tracking: Segmentation propagation



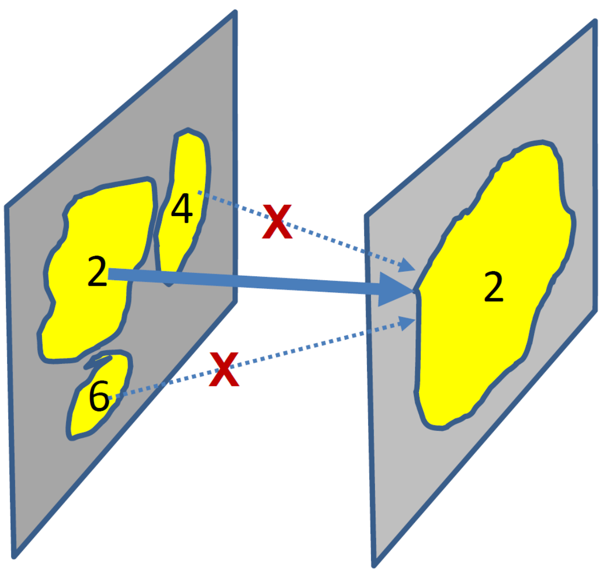


- Propagate Segmentation Information
- **Foreground information** using eroded mask
  → foreground constraint
- **Partitioning information** using borders of „support regions“
  → background constraint

Tracking: Label propagation



- Propagate Labels to overlapping Segments
- Resolve **one-to-many** correspondences
  - Propagate label to max. IOU
  - Invent new labels



- Resolve **many-to-one** correspondences
  - Take label from max. IOU
  - Kill other labels

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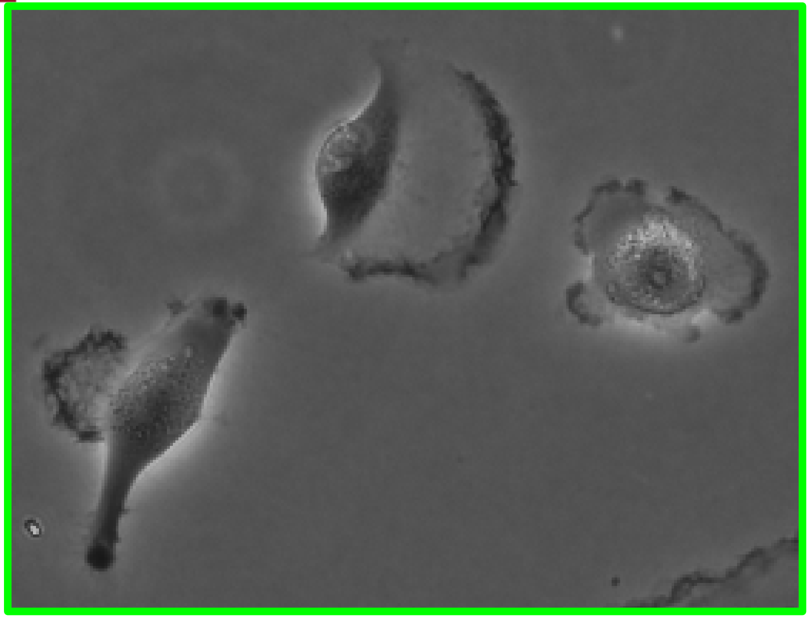
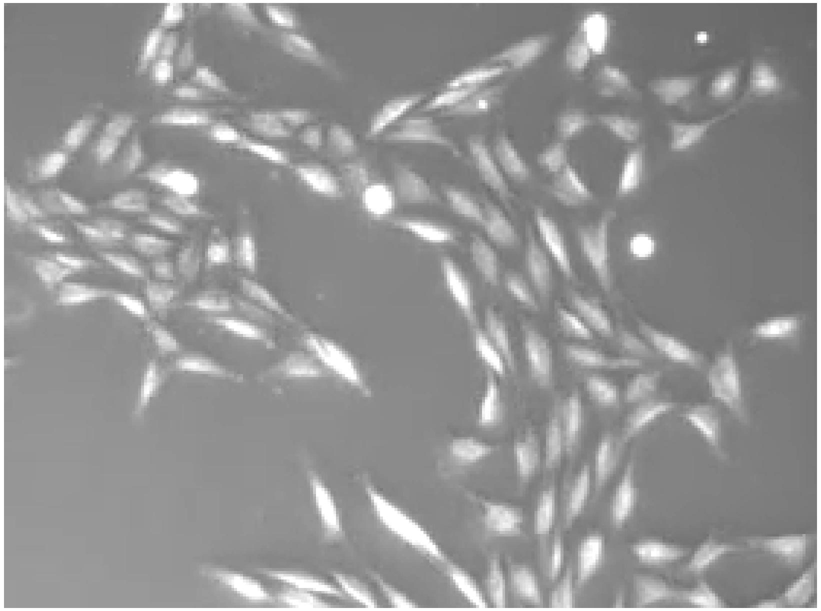
Datasets: ISBI cell tracking challenge[1,2]



Glioblastoma-astrocytoma U373 cells on a polyacrylimide substrate*



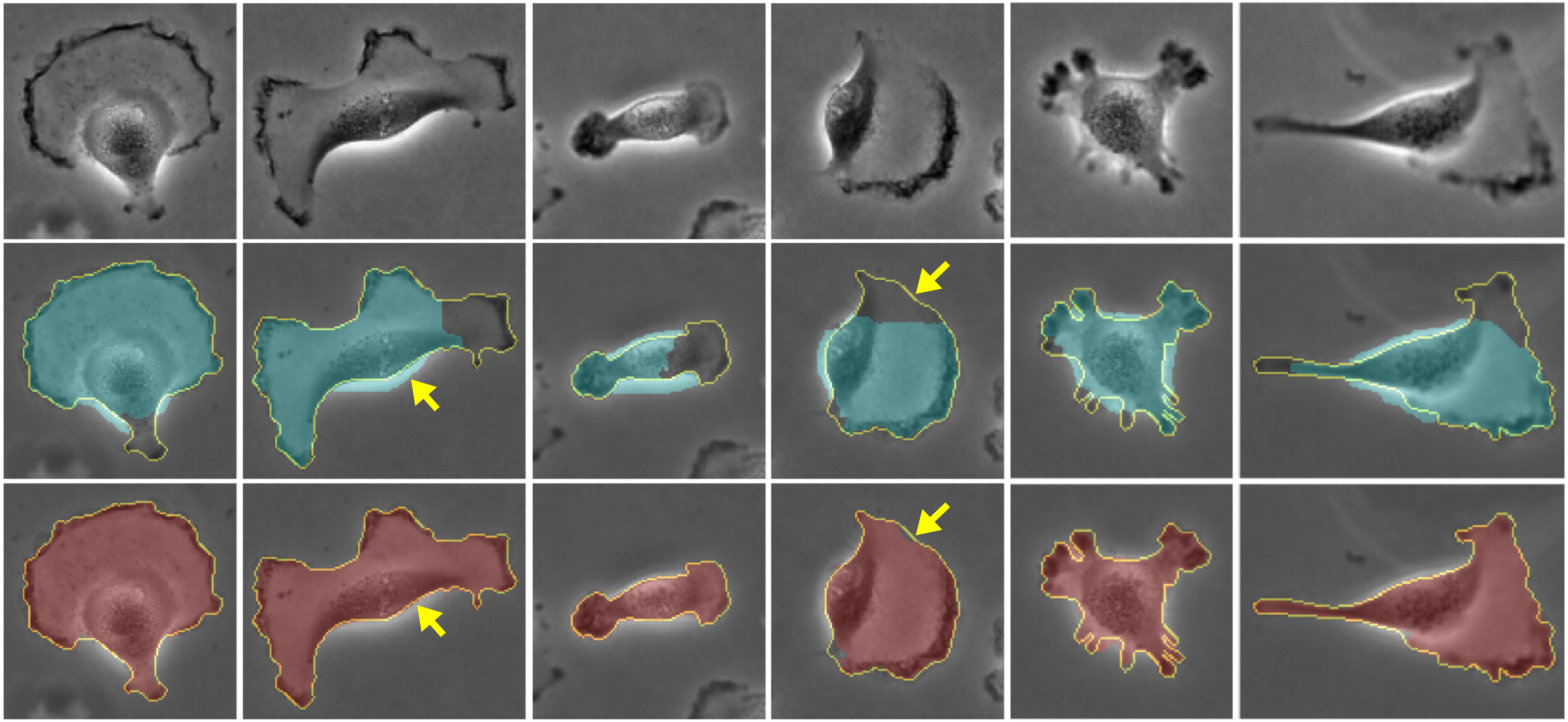
Pancreatic Stem Cells on a Poly-styrene substrate (2D)†

- Strong shape variations
- Weak outer borders, strong irrelevant inner borders
- Cytoplasm has same structure as background

(1) ISBI Cell Tracking Challenge, Available at: http://www.codesolorzano.com/celltrackingchallenge.
(2) M. Maška, V. Ulman, D. Svoboda, P. Matula, and P. Matula, et al., "A benchmark for comparison of cell tracking algorithms," Bioinformatics, vol. 30, no. 11, pp. 1609–1617, 2014.

*Data provided by Dr. Sanjay Kumar. Department of Bioengineering University of California at Berkeley. Berkeley CA (USA).
†Data provided by Dr. Tim Becker. Fraunhofer Institution for Marine Biotechnology. Lübeck. Germany

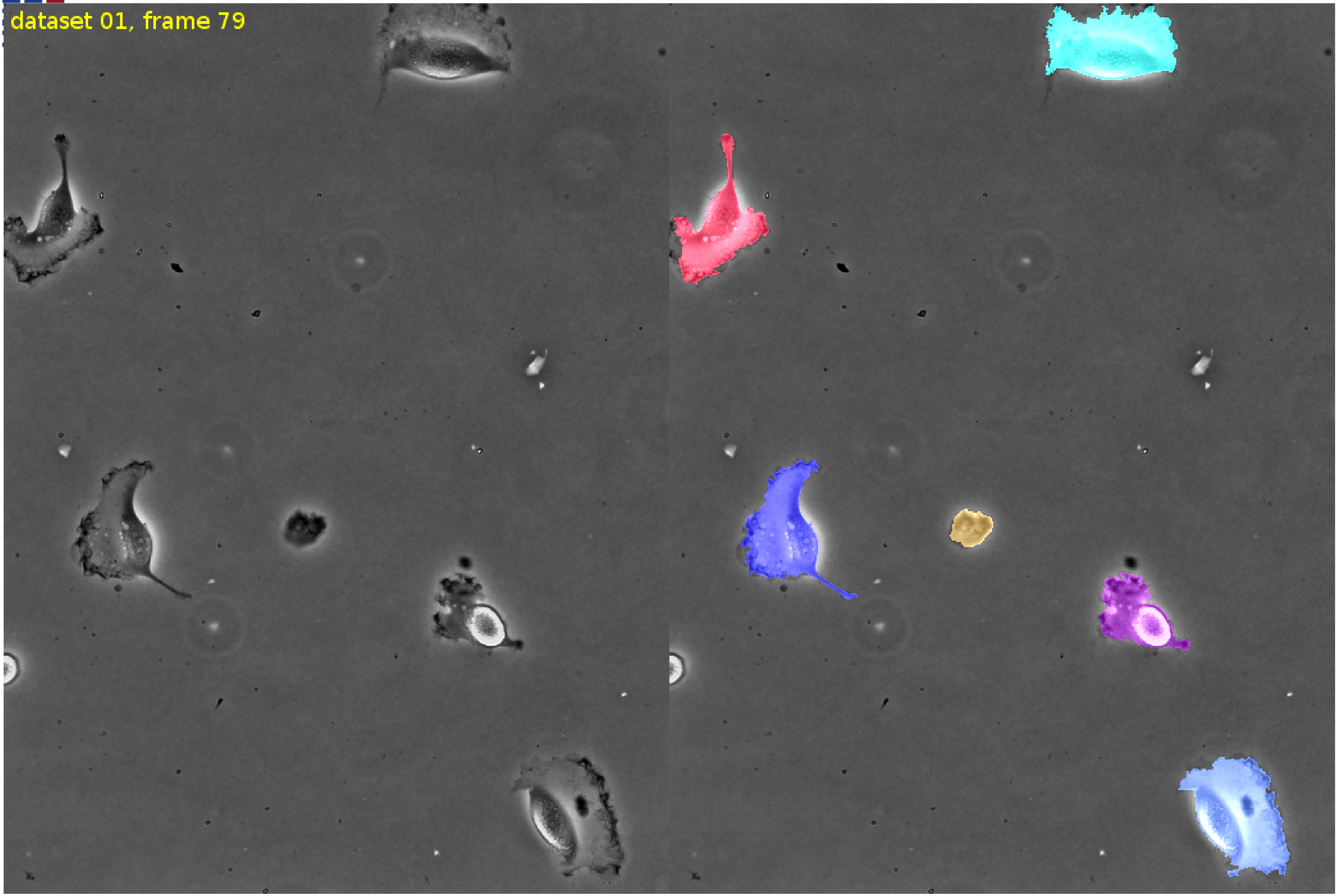
Experiments: Symmetric vs. asymmetric costs



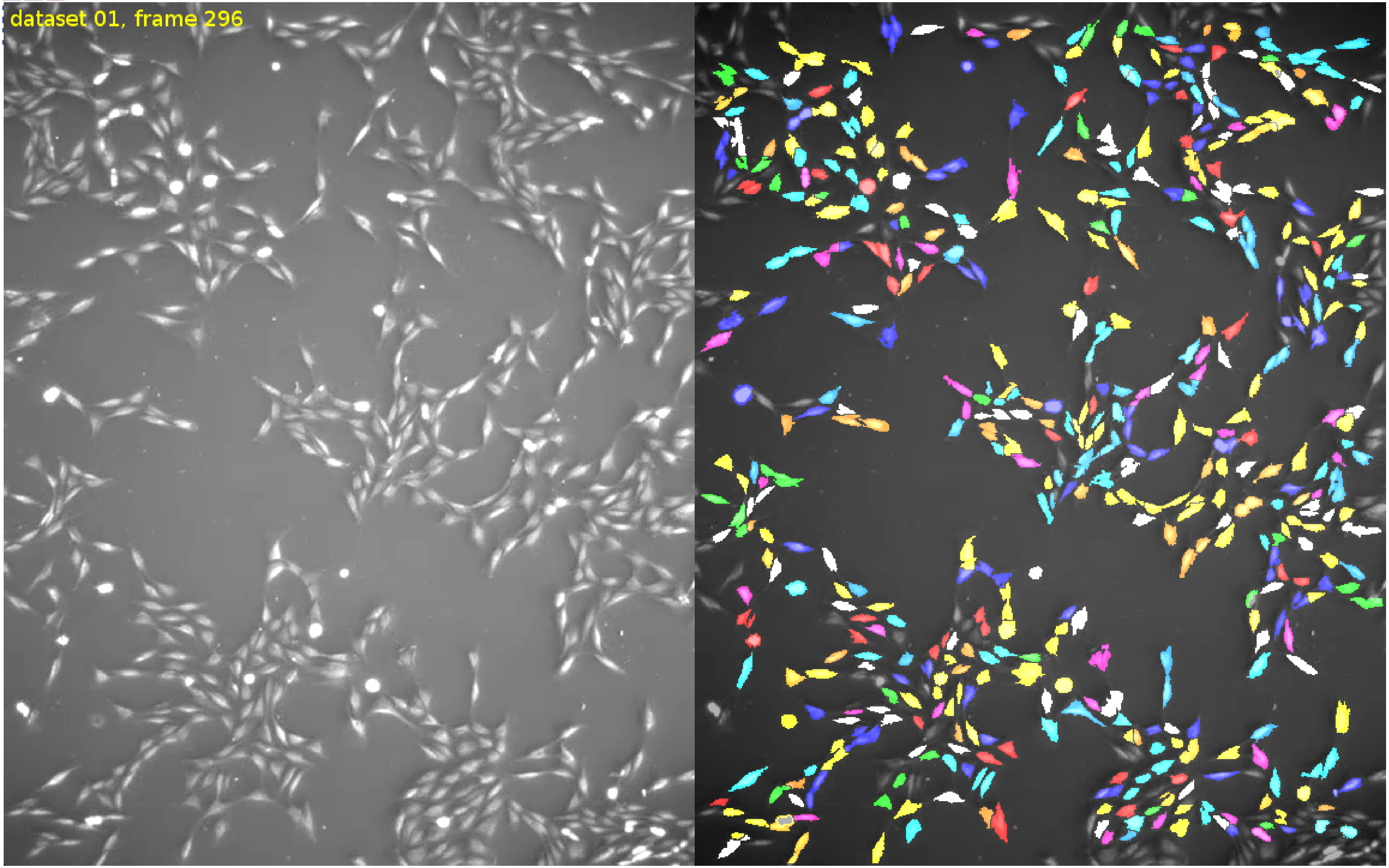
Cyan masks: Graph cut with symmetric costs, Red masks: Our approach with asymmetric costs, Yellow borders: Our manual ground truth

- Improved detection of very **weak boundaries**
- **Halo boundaries** are handled well

Submitted results: PhC-C2DH-U373



Submitted results: PhC-C2DL-PSC



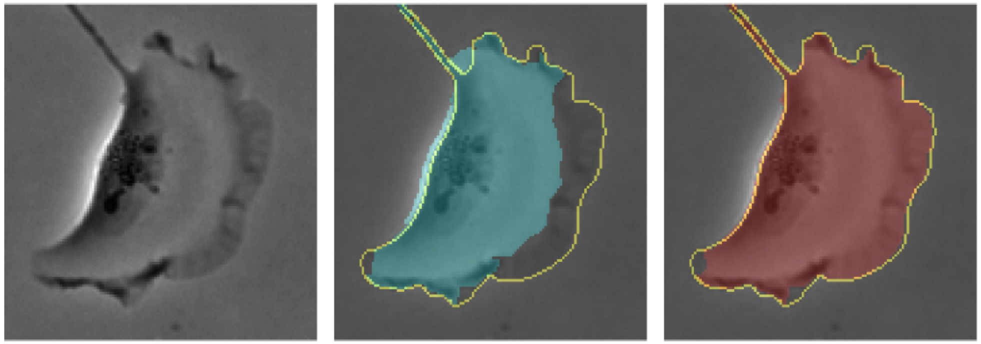
Conclusion

- Direction dependent boundary costs improve segmentation in phase contrast microscopy
- Our approach outperforms standard min-cut segmentation with symmetric costs

→ *Profit for cell segmentation in other modalities*

→ *Open-source MATLAB code (and ImageJ plugin)*:*

http://lmb.informatik.uni-freiburg.de/resources/opensource/CellTracking/

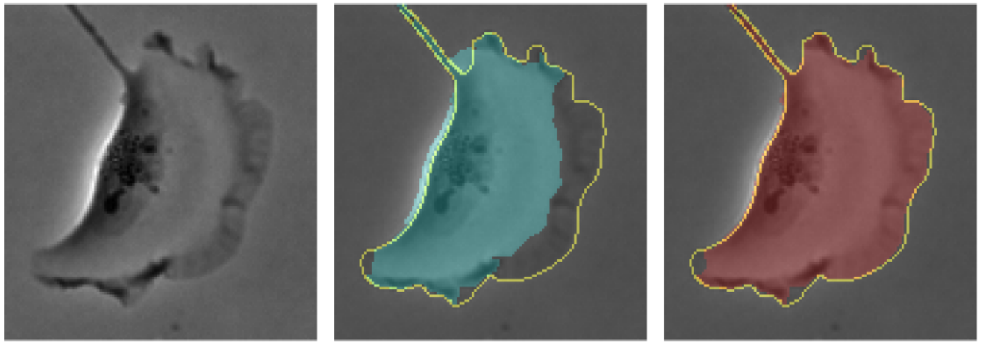


*(coming soon ;)

Thank you!

→ Talk on Saturday, April 18, 14:45–15:00, Session: Segmentation for Microscopy Imaging – SaCT4, Room: Salon C

→ Open-source MATLAB code (and ImageJ plugin):*
http://lmb.informatik.uni-freiburg.de/resources/opensource/CellTracking/



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