Outline

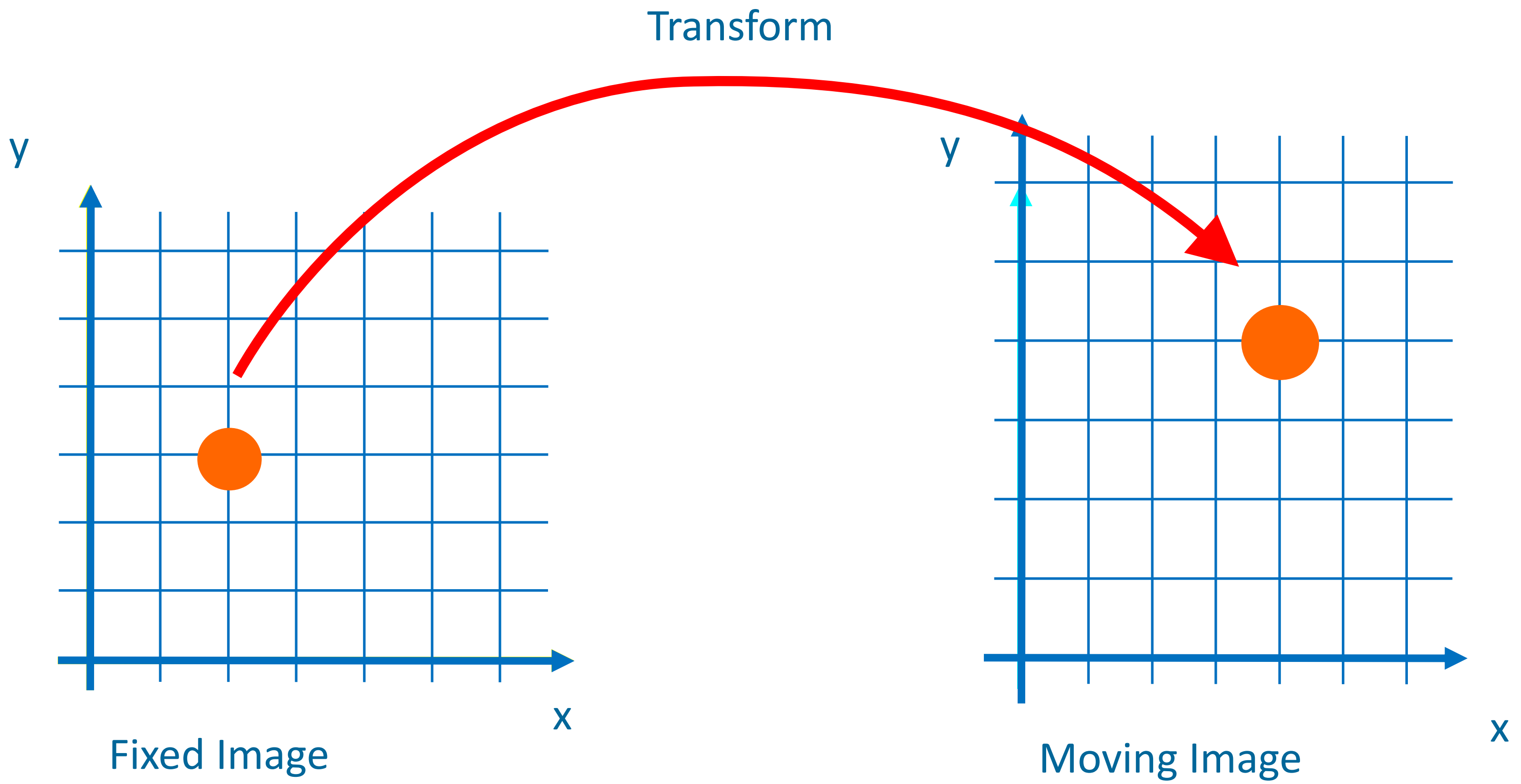
- Introduction, principles
- **Method n°1 : Demons**
- Evaluation
- Method n°2 : B-Splines
- Method n°3 : TPS (Thin Plate Spline)
- The « sliding » problem
- Spatio-temporal deformable registration
- Conclusion

Example 1: the « Demons » algorithm

Method proposed by **[Thirion1998] [Pennec1999]**
J.P. Thirion. Image matching as a diffusion process: an analogy with Maxwell's demons.
Med Image Analysis, 2(3):243–260, 1998.

- Popular
- "Simple" to implement
- A posteriori explanation
- Numerous developments

Principle



Principle

- Iterative algorithm
- A each iteration
  - Step1: estimate the deformation vector field (DVF)
  - Step2 : regularize the DVF
- Stopping criteria to determine

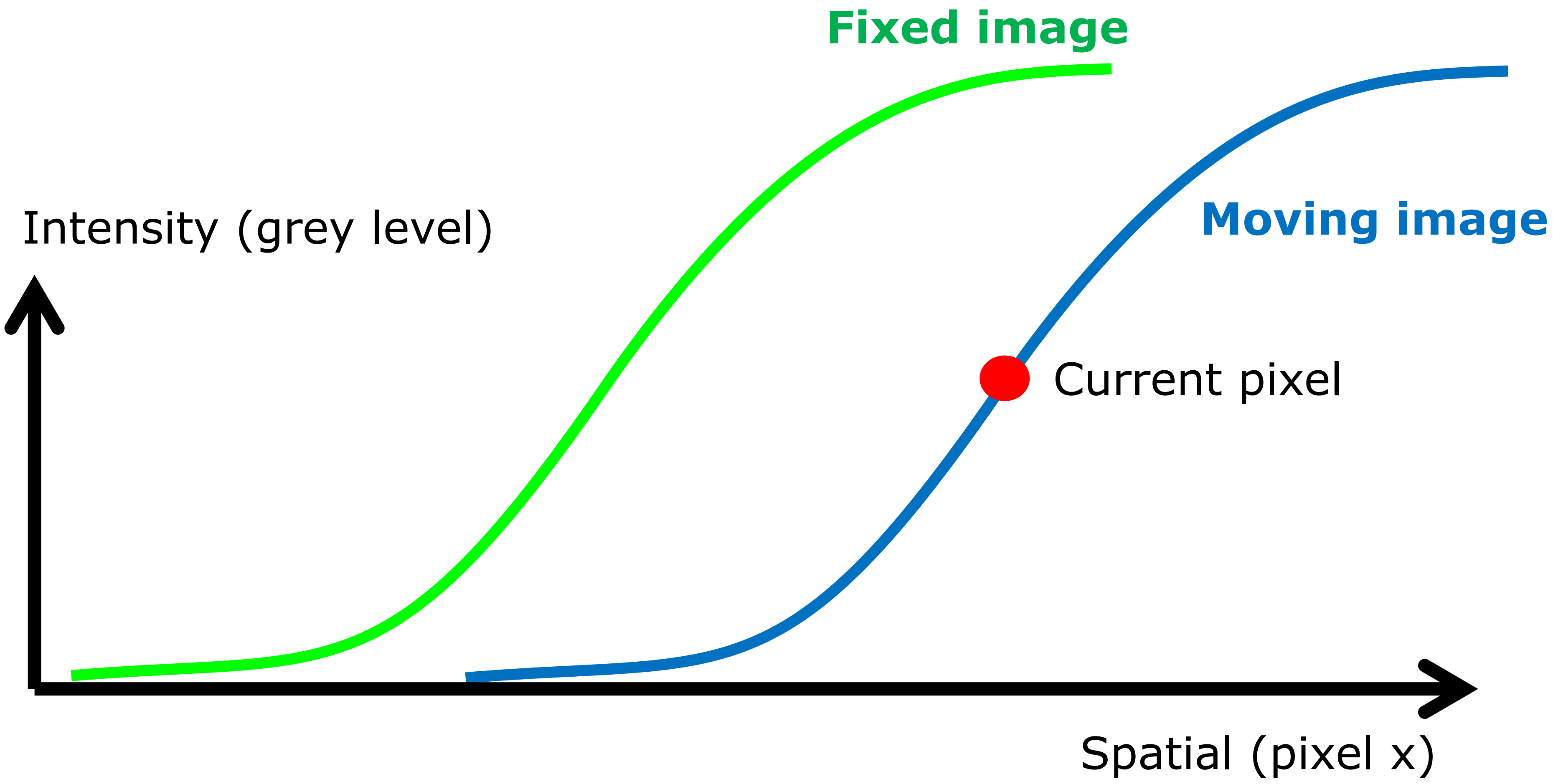
Images to register	$I_1 \; I_2$
Displacement at x	$\mathbf{u}(\mathbf{x})$
DVF	$\phi(\mathbf{x}) = \mathbf{x} + \mathbf{u}(\mathbf{x})$

Principle: step 1

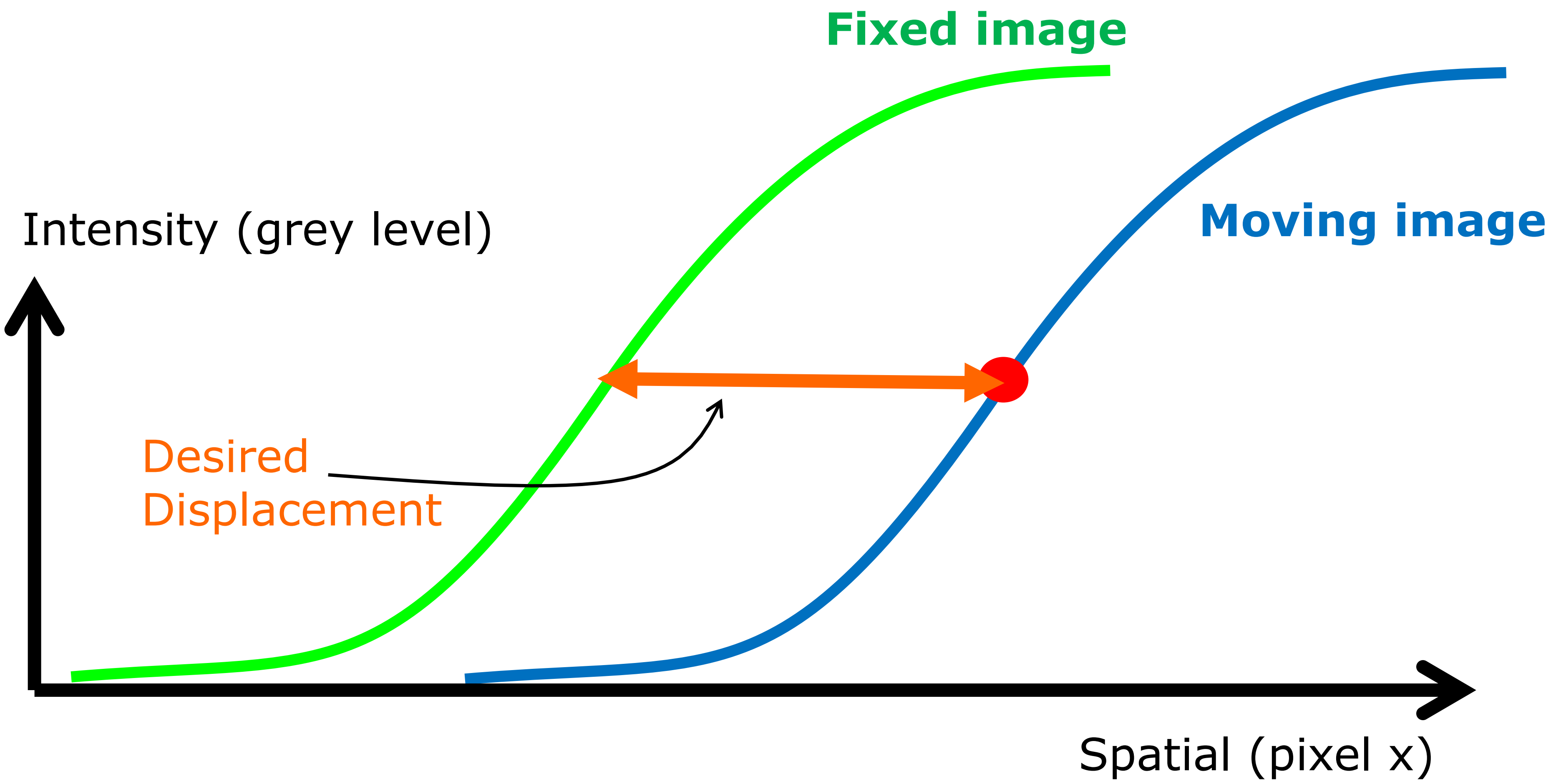
- Displacement evaluation at every pixel x
- This displacement is:
  - It is // to the image I1 gradient (I1 is the moving image)
  - Proportional to pixel grey level difference between the 2 images at location x.
- « Small » displacement, bounded by $1/(2\alpha)$
- Alpha = user parameter

$$\nabla D_{SSD}(\boldsymbol{x}, \boldsymbol{u}) = \frac{I_2(\boldsymbol{x} + \boldsymbol{u}(\boldsymbol{x})) - I_1(\boldsymbol{x})}{||\nabla I_1(\boldsymbol{x})||^2 + \alpha^2 (I_2(\boldsymbol{x} + \boldsymbol{u}(\boldsymbol{x})) - I_1(\boldsymbol{x}))^2} \nabla I_1(\boldsymbol{x})$$

Explanation



Explanation



Fixed image

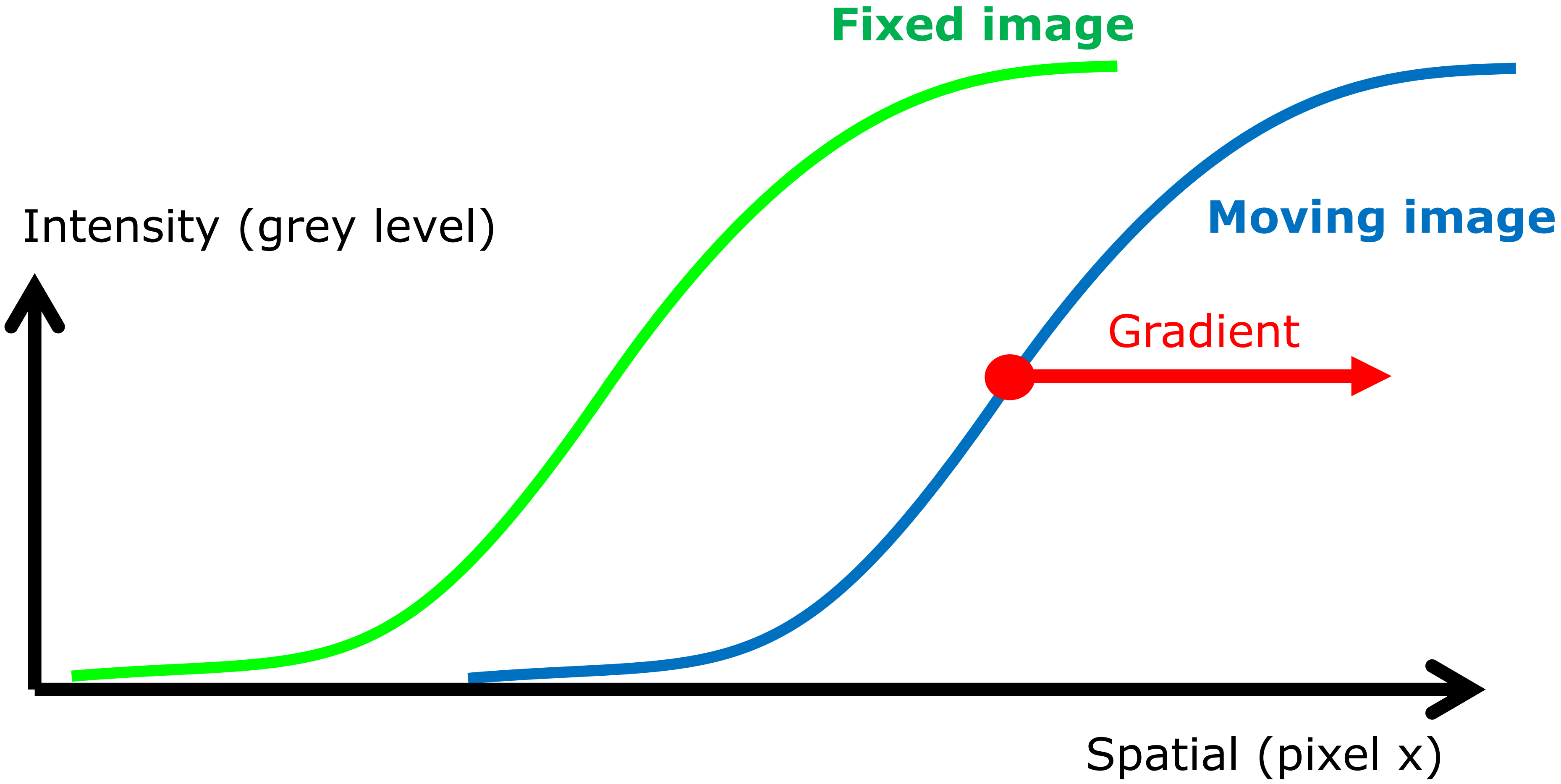
Moving image

Intensity (grey level)

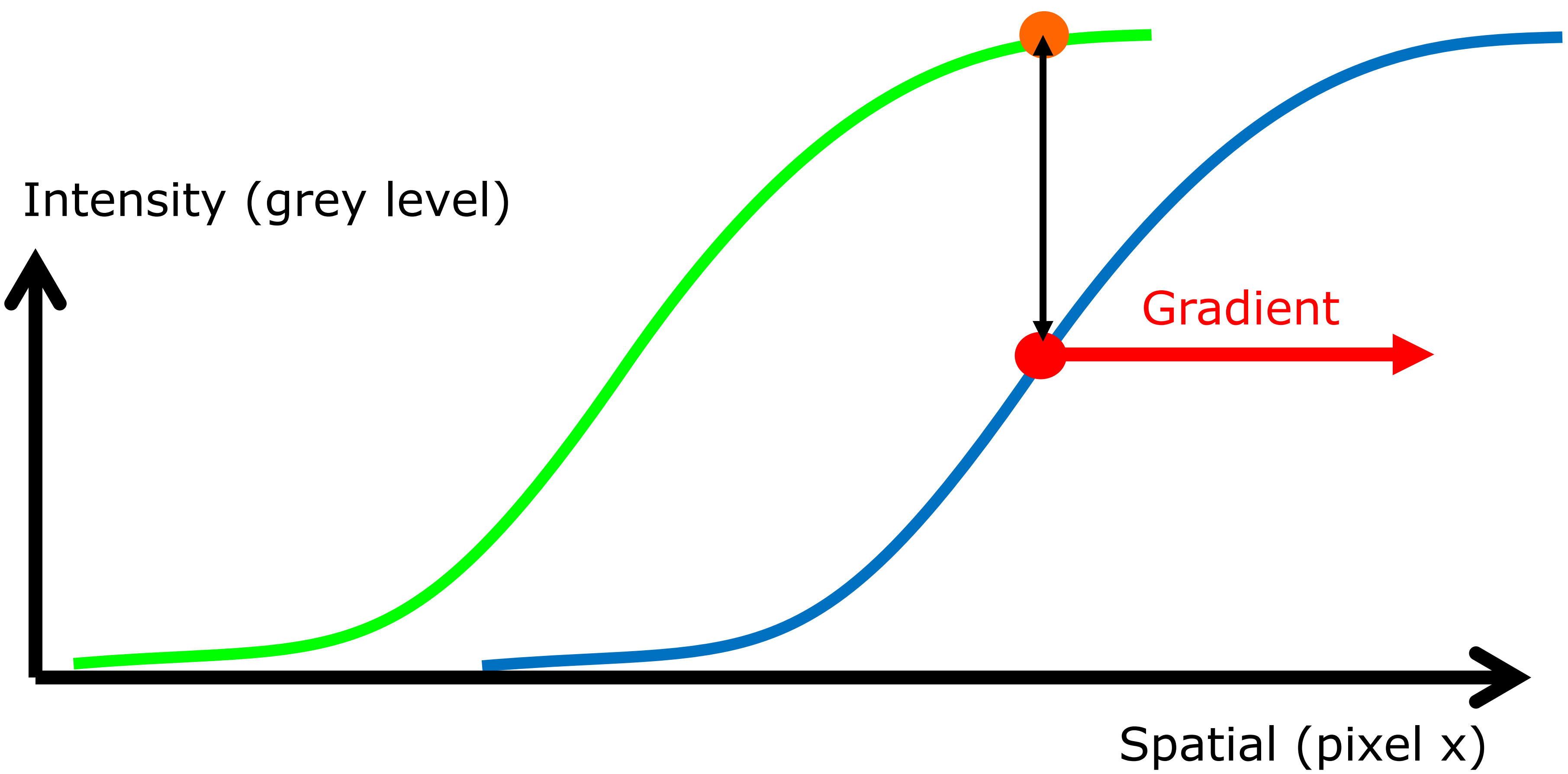
Desired Displacement

Spatial (pixel x)

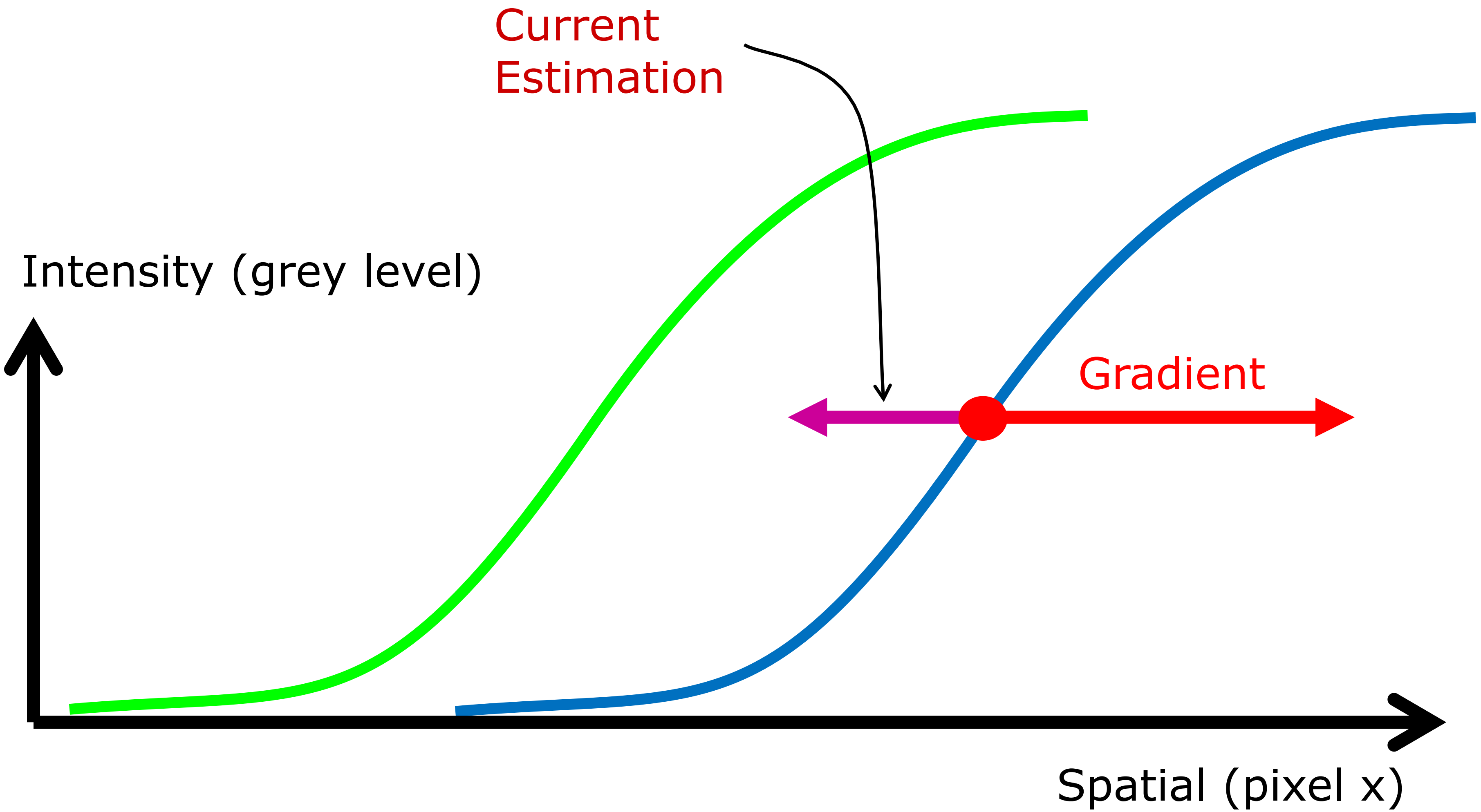
Explanation



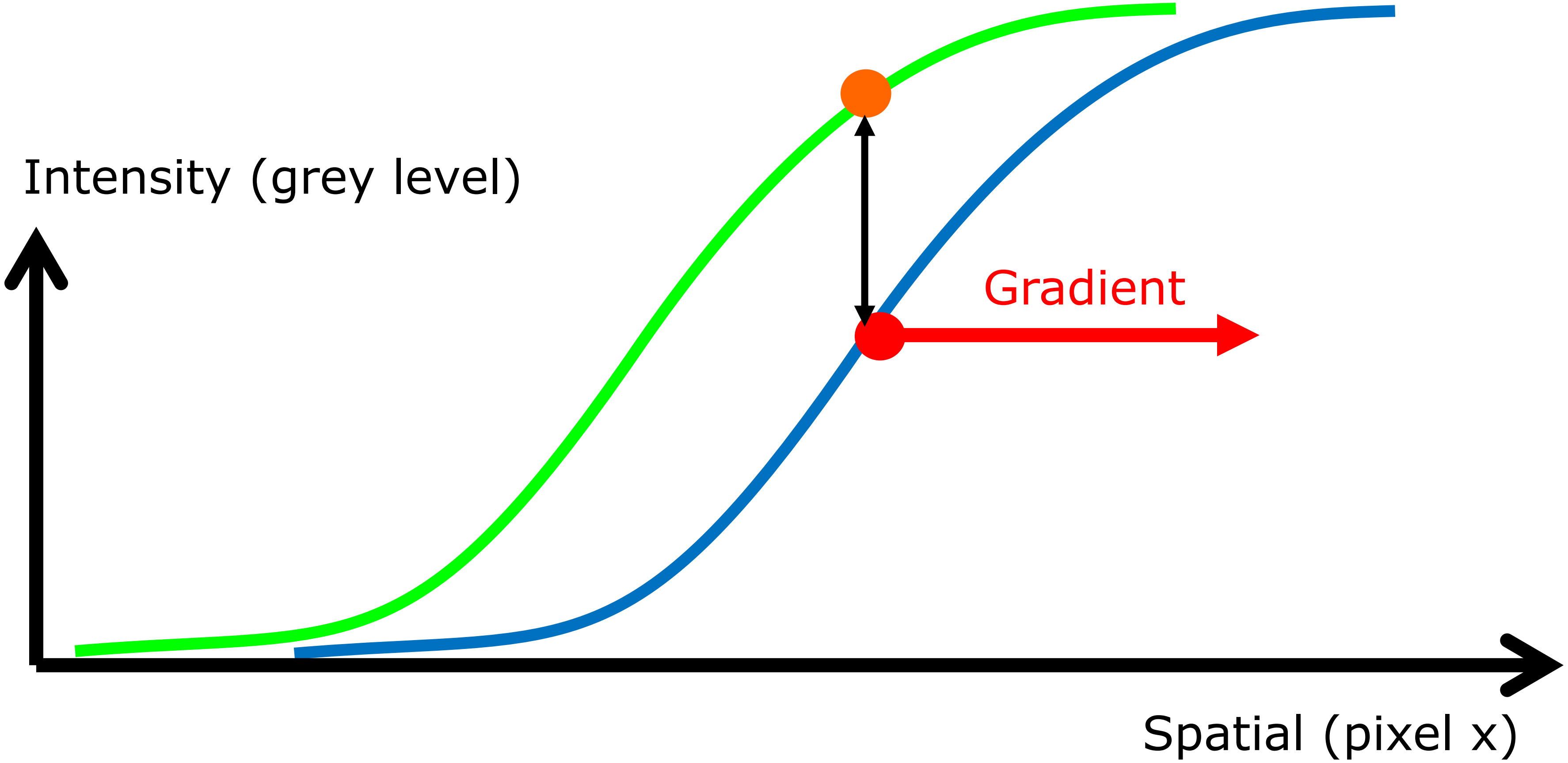
Explanation



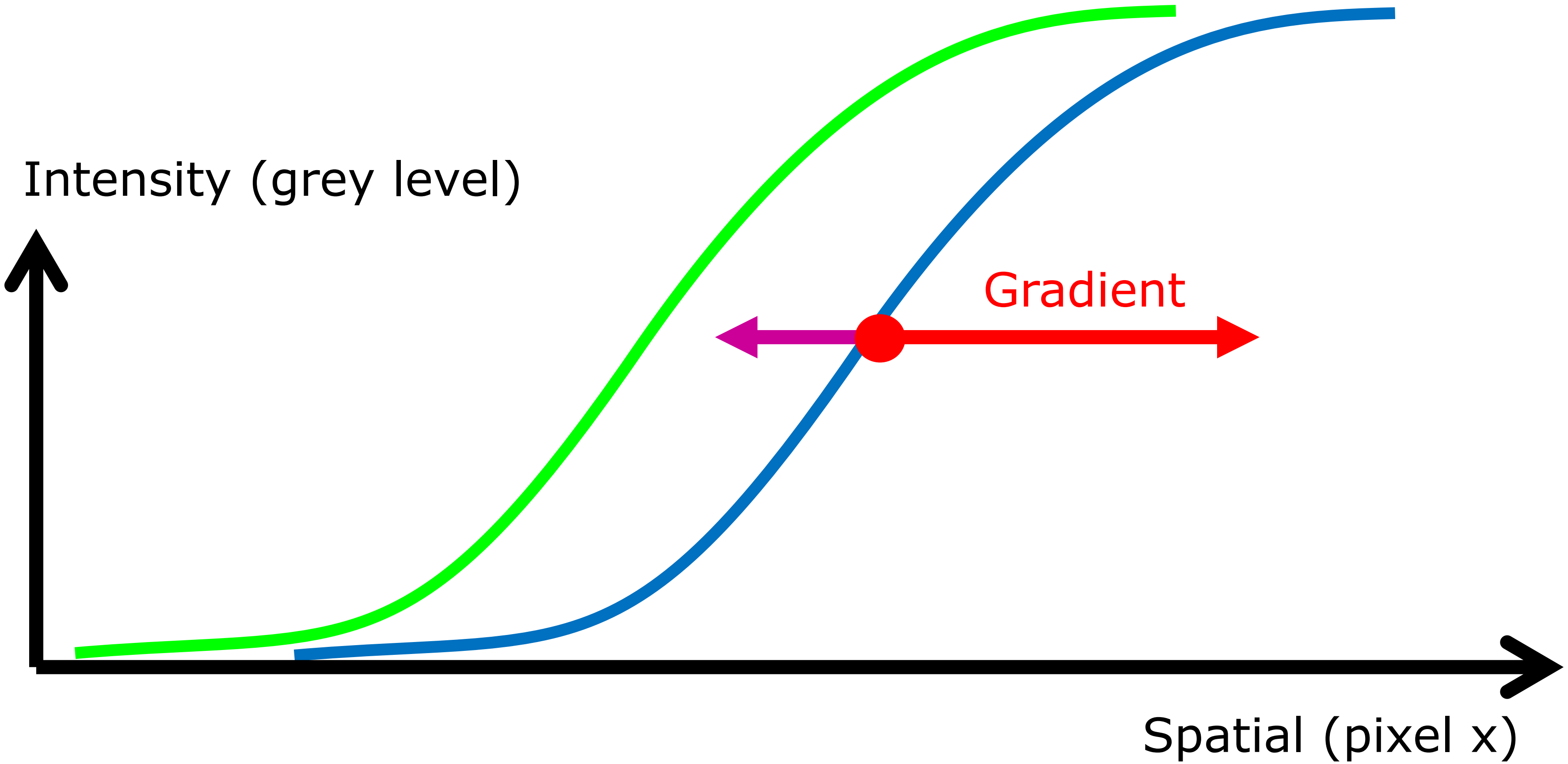
Explanation



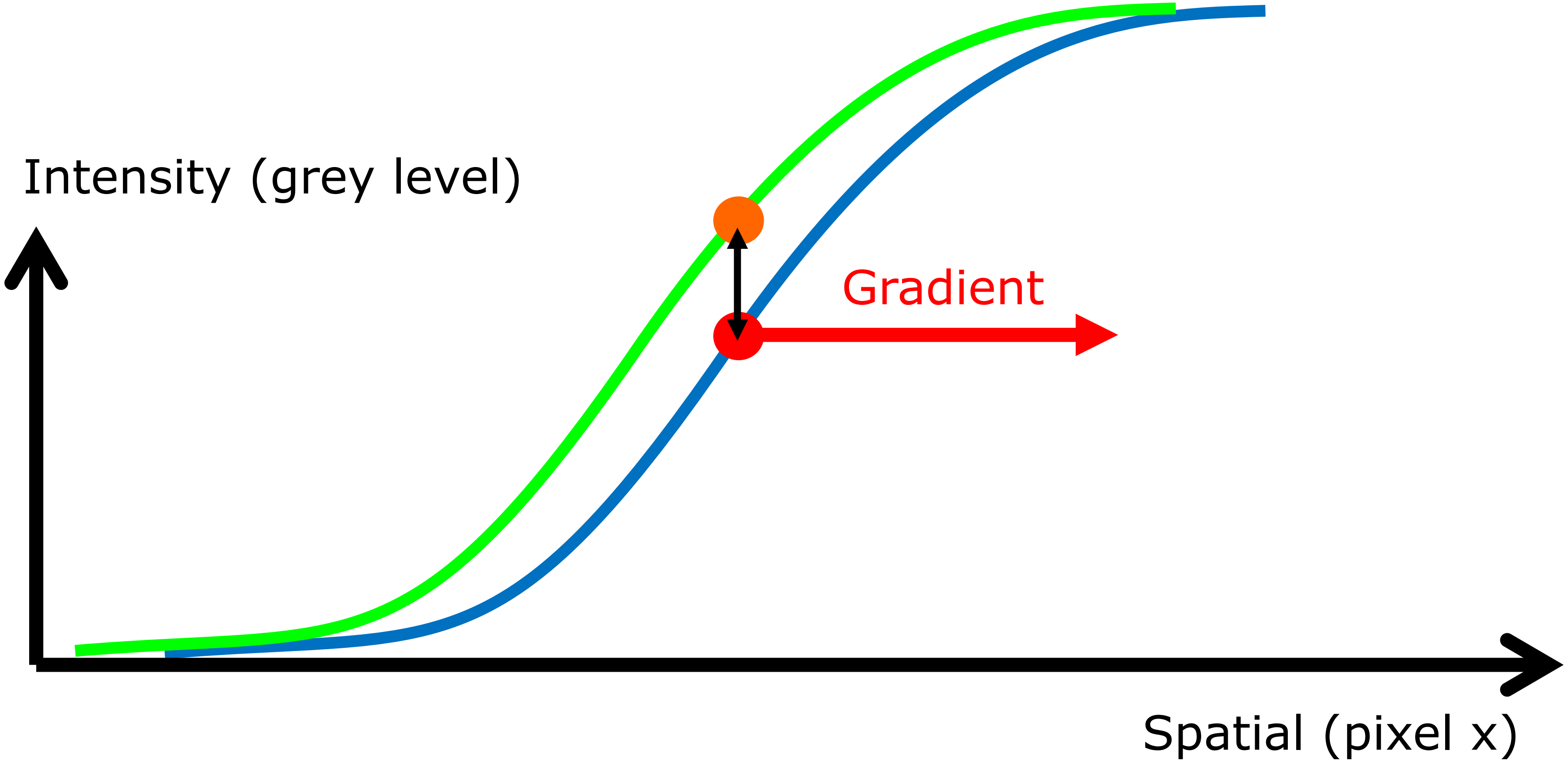
Explanation



Explanation



Explanation



Principle: step 2

- Regularize the DVF with a Gaussian filter (need parameter sigma)

- Possible to regularize:
  - The total displacement (previous + total)
  - The current displacement only (*fluid registration*)

$$\boldsymbol{u}_{i+1}(\boldsymbol{x}) = G_\sigma(\nabla D_{SSD}(\boldsymbol{x}, \boldsymbol{u}_i) \circ \boldsymbol{u}_i(\boldsymbol{x}))$$

$$G_\sigma(\boldsymbol{x}) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{\boldsymbol{x}^2}{2\sigma^2}}$$

Practical considerations

- Iterative algorithm $\nabla I_1(\boldsymbol{x})$

- Estimation of the image gradient
  - Only once
  - One 3D vector by pixel

- Displacement estimation at each pixel
  - One 3D vector by pixel for the current field $\boldsymbol{u}_i(\boldsymbol{x})$
  - One 3D vector by pixel for the current displacement $\nabla D_{SSD}(\boldsymbol{x}, \boldsymbol{u}_i)$

Practical considerations

3D Gaussian filter on the DVF

- Separable, **with 1D Gaussian filter**
- [Deriche 1993]
- Apply to dimensions 1,2,3 on all vector components: 9 loops

Stopping criteria

- Number of iterations (by experiment)
- DVF norm < threshold
- etc …

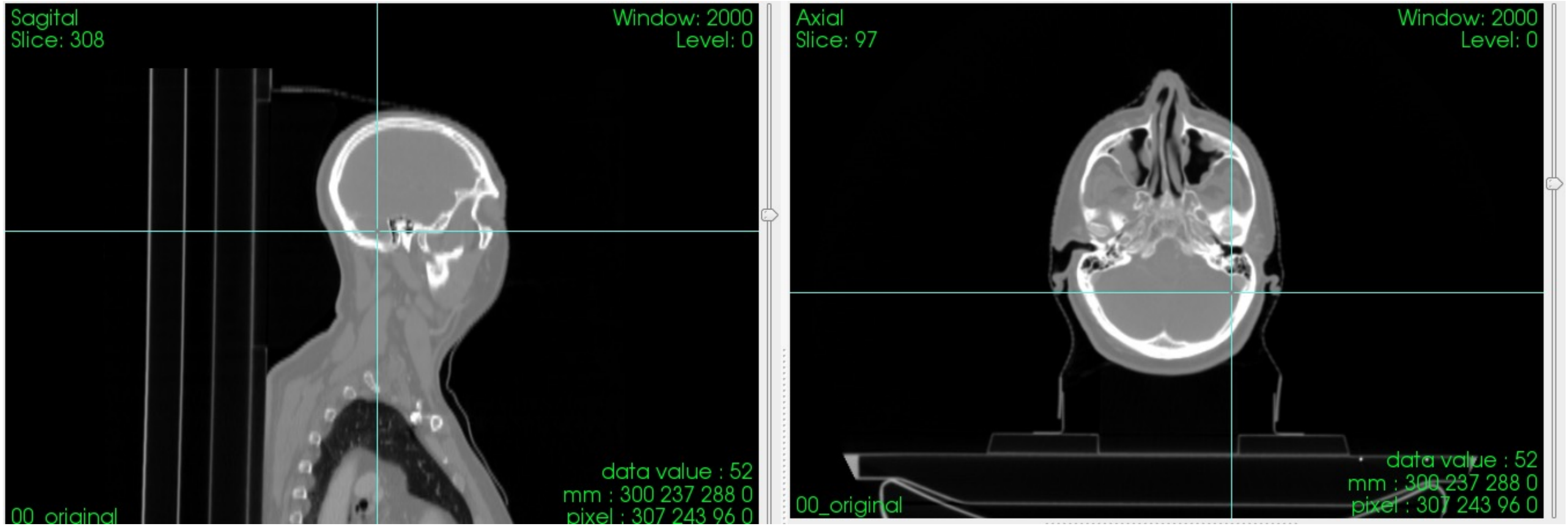
Interpolation of non integer coordinates

- Nearest neighbours
- Linear
- Other …

Practical considerations

Computing time linear to the number of pixels

« Crop » the images

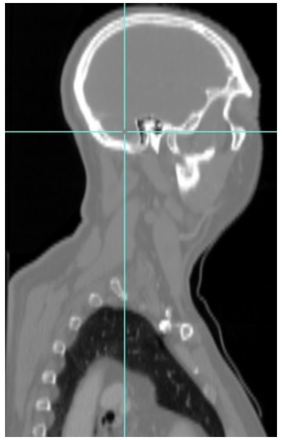


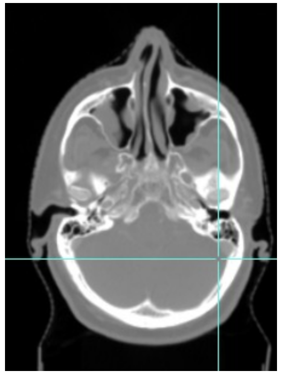
Practical considerations

Computing time linear to the number of pixels

« Crop » the images = 50% time gain (here) !

Can be automatized (segmentation)





Practical considerations

Computing time linear to the number of pixels

Images sub-sampling

- = increase the « spacing » (2mm pixel size instead of 1mm)
- In 3D, if divide by 2 : 8 times less pixels

Multi-scale strategy

Interpretations

[Thirion1998] relates Gaussian filtering to the diffusion of heat in homogeneous material, by analogy with the Maxwell 's demons.

[Cachier2004] This criterion was shown to be an approximation of a second order gradient descent of the SSD

[Bro-Nielsen1996] showed that such Gaussian filtering may be considered as an approximation of the linear elastic filter used in the viscous-fluid modelling.

Variants

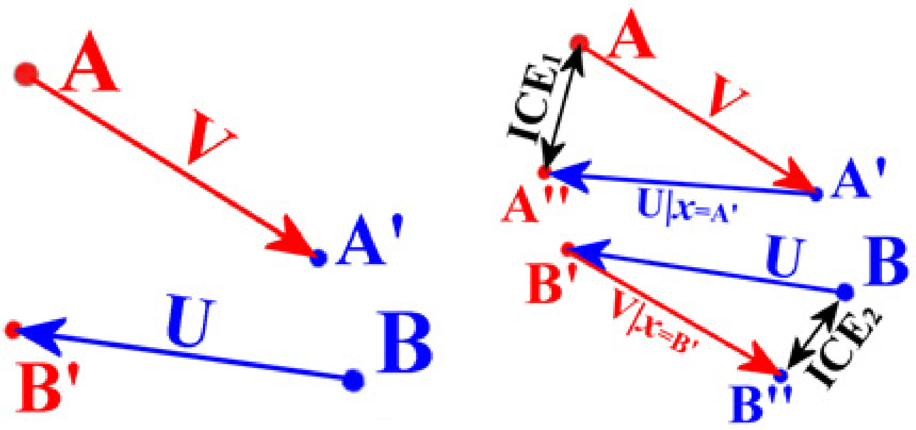
Symmetric Demons

[Wang2005]
H. Wang, L. Dong, J. O'Daniel, R. Mohan, AS. Garden, KK. Ang, DA. Kuban, M. Bonnen, JY. Chang, and R. Cheung. Validation of an accelerated 'demons' algorithm for deformable image registration in radiation therapy. Phys Med Biol, 50(12):2887-905, June 2005.

$$\vec{u} = (m - s) \times \left(\frac{\vec{\nabla} s}{|\overrightarrow{\nabla} s|^2 + \alpha^2 (s - m)^2} + \frac{\vec{\nabla} m}{|\overrightarrow{\nabla} m|^2 + \alpha^2 (s - m)^2} \right)$$

- Improve speed by 40% (longer, but fewer iteration)
- Maybe more robust

Inverse consistency error



(a) (b)

Figure 1. Illustration of asymmetric registration and inverse consistency error. Point A (in image *I*) and B (in image *J*) are matching points. *V* is computed by registering *I* to *J*. *U* is computed by registering image *J* to image *I*. (a) After imperfect asymmetric registrations, point A moves to point A′ and point B moves to point B′. (b) Using *U*, A′ will be moved to A″. Similarly, B″ is B′ moved by using *V*. The distance from A to A″, and from B to B″, are the inverse consistency errors.

Variants

Fast inverse consistent Demons

[Yang et al 2008]

Deshan Yang, Hua Li, Daniel A Low, Joseph O Deasy, and Issam El Naqa. A fast inverse consistent deformable image registration method based on symmetric optical flow computation. Phys Med Biol, 53(21):6143-6165, Nov 2008.

- The two images were symmetrically deformed toward the other until both deformed images are matched.
- This principle is called “consistent” because it insure implicitly that the inverse deformation field exist.
- The computation time is typically higher than conventional Demons, but lower than Symmetric Demons.
- Convergence speed seems to be improved by this version.

Variants

Diffeomorphic Demons

[Vercauteren et al 2007, 2009]
Tom Vercauteren, Xavier Pennec, Ezio Malis, Aymeric Perchant, and Nicholas Ayache. Insight into efficient image registration techniques and the demons algorithm. Inf Process Med Imaging, 20:495-506, 2007.

- Modification to constrain the deformation to be a *diffeomorphism*
- *Diffeomorphism*: that is a continuous, one-to-one, onto, and differentiable mapping.
- Such kind of deformation maintains the topology and guarantees that connected regions of an image remain connected
- This approach leads to similar results in term of accuracy than the ones given by the initial approach, but with smoother transformation.

Conclusion

« Demons » algorithm

- Simple, very used, efficient
- Assumption on pixel intensity conservation (SSD)
- Smooth transformation but non necessarily physically plausible
- GPU implementation also available
- Still studied

Tiny poll …

https://www.wooclap.com/SAXELC

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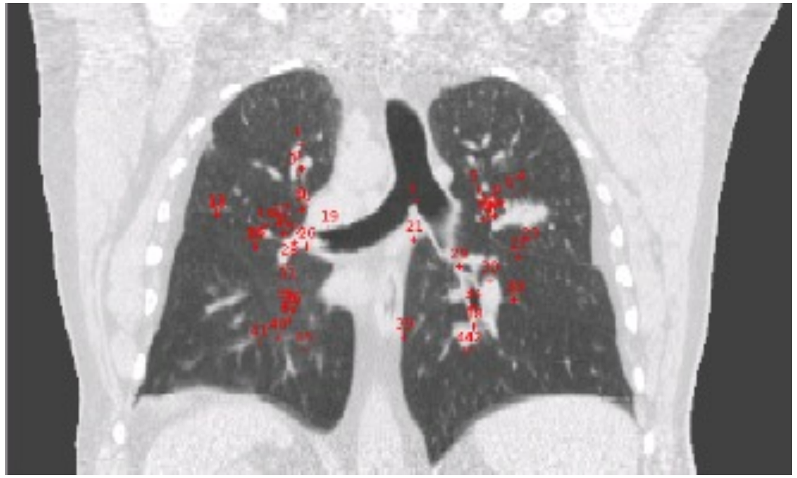
Evaluation

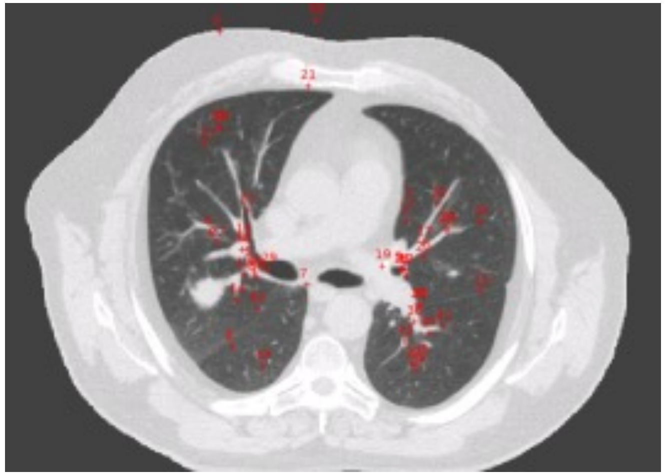
How to evaluate the result of DIR algorithm ?

Evaluation

How to evaluate ?

- No gold-standard
- Use of phantom: real or numeric
- Consistency (symmetry, negative Jacobian)
- Use of manual anatomical landmarks,
  - Distances between reference and deformed landmarks
  - **TRE** = Target Registration Error
- Overlap of segmented structures (**DICE** coefficient)

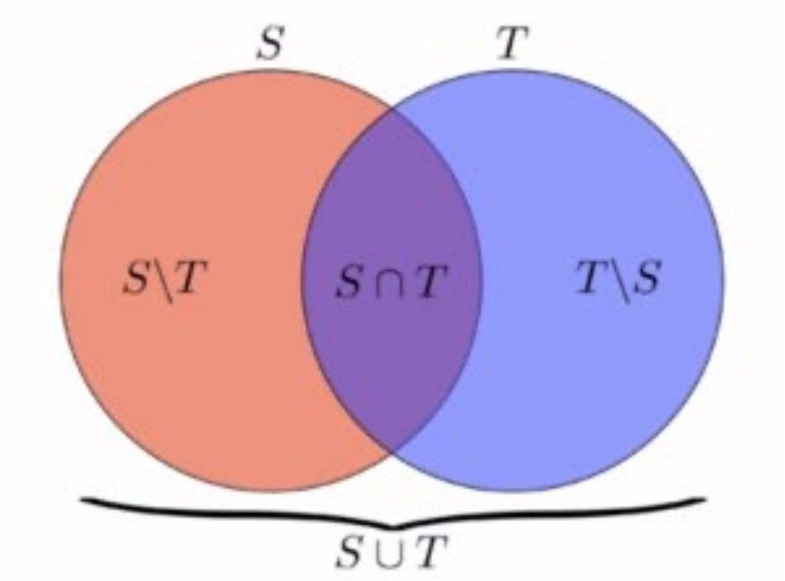




Dice Similarity Coefficient (DSC)

Quantifier le chevauchement (overlap) entre deux structures

$$DSC(S,T)=\frac{2|S\cap T|}{|S|+|T|}$$



Index de Jacquard

$$JSC(S,T)=\frac{|S\cap T|}{|S\cup T|}$$

Evaluation

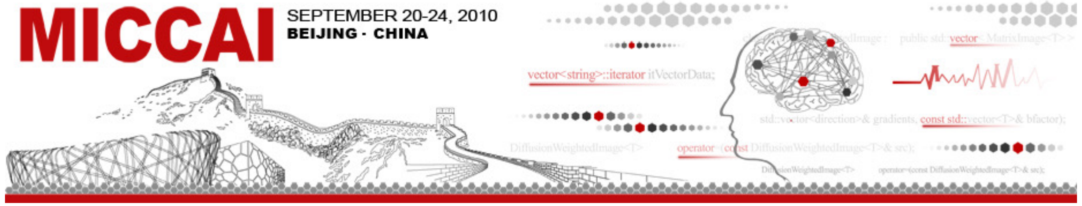
Examples:

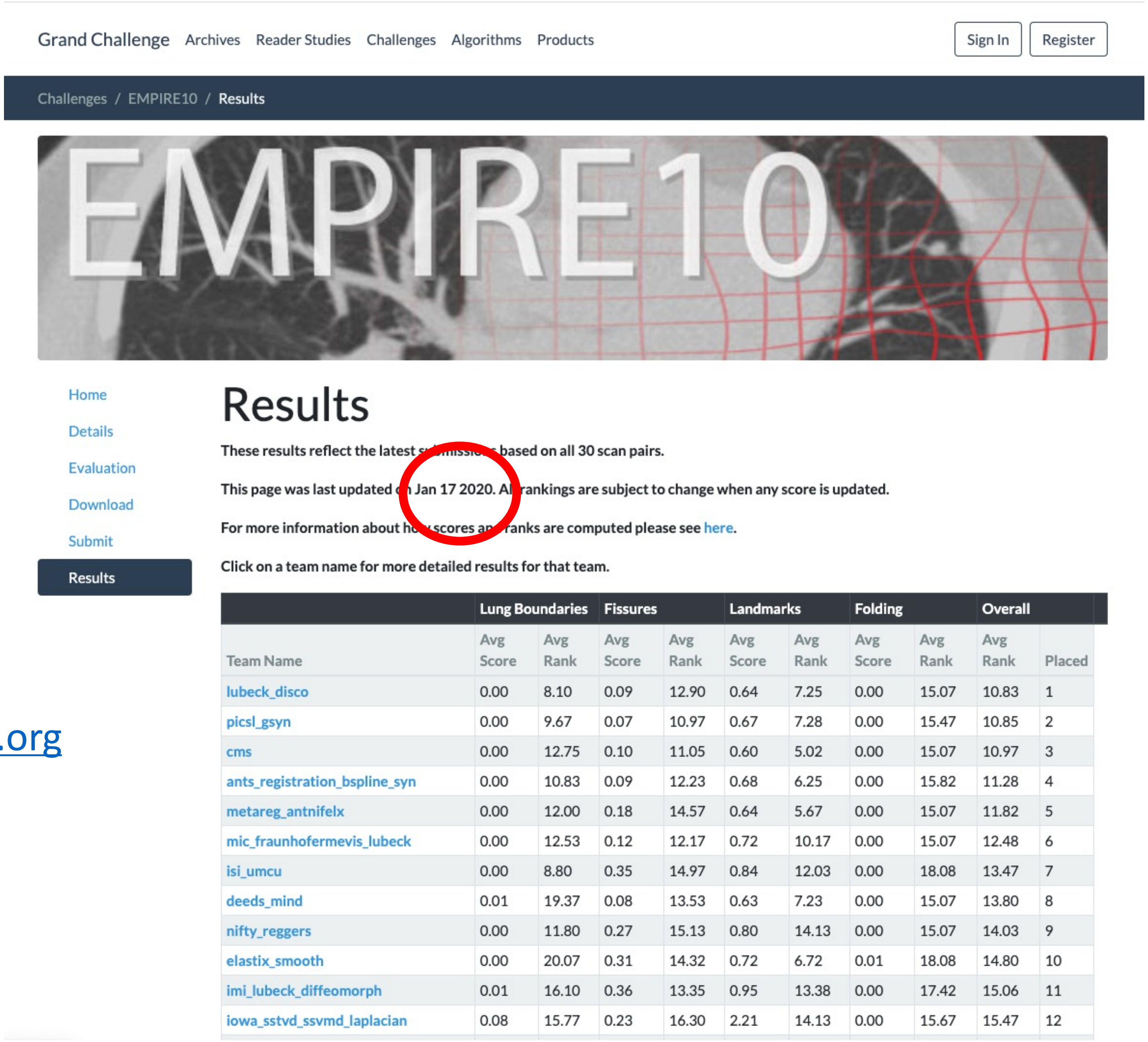
[Sarrut et al. IEEE TMI 2007] [Brock et al IJROBP 2010] [Murphy et al IEEE TMI 2011]

“EMPIRE “challenge:

Evaluation of Methods for Pulmonary Image Registration

- 20 thorax inhale/exhale pairs of images
- 34 teams worldwide
- TRE error : ~10 first <1 mm and ~20 first <2mm
- (we were 1.5mm, 14/34)





Results

These results reflect the latest submissions based on all 30 scan pairs.

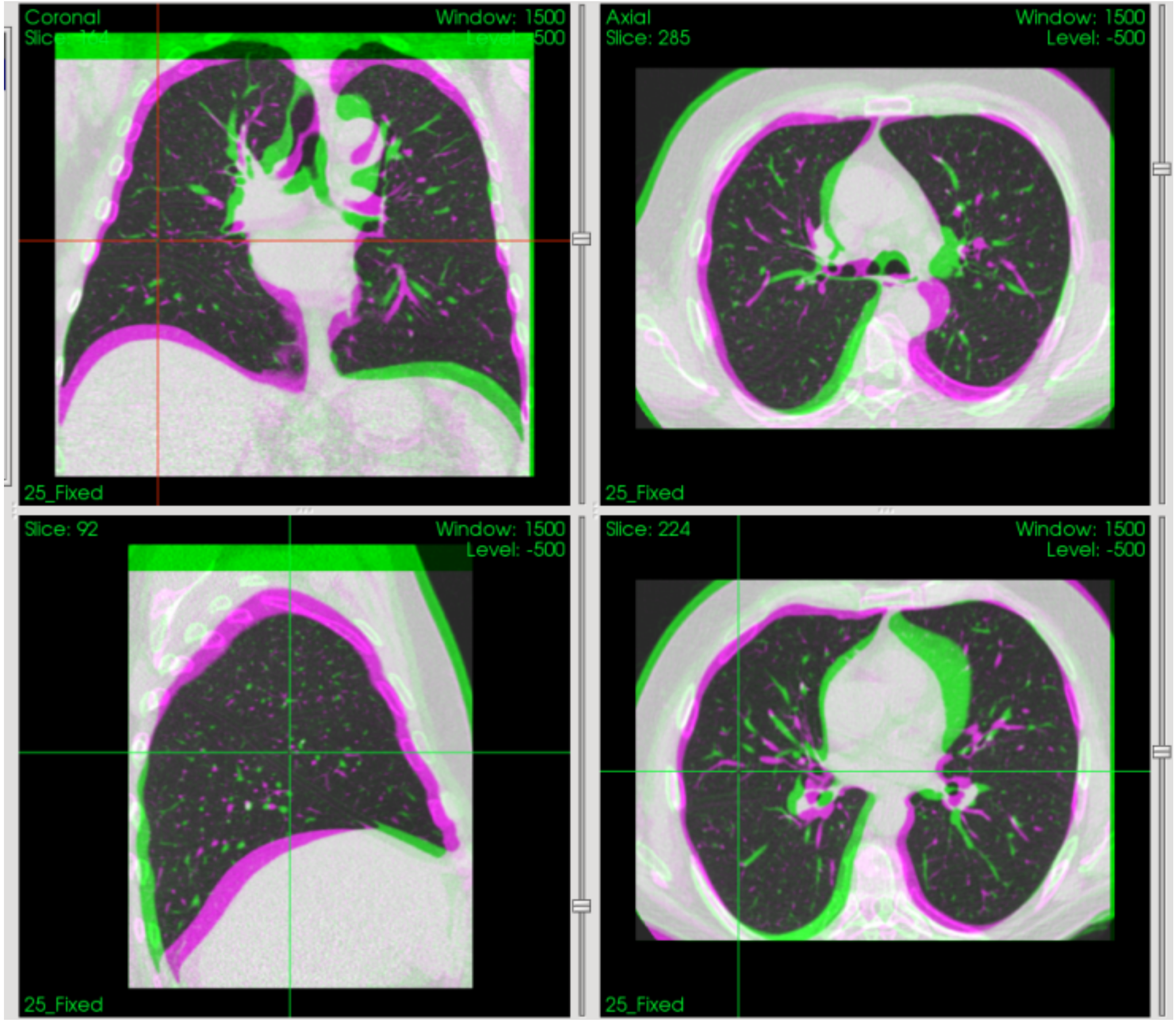
This page was last updated on Jan 17 2020. All rankings are subject to change when any score is updated.

For more information about how scores and ranks are computed please see here.

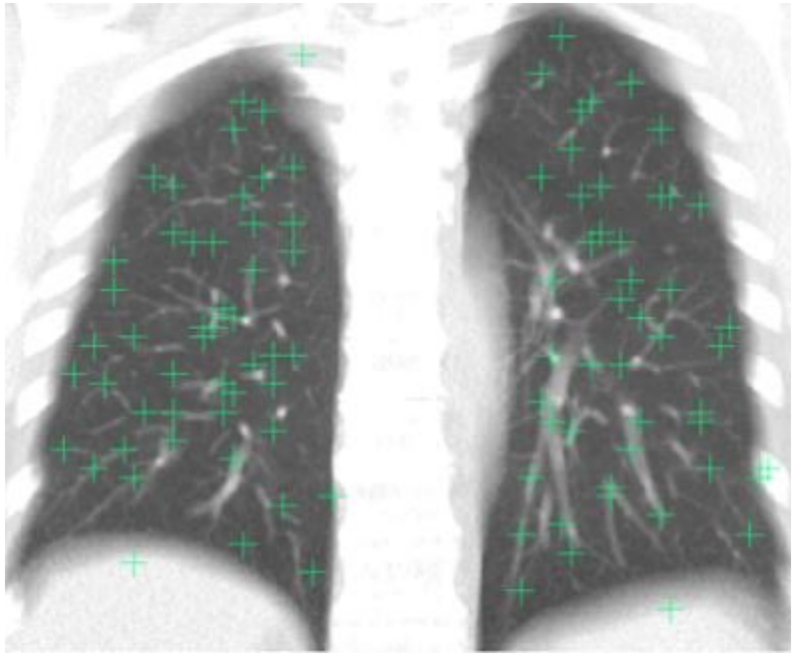
Click on a team name for more detailed results for that team.

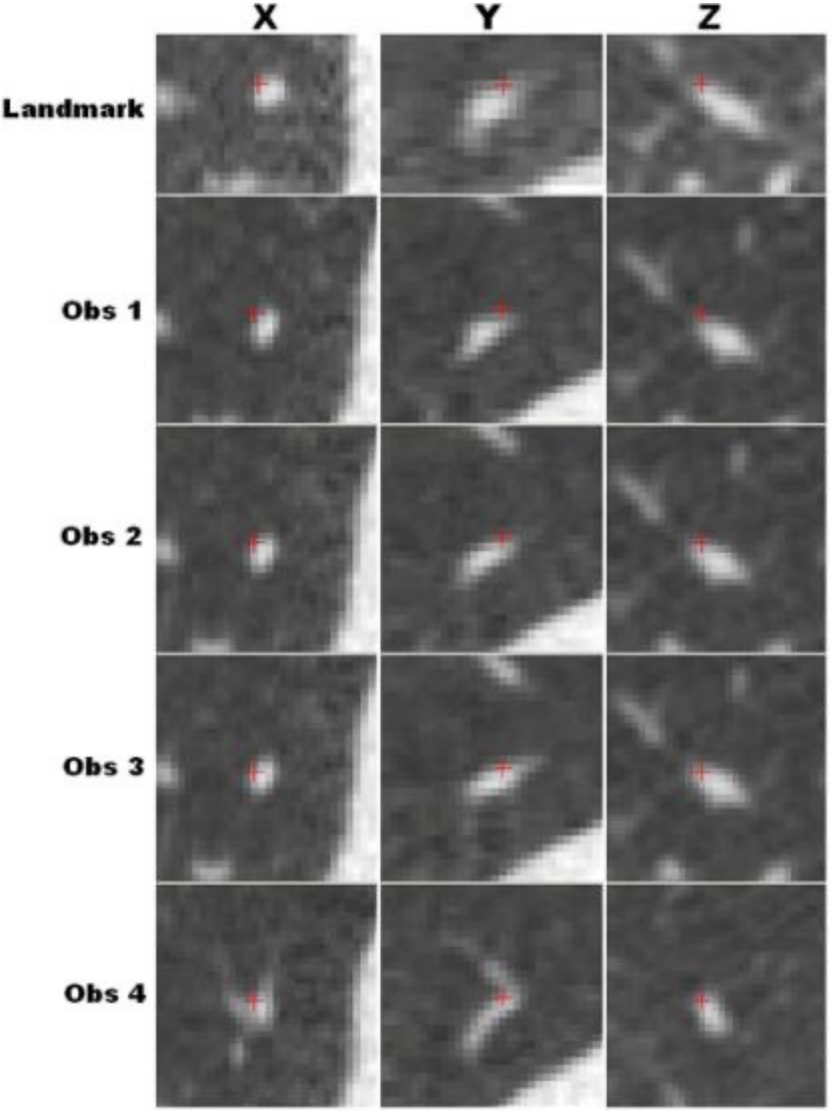
	Lung Boundaries		Fissures		Landmarks		Folding		Overall	
Team Name	Avg Score	Avg Rank	Avg Score	Avg Rank	Avg Score	Avg Rank	Avg Score	Avg Rank	Avg Rank	Placed
lubeck_disco	0.00	8.10	0.09	12.90	0.64	7.25	0.00	15.07	10.83	1
picsl_gsyn	0.00	9.67	0.07	10.97	0.67	7.28	0.00	15.47	10.85	2
cms	0.00	12.75	0.10	11.05	0.60	5.02	0.00	15.07	10.97	3
ants_registration_bspline_syn	0.00	10.83	0.09	12.23	0.68	6.25	0.00	15.82	11.28	4
metareg_antnifelx	0.00	12.00	0.18	14.57	0.64	5.67	0.00	15.07	11.82	5
mic_fraunhofermevis_lubeck	0.00	12.53	0.12	12.17	0.72	10.17	0.00	15.07	12.48	6
isi_umcu	0.00	8.80	0.35	14.97	0.84	12.03	0.00	18.08	13.47	7
deeds_mind	0.01	19.37	0.08	13.53	0.63	7.23	0.00	15.07	13.80	8
nifty_reggers	0.00	11.80	0.27	15.13	0.80	14.13	0.00	15.07	14.03	9
elastix_smooth	0.00	20.07	0.31	14.32	0.72	6.72	0.01	18.08	14.80	10
imi_lubeck_diffeomorph	0.01	16.10	0.36	13.35	0.95	13.38	0.00	17.42	15.06	11
iowa_sstvd_ssvmd_laplacian	0.08	15.77	0.23	16.30	2.21	14.13	0.00	15.67	15.47	12

https://empire10.grand-challenge.org


Coronal
Slice: 164
Window: 1500
Level: -500
25_Fixed
Axial
Slice: 285
Window: 1500
Level: -500
25_Fixed
Slice: 92
Window: 1500
Level: -500
25_Fixed
Slice: 224
Window: 1500
Level: -500
25_Fixed

EMPIRE





Evaluation - conclusion

Evaluation with TRE or structures overlap : « **offline** »

- Time consuming
- Not perfect (what happens in areas within landmarks ?)

If DIR is proposed in clinic, how to evaluate « **online** » ?