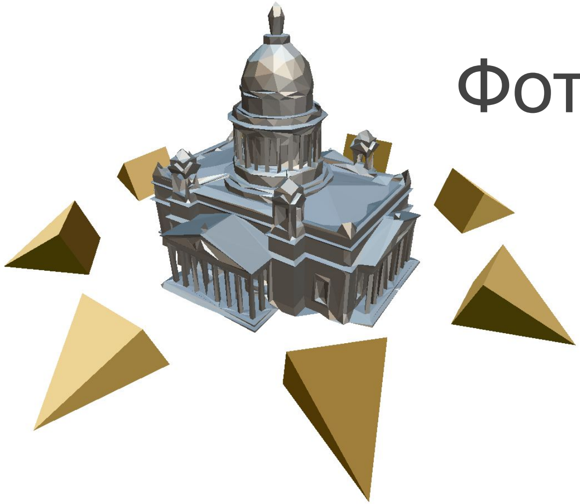
Введение в фотограмметрию
3D модель из карт глубины



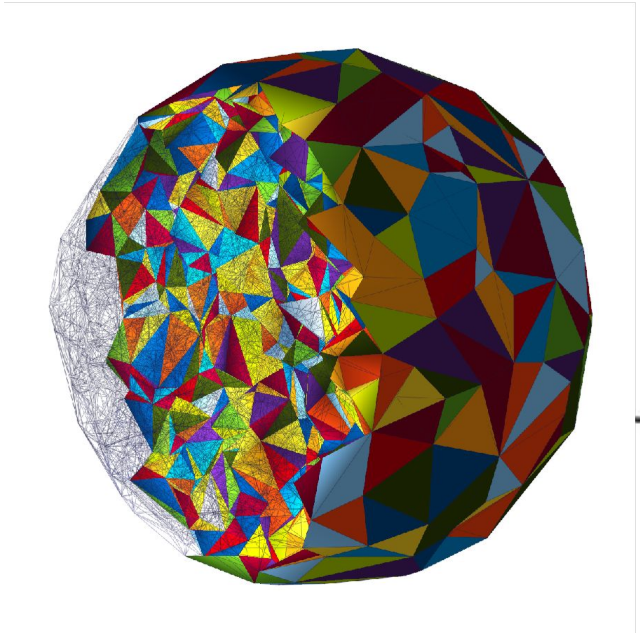
Фотограмметрия. Лекция 17

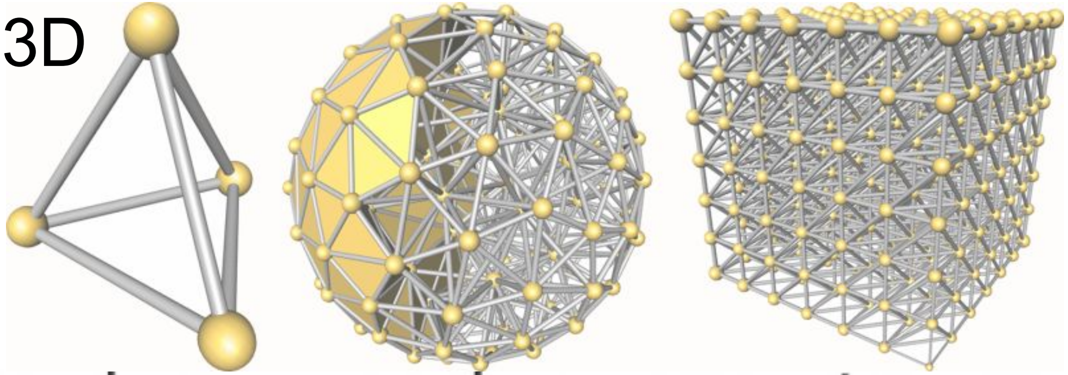
- **3D реконструкция через триангуляцию Делоне + минимальный разрез**
- **Реконструкция слабых поверхностей**

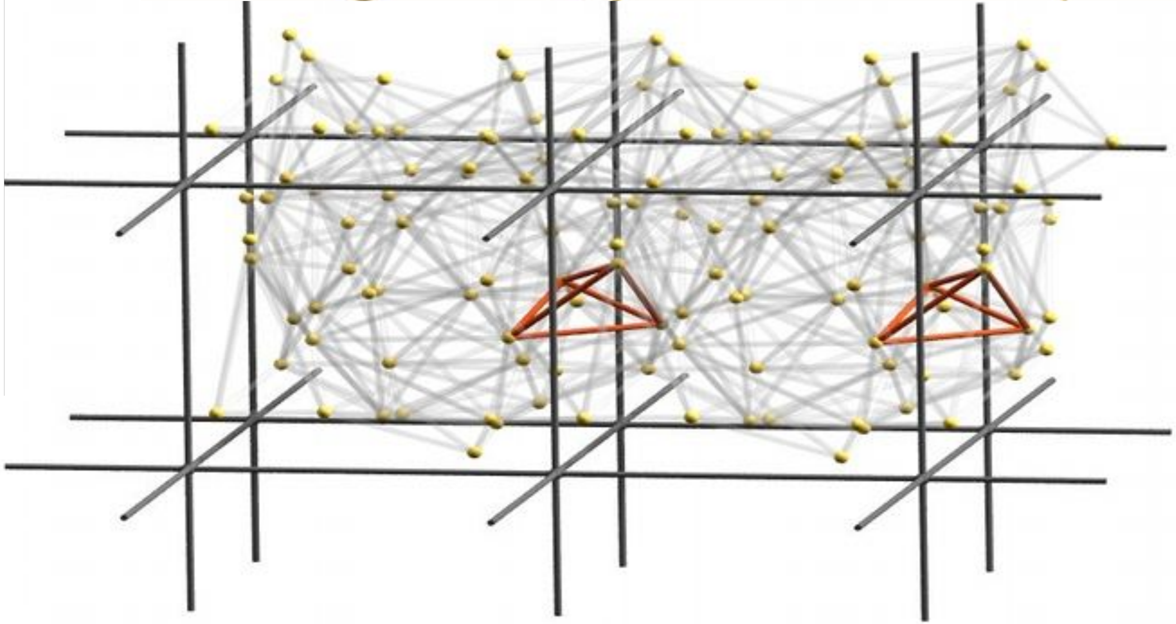
Полярный Николай

polarnick239@gmail.com

Триангуляция Делоне в 3D



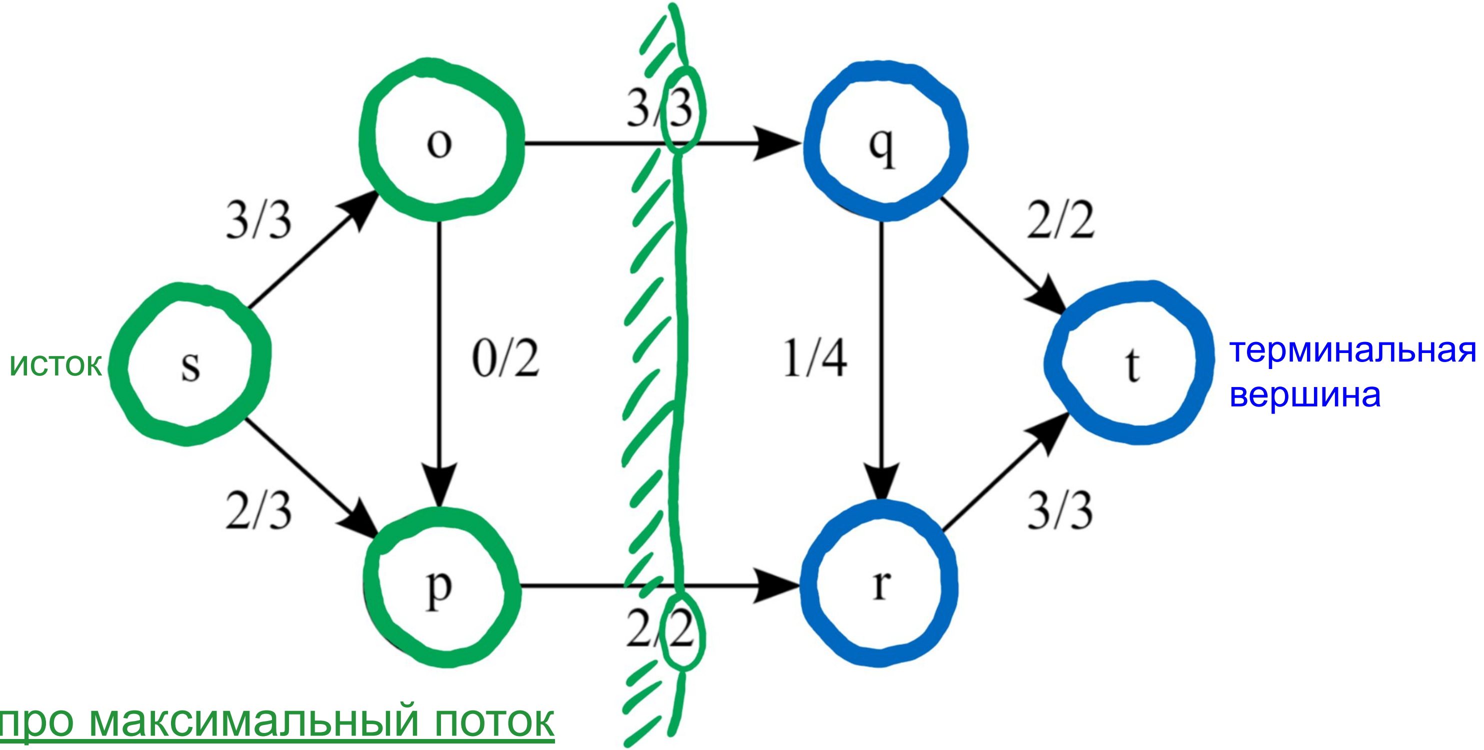




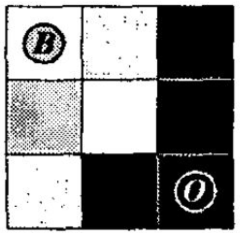
[CGAL: 3D triangulation]

Минимальный разрез в графе (Graph **Min-Cut**)

Есть ориентированный граф, на ребрах указана максимальная пропускная способность. Найти **минимальный разрез** - разбиение вершин на **два множества** (мощность разреза - пропускной способности ребер между множествами).

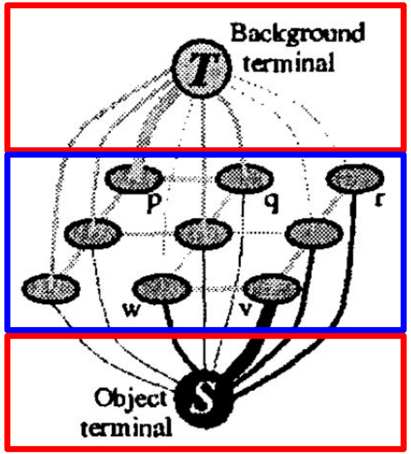


Статья про максимальный поток



(a) Image with seeds.

$\Downarrow$

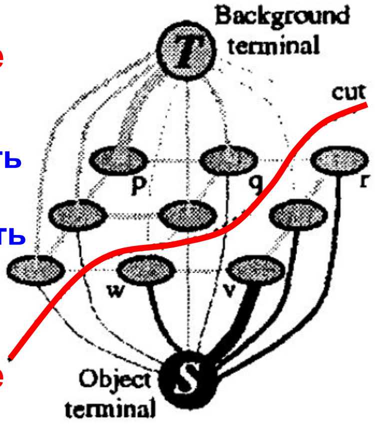


Данные

Гладкость
+ $\Rightarrow$
похожесть
цветов

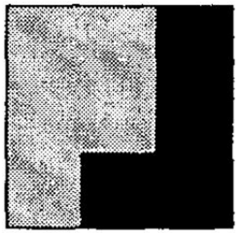
Данные

(b) Graph.



(c) Cut.

$\Uparrow$

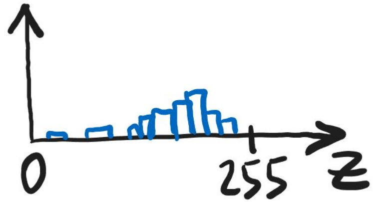


(d) Segmentation results.

Figure 1. A simple 2D segmentation example for a 3×3 image. The seeds are $\mathcal{O} = \{v\}$ and $\mathcal{B} = \{p\}$. The cost of each edge is reflected by the edge's thickness. The regional term (2) and hard constraints (4,5) define the costs of t-links. The boundary term (3) defines the costs of n-links. Inexpensive edges are attractive choices for the minimum cost cut.

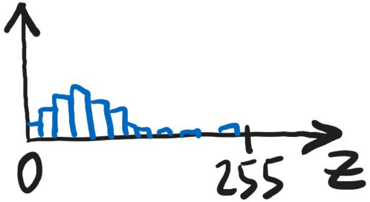
foreground

$h(z; \alpha = 1)$:



background

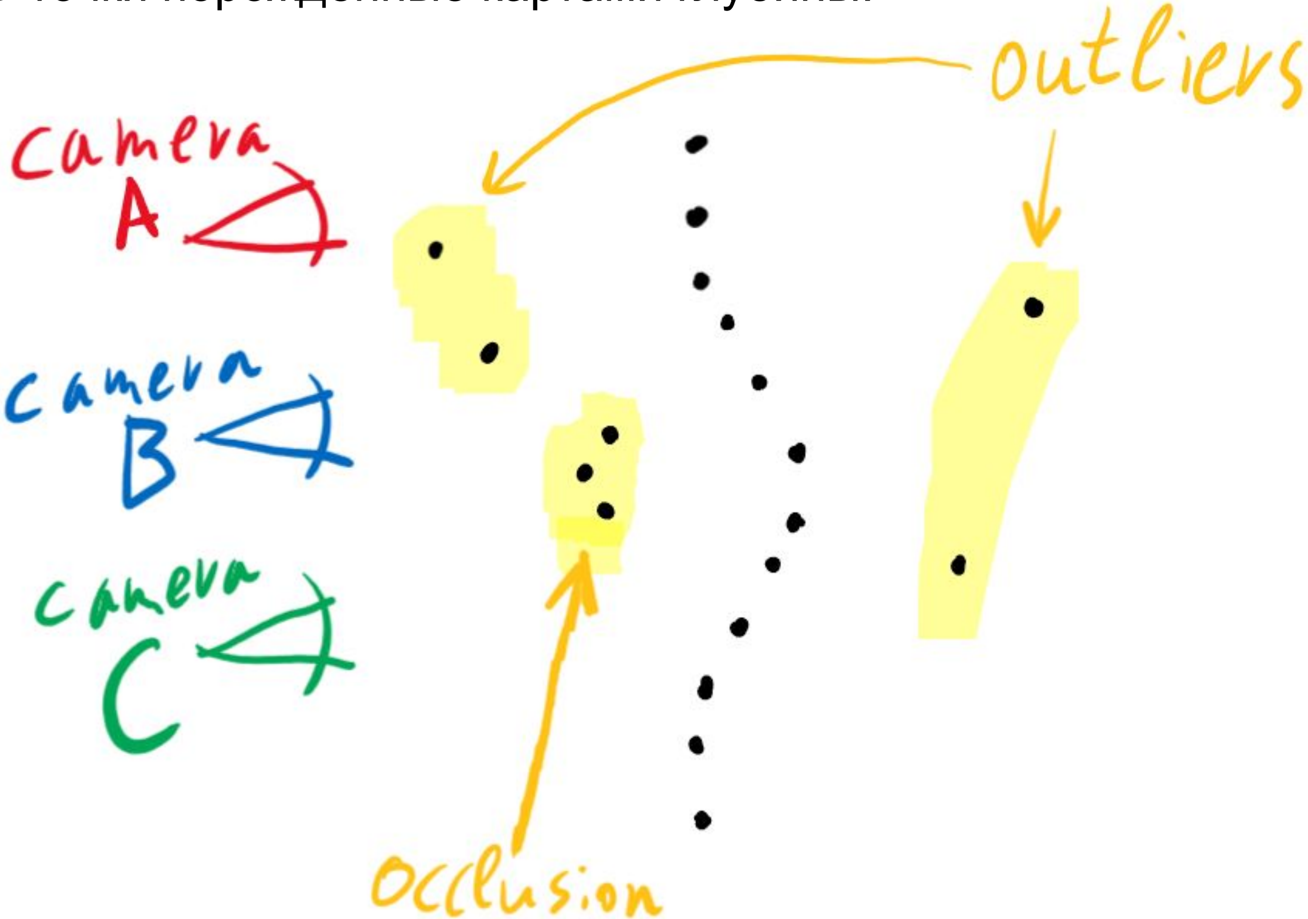
$h(z; \alpha = 0)$:



Interactive graph cuts for optimal boundary and region segmentation of objects in N-D images, Boykov et. al., 2001

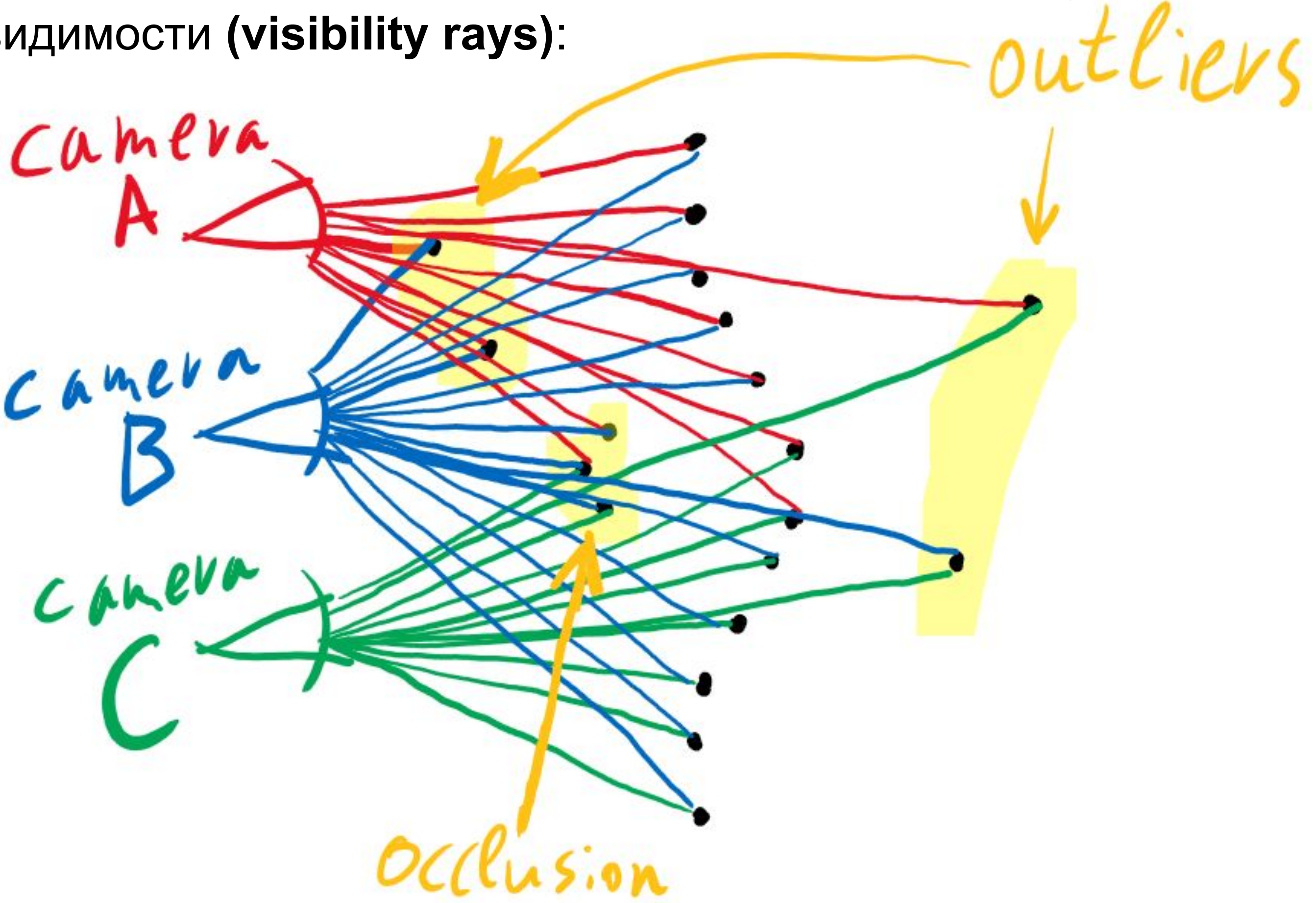
Алгоритм построения 3D модели

На вход даны 3D точки порожденные картами глубины:



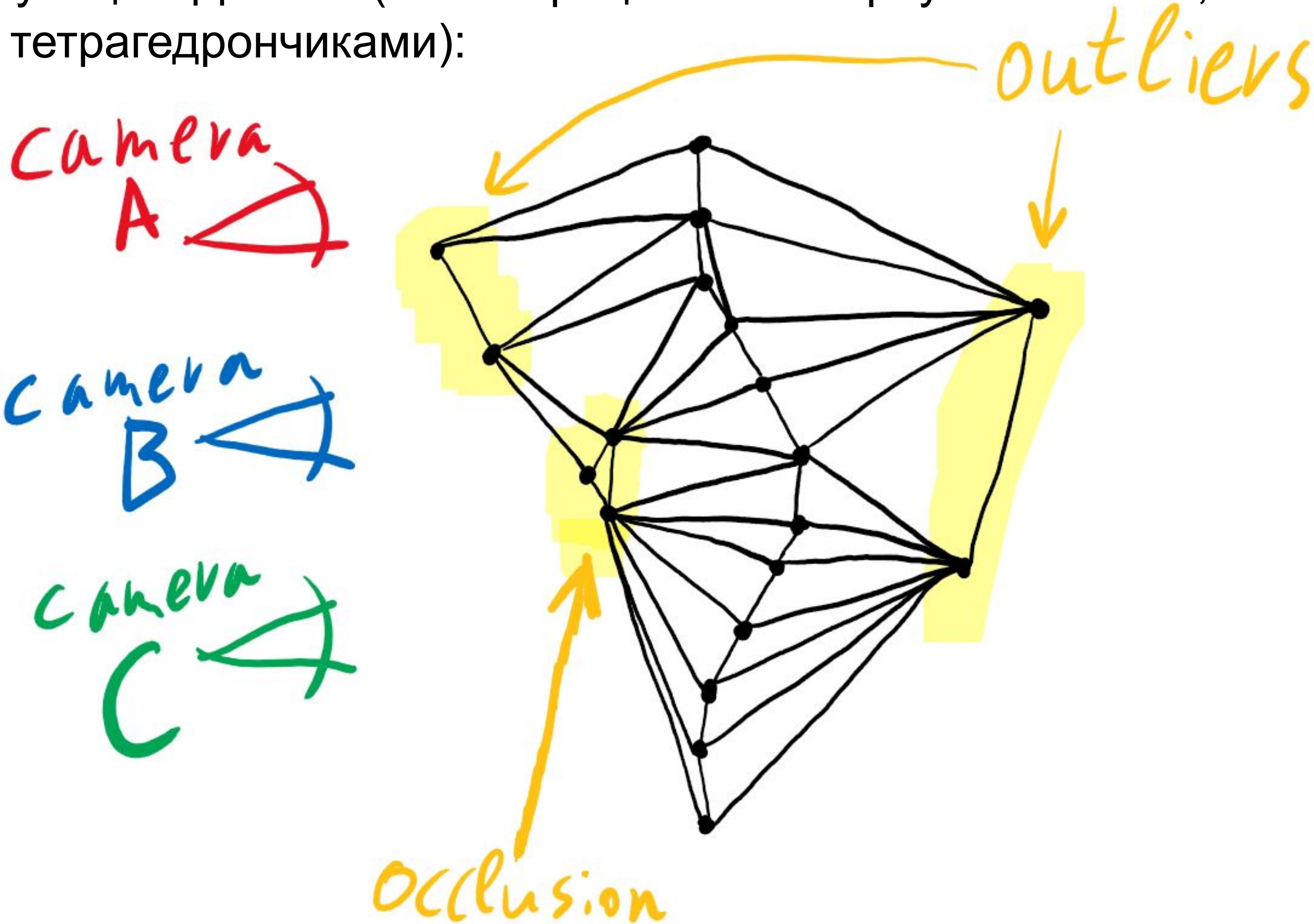
Алгоритм построения 3D модели

У каждой точки есть множество камер которые ее породили, т.е. у нас есть пучки отрезков видимости **(visibility rays)**:



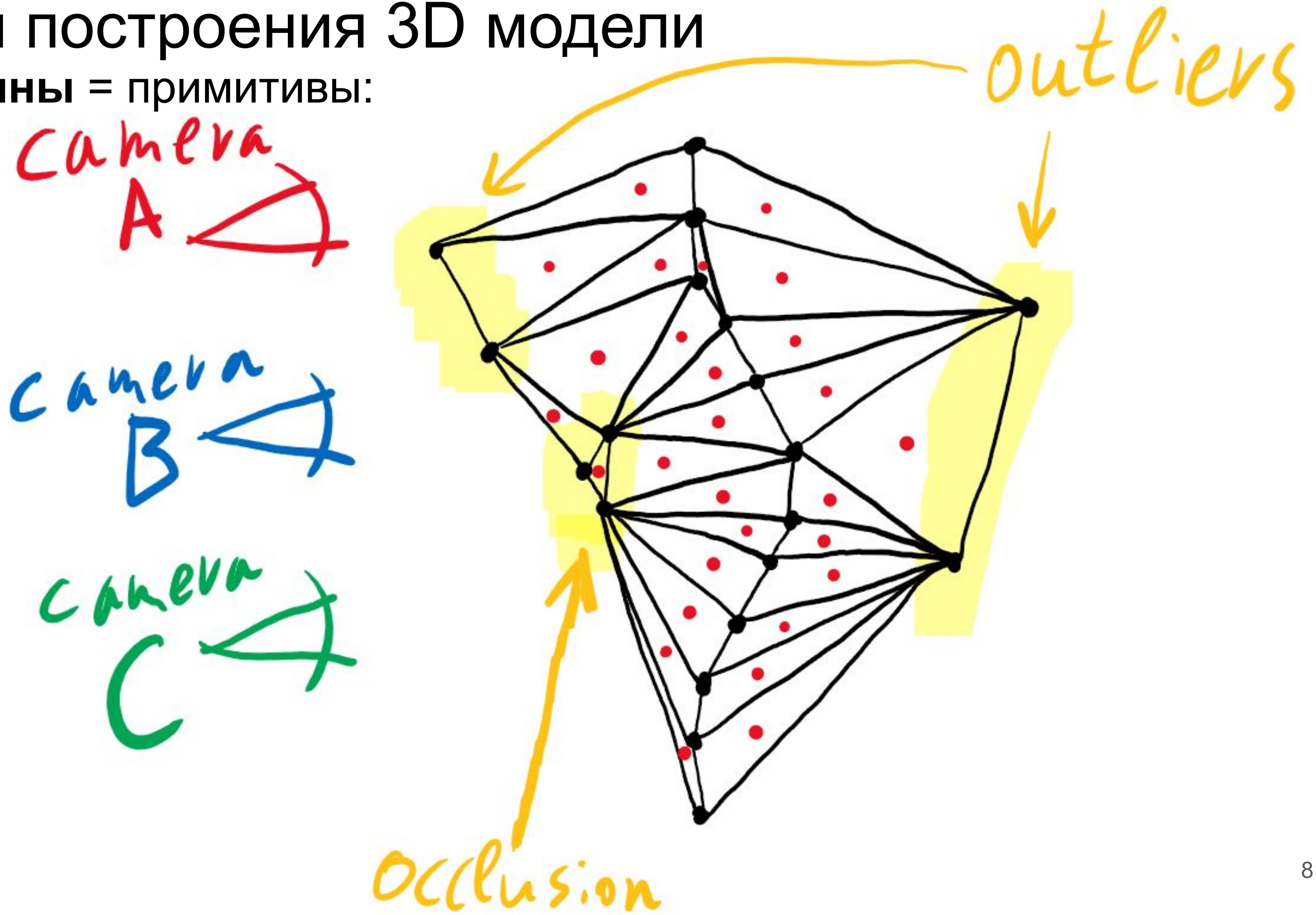
Алгоритм построения 3D модели

Построим триангуляцию Делоне (иллюстрация в 2D с треугольниками, но нас интересует 3D с тетрагедрончиками):



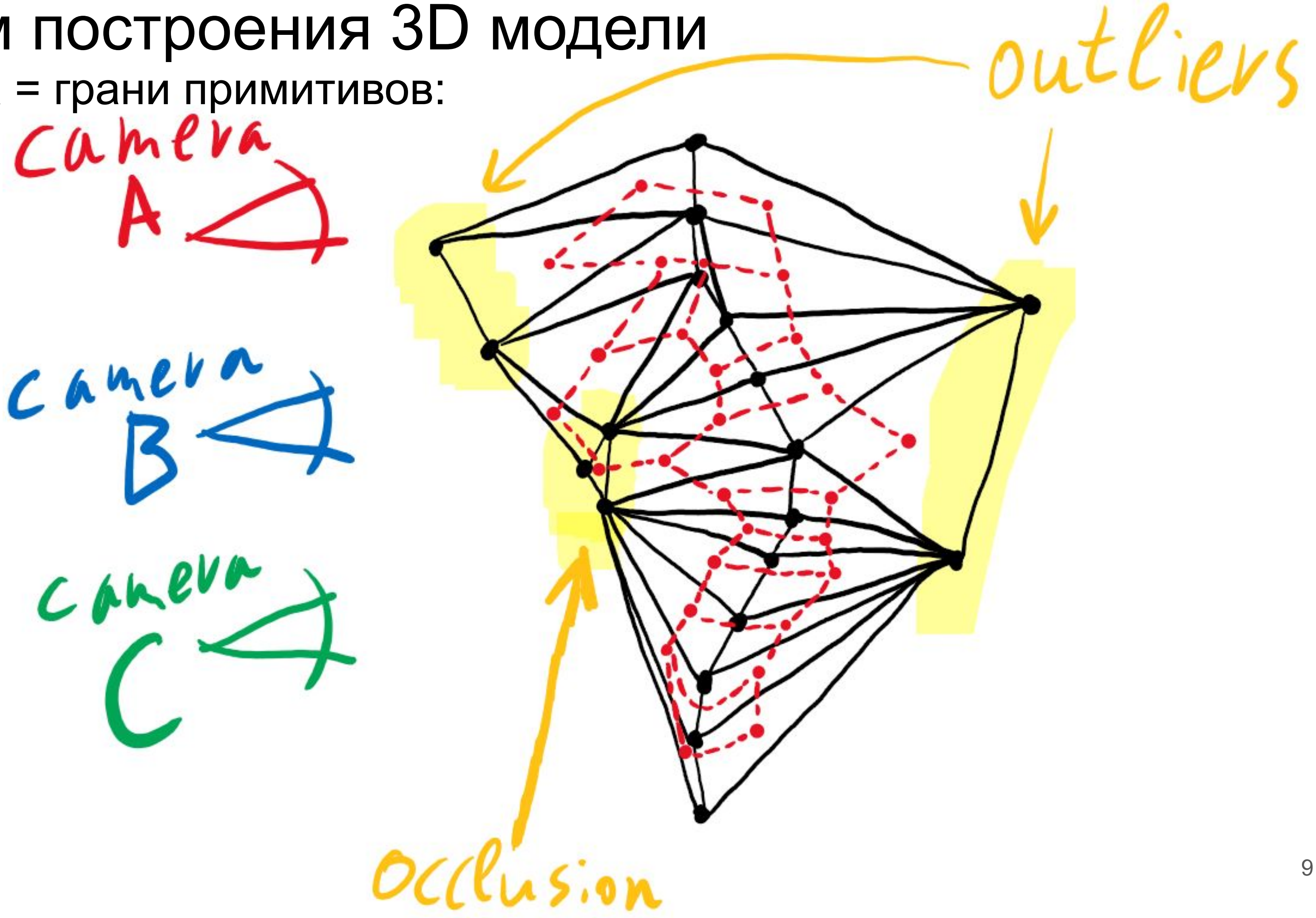
Алгоритм построения 3D модели

Граф: **вершины** = примитивы:



Алгоритм построения 3D модели

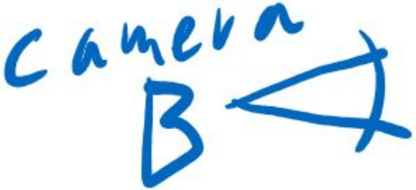
Граф: **ребра** = грани примитивов:

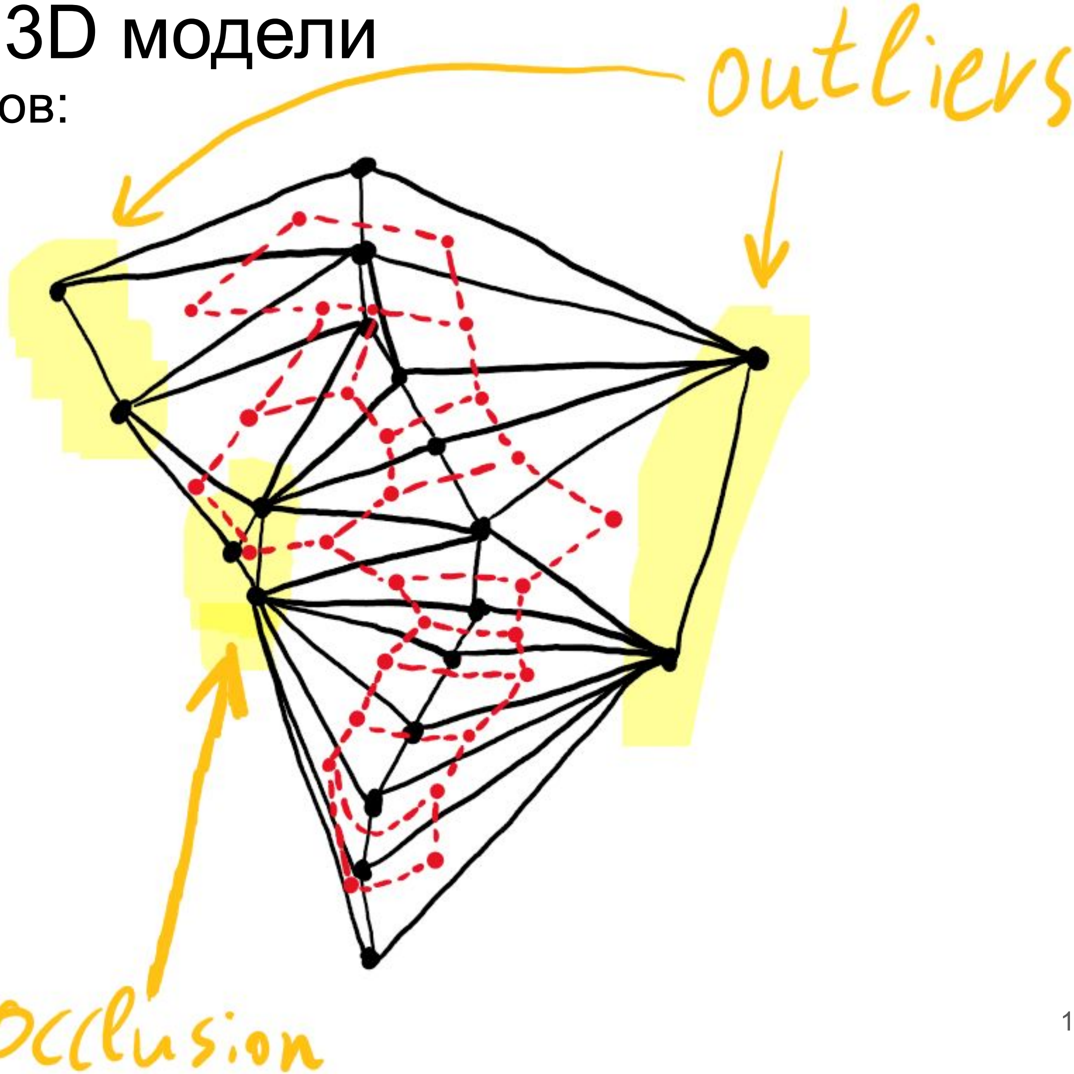


Алгоритм построения 3D модели

Граф: **ребра** = грани примитивов:

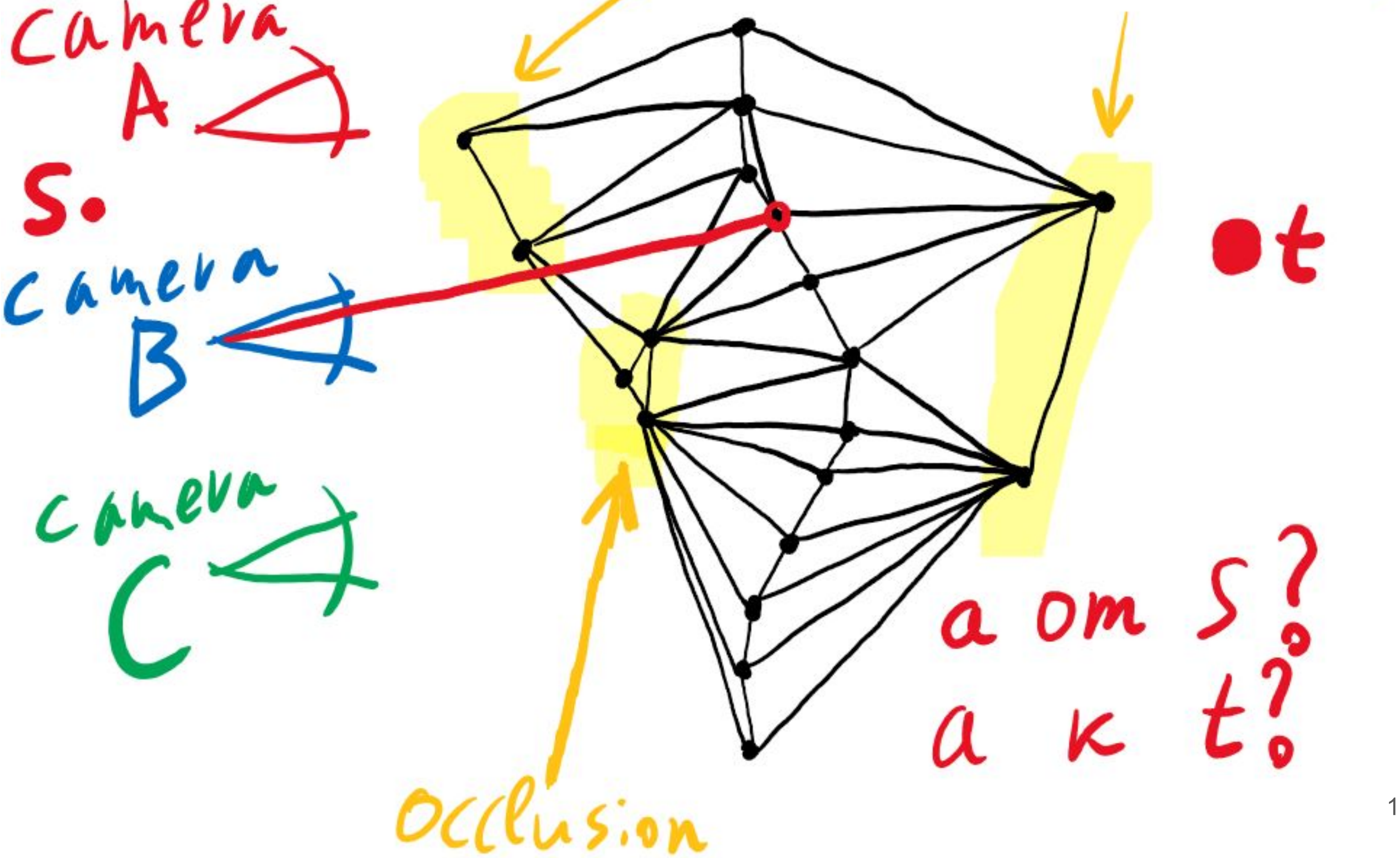
Но где исток ***s*** и сток ***t***?





Алгоритм построения 3D модели

Какие **пропускные способности**?



Алгоритм построения 3D модели

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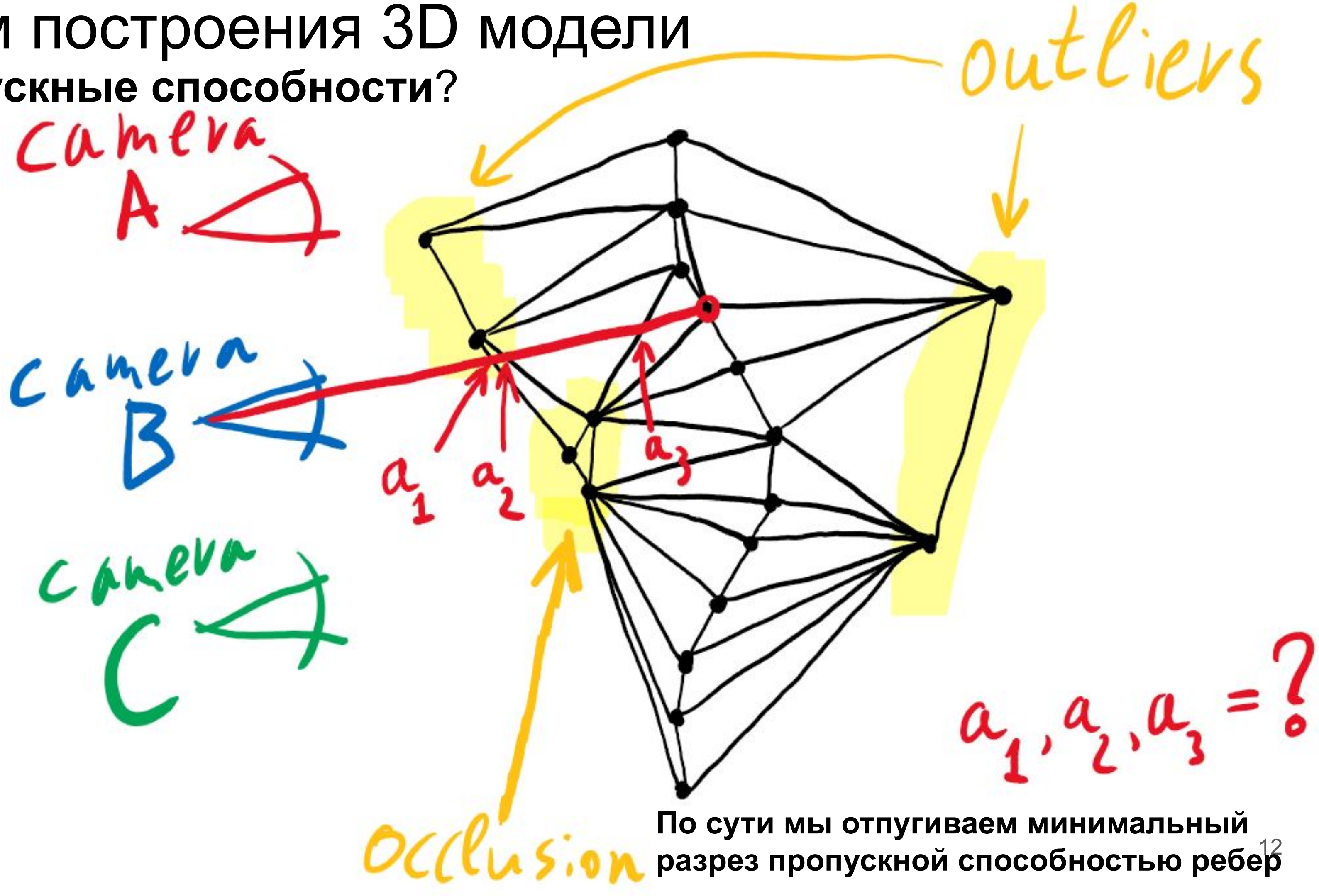
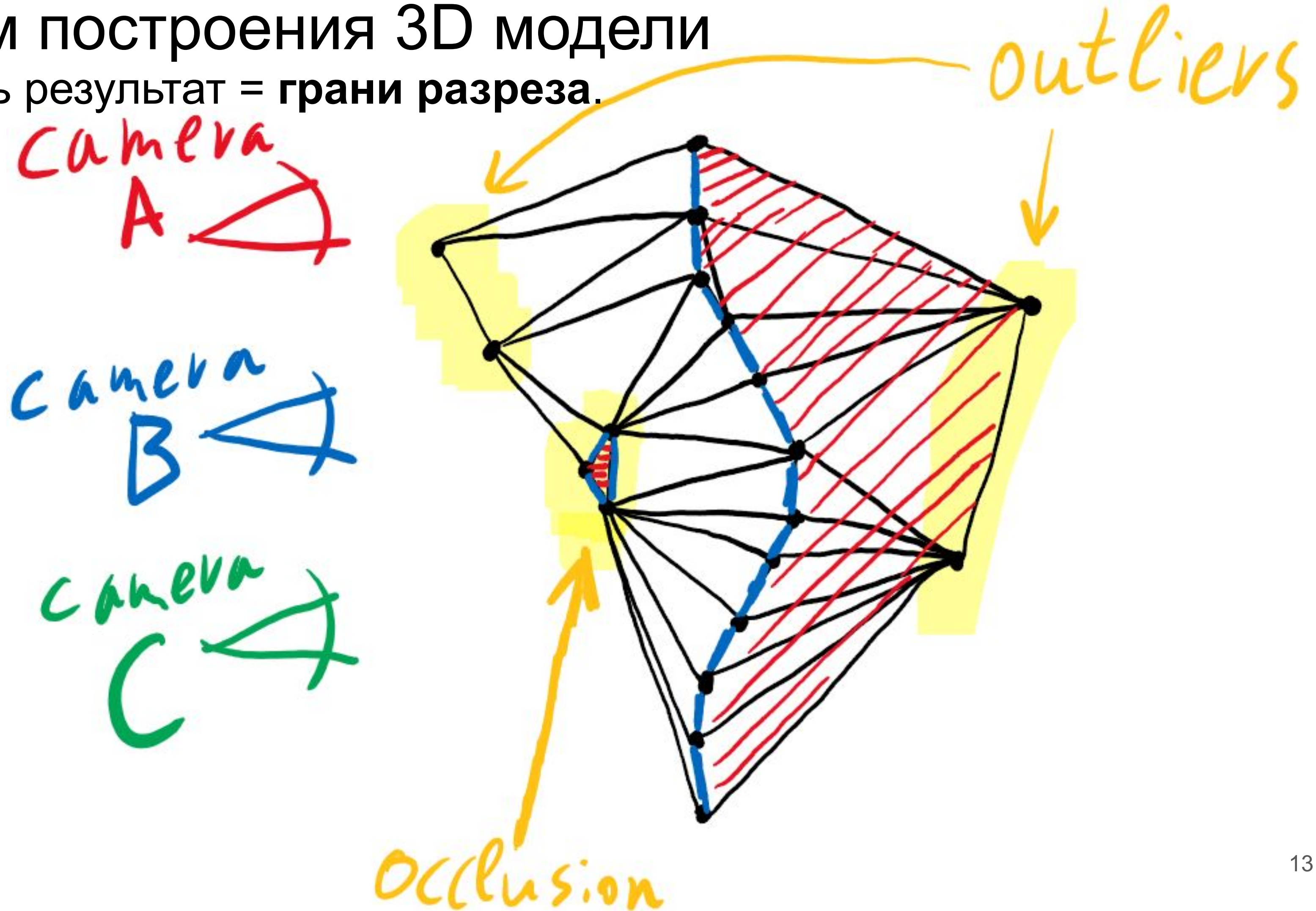


По сути мы отпугиваем минимальный разрез пропускной способностью ребер

Алгоритм построения 3D модели

Поверхность результат = **грани разреза**.



1) [Efficient Multi-View Reconstruction of Large-Scale Scenes using Interest Points, Delaunay Triangulation and Graph Cuts, Labatut et. al., 2007]

1) Изначальные точки - ключевые SIFT-точки со списком проекций
2) Точки объединяются если максимальная ошибка репроекции мала

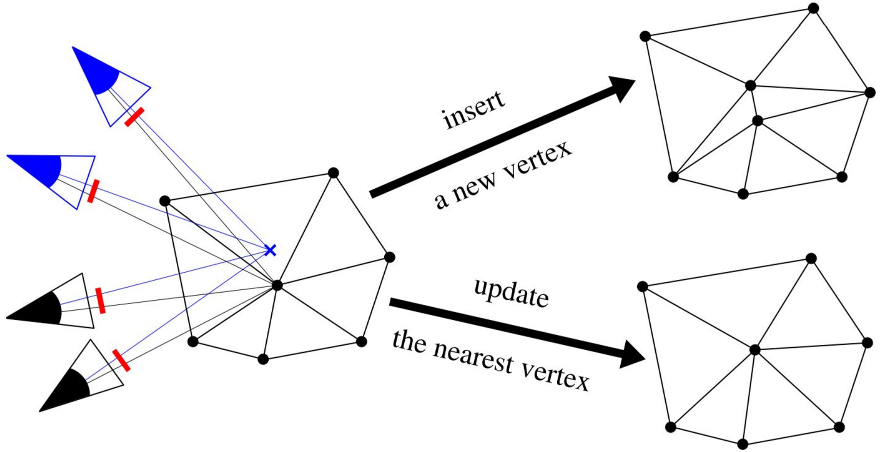


Figure 2. A candidate point (blue cross) updates the Delaunay triangulation depending on the maximum reprojection error between it and the nearest vertex: either it is inserted as a new vertex, or it updates the position of the nearest vertex.

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учет лучей видимости?

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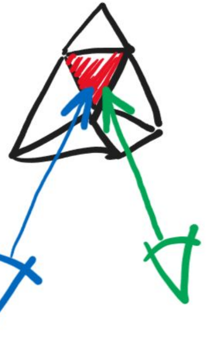

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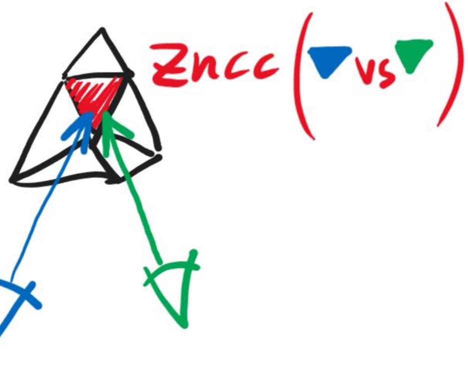

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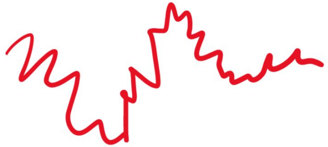

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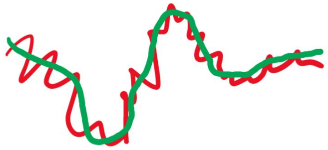

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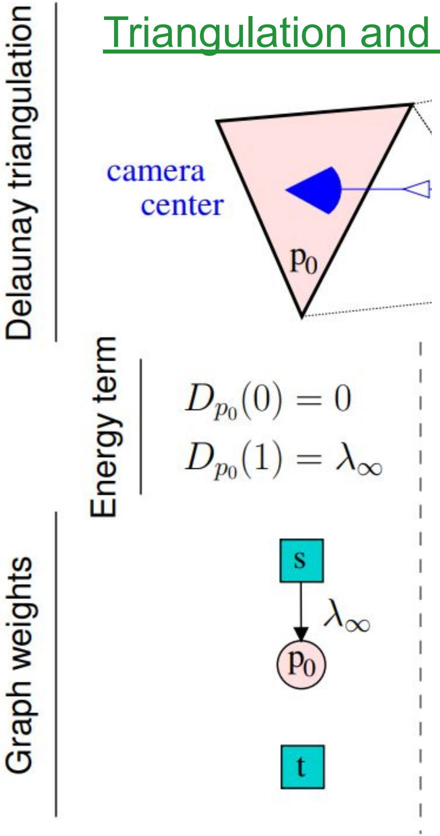

Figure 3. A ray emanating from a vertex to a camera center (and the putative surface), the corresponding visibility-related energy term that penalizes the number of intersections with the ray (the label 0 means s / "outside" and the label 1 means t / "inside") and the edge weights of the crossed tetrahedra in the graph.

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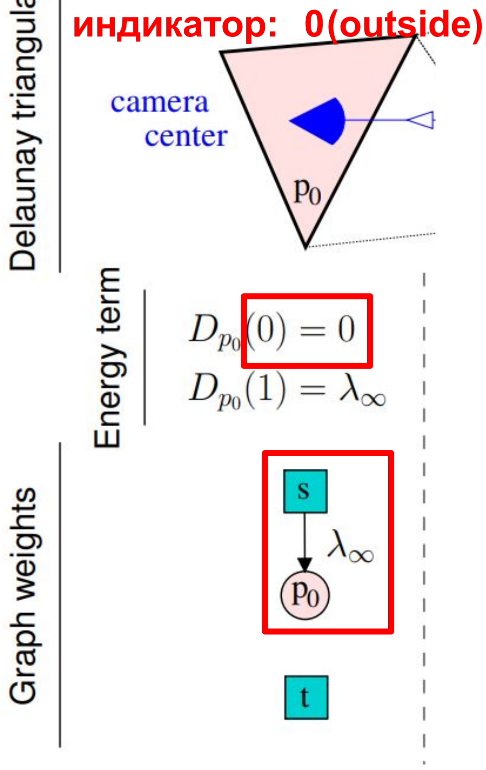

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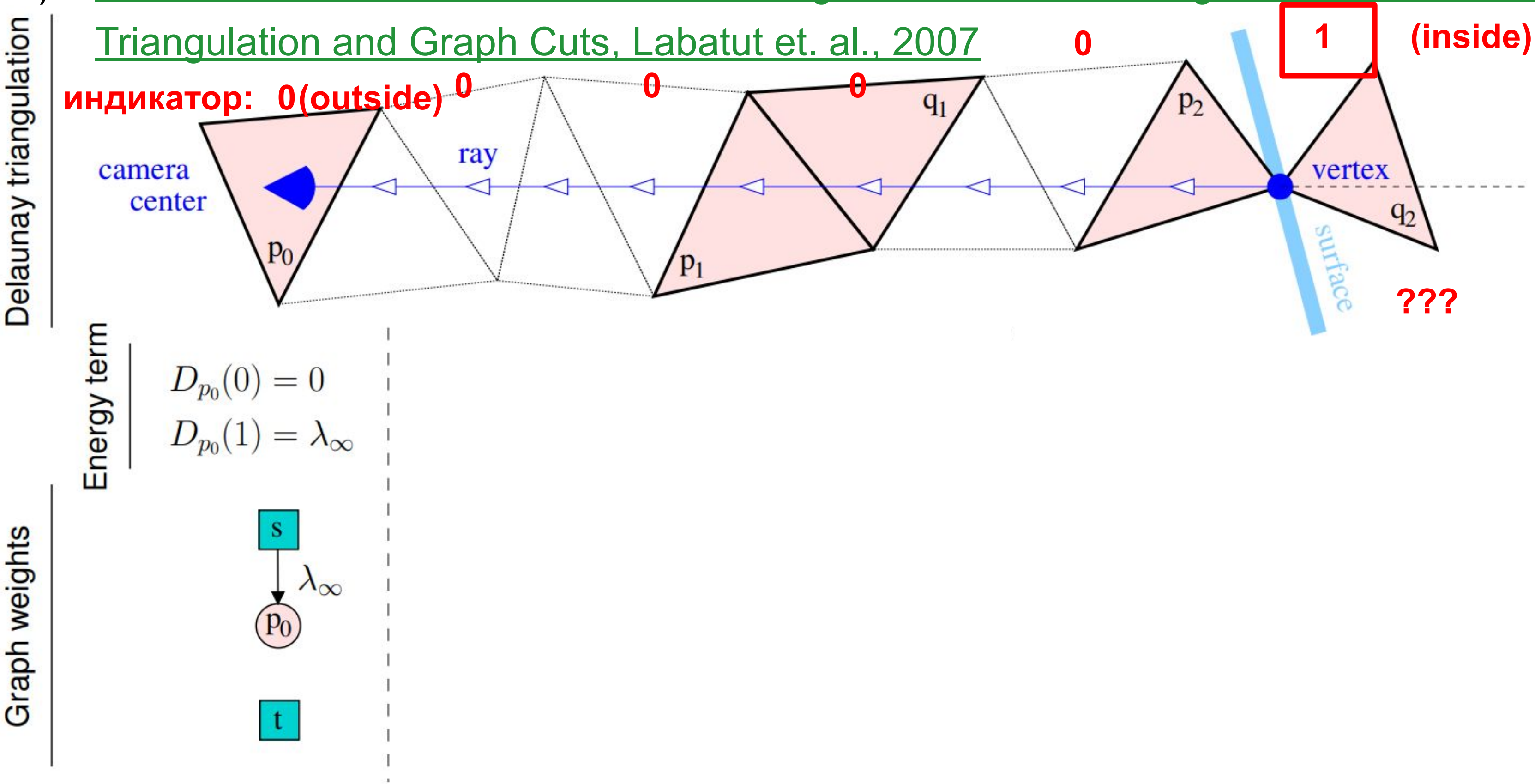

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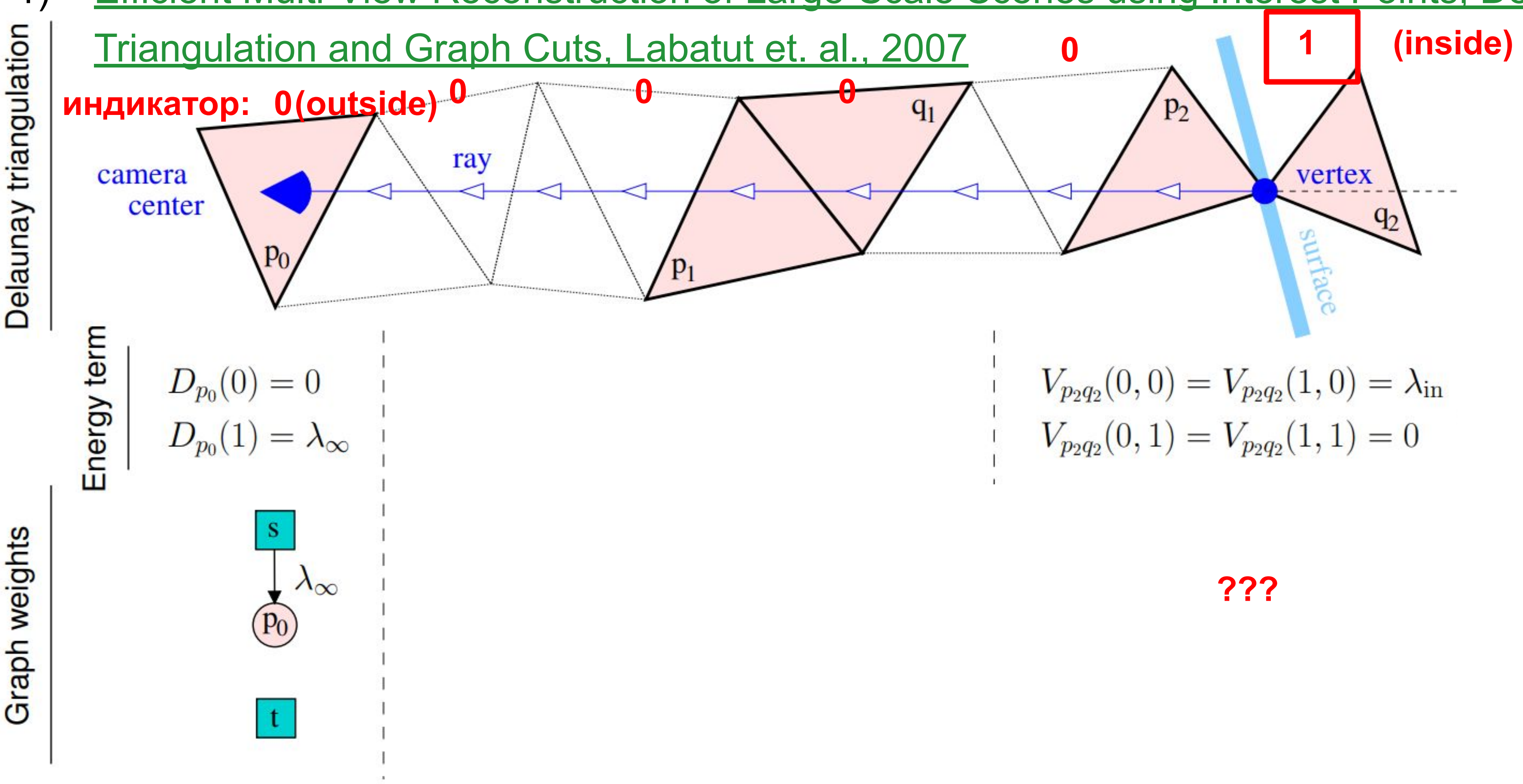

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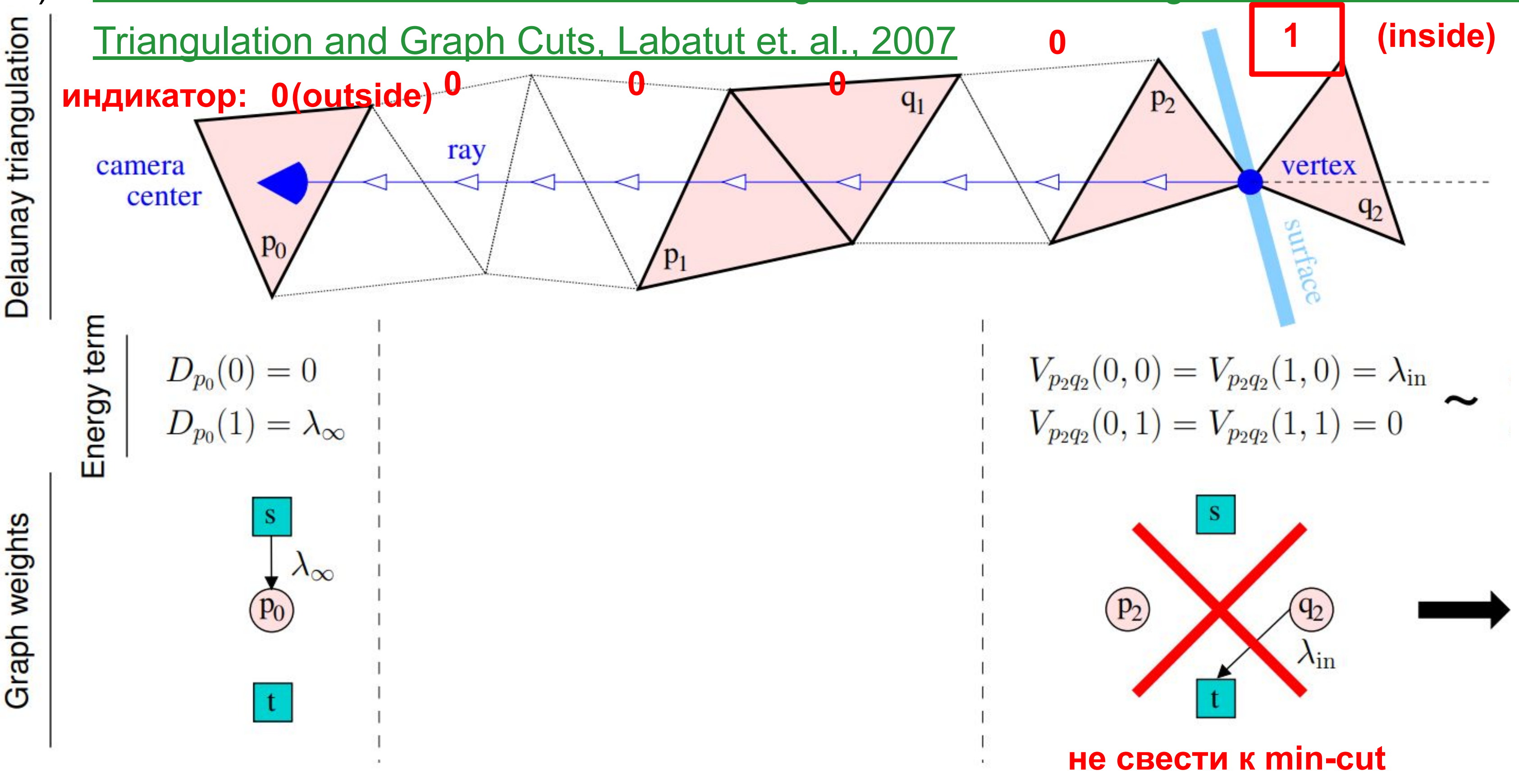

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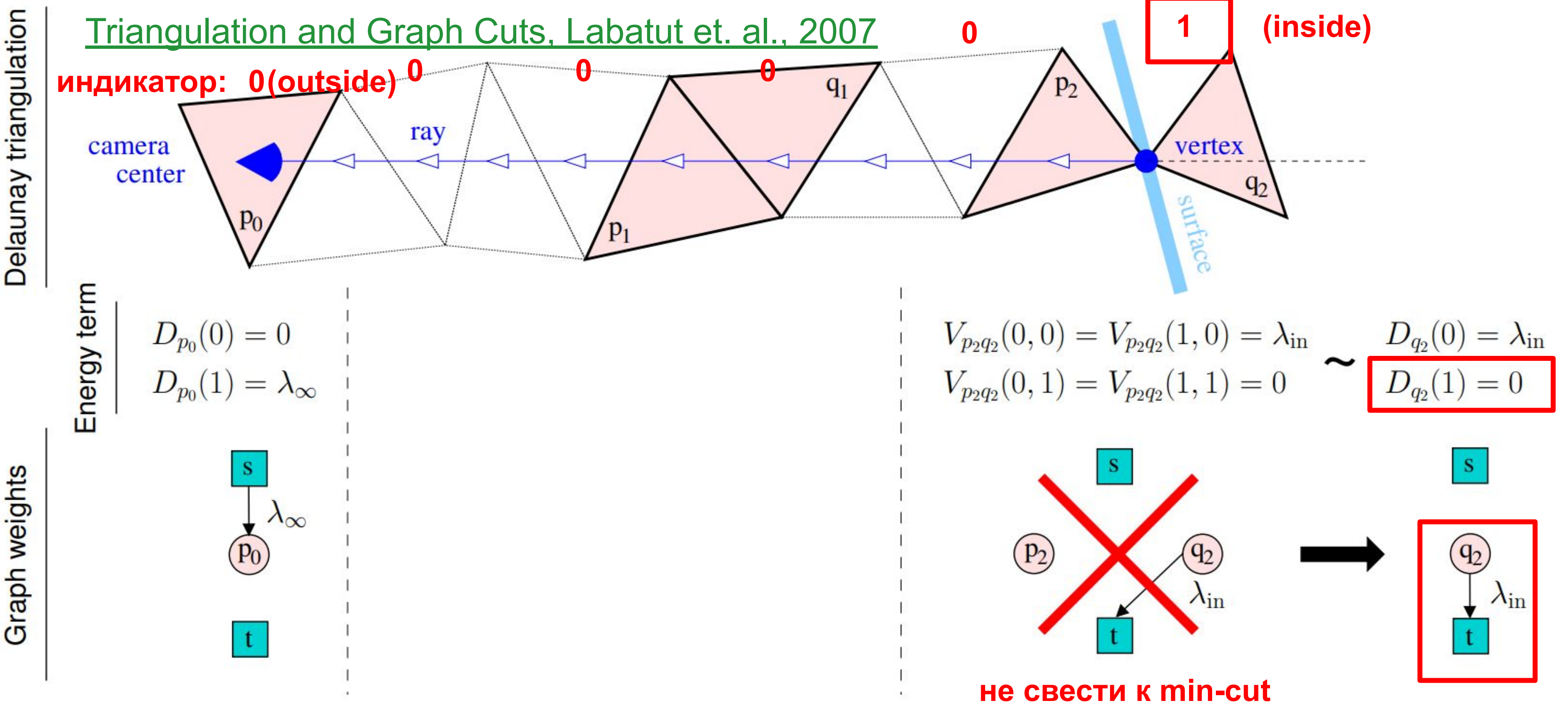

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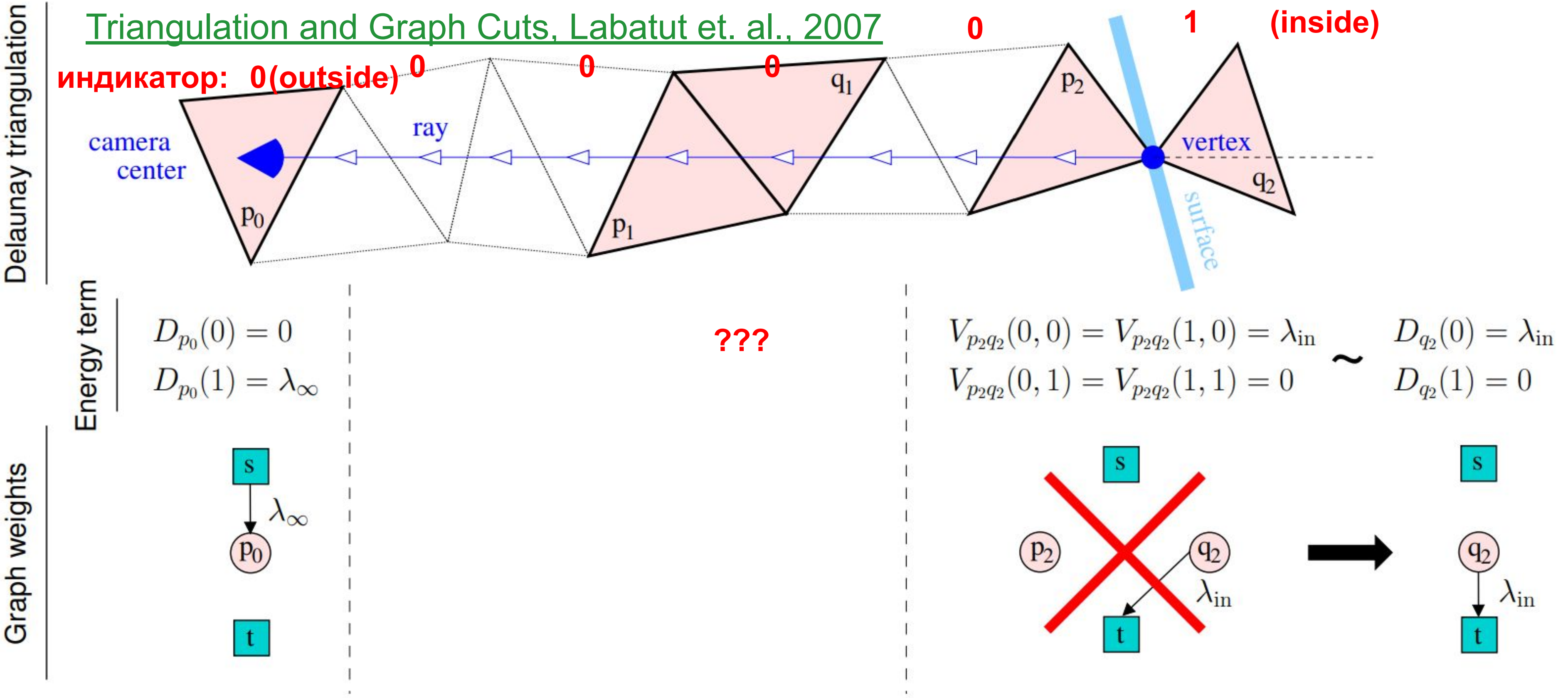

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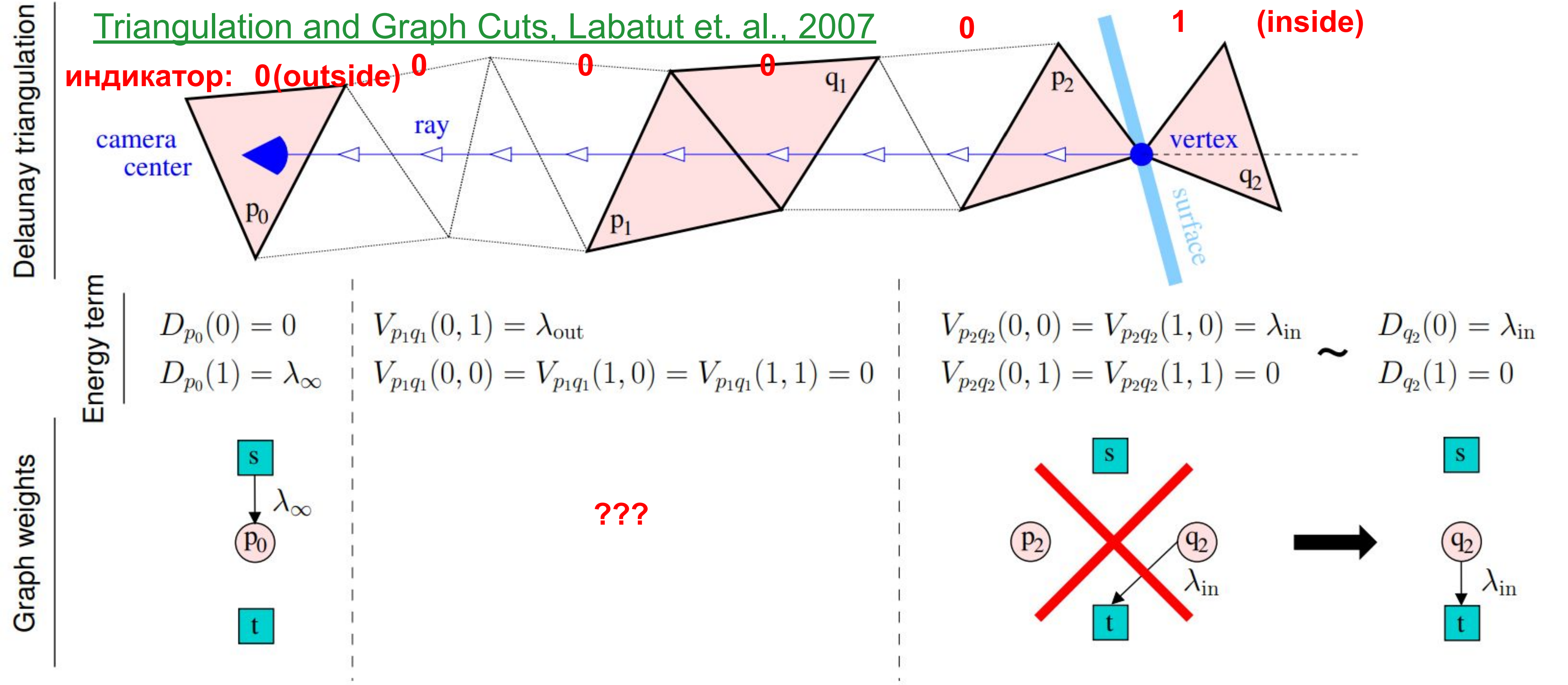

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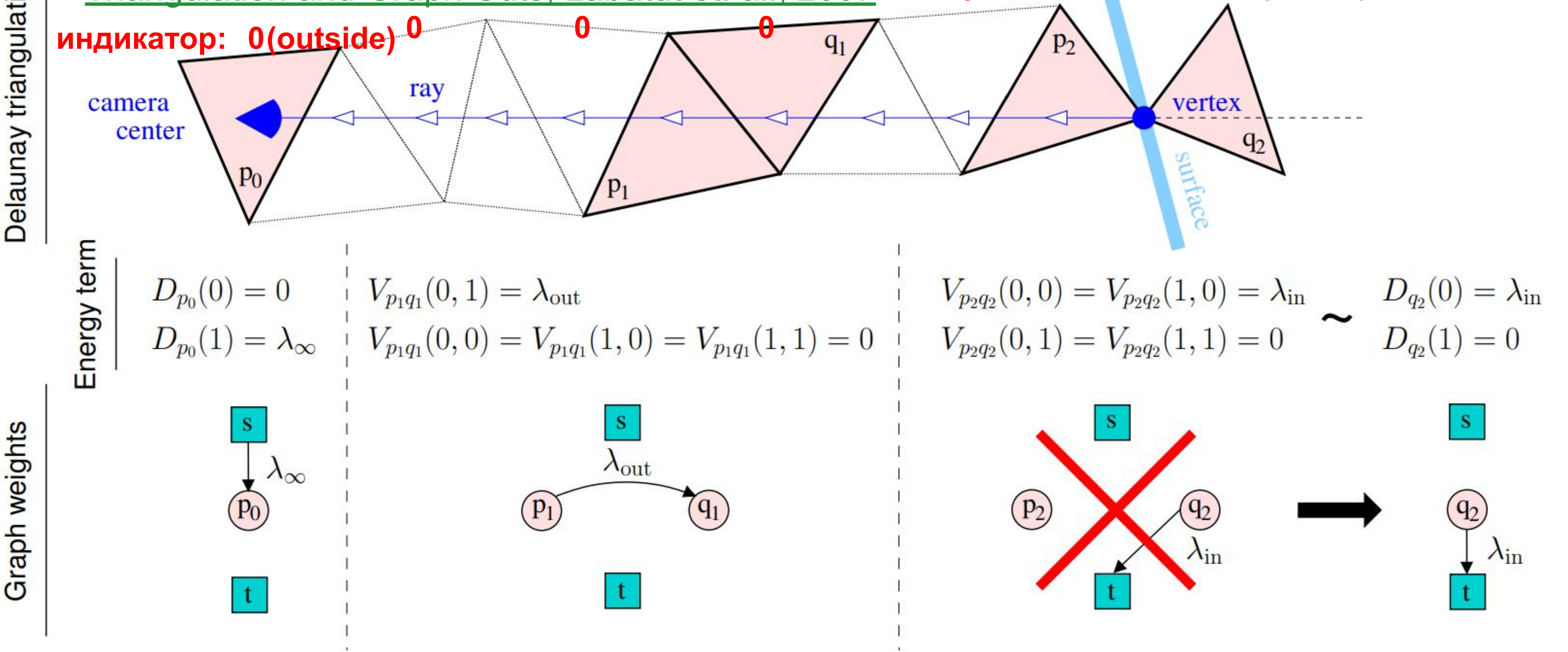

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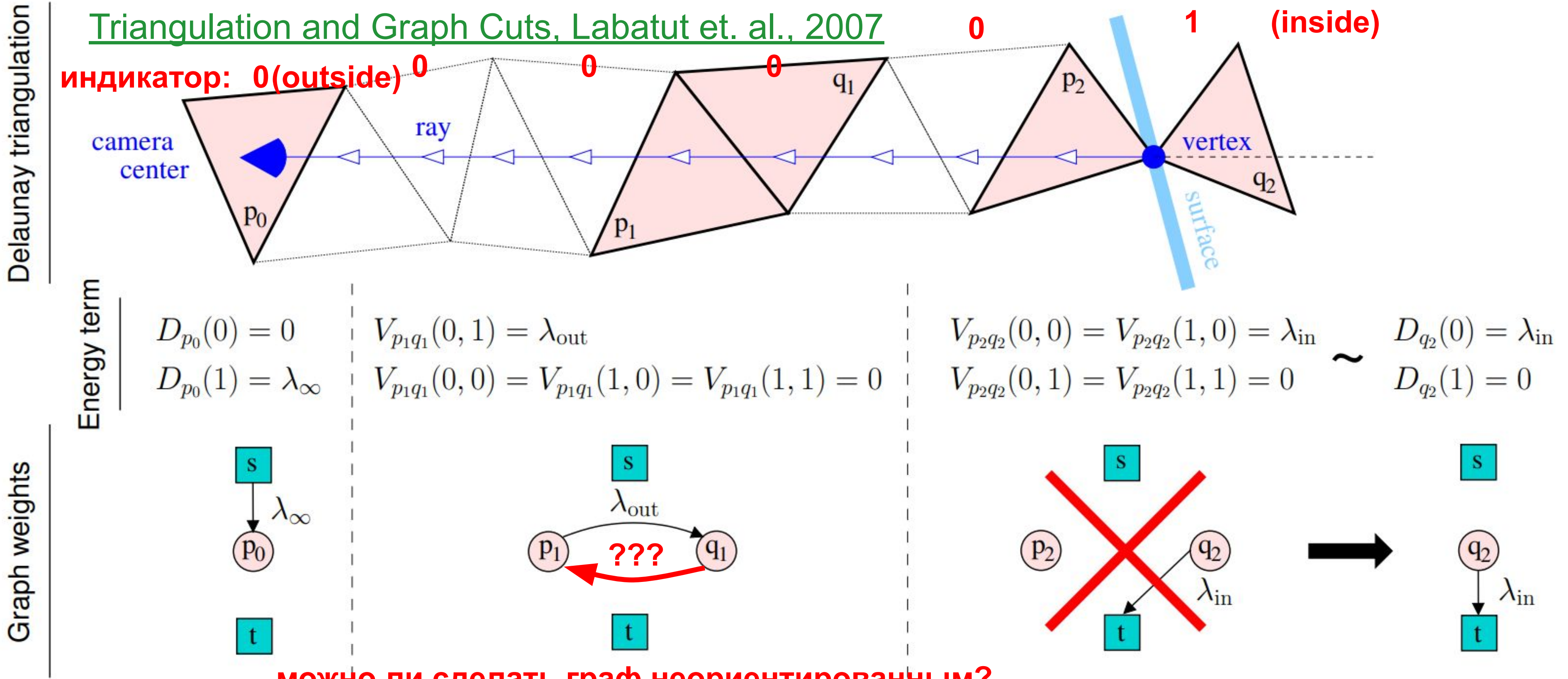

можно ли сделать граф неориентированным?
(проводя симметричные ребра)

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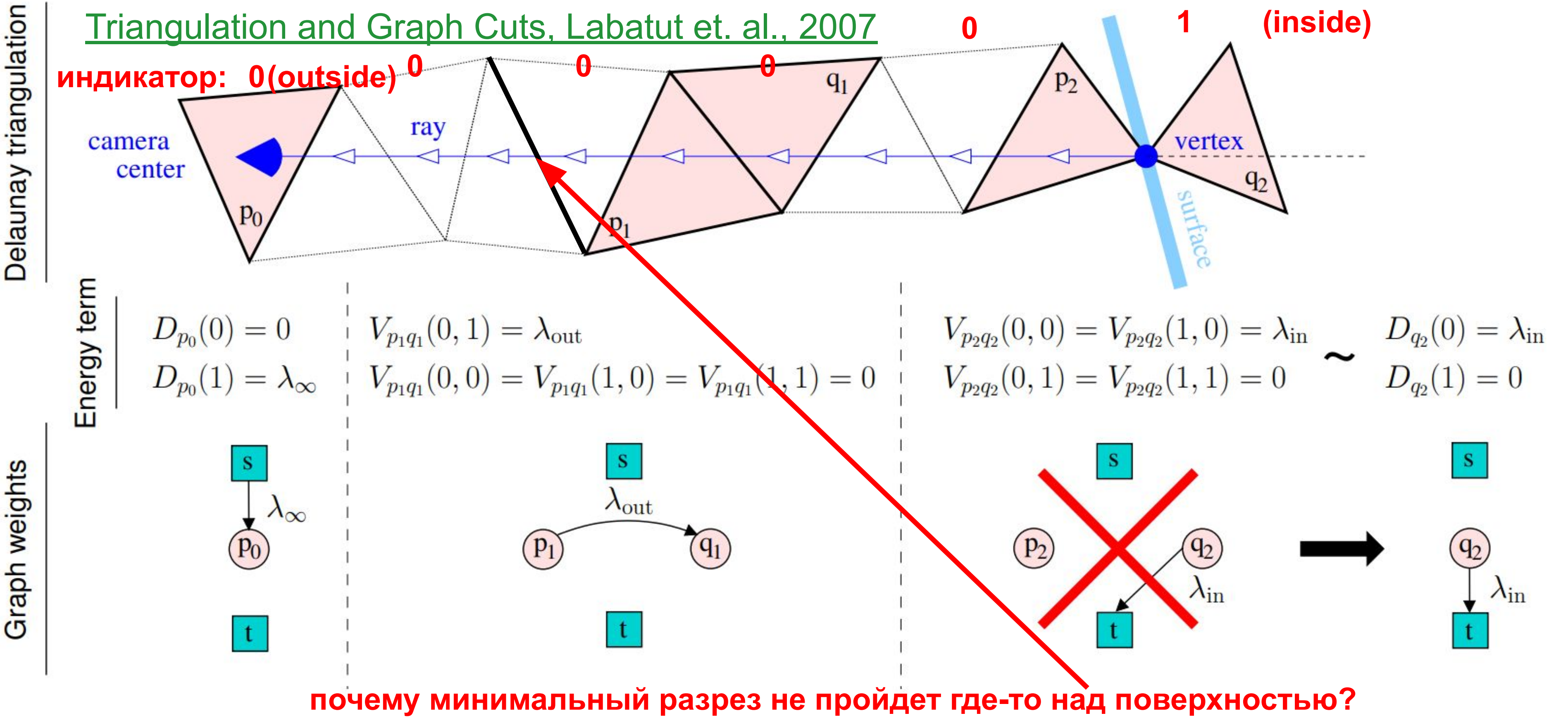

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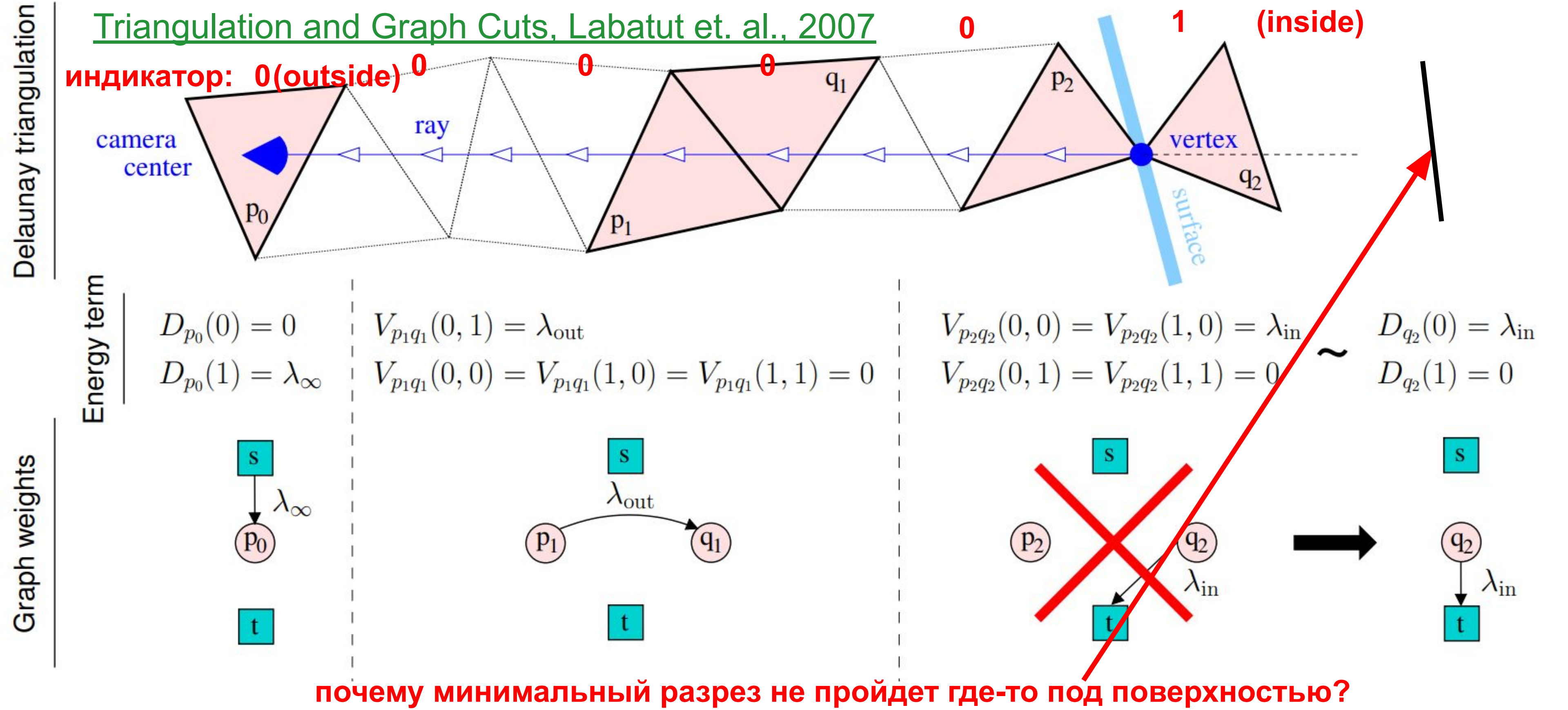

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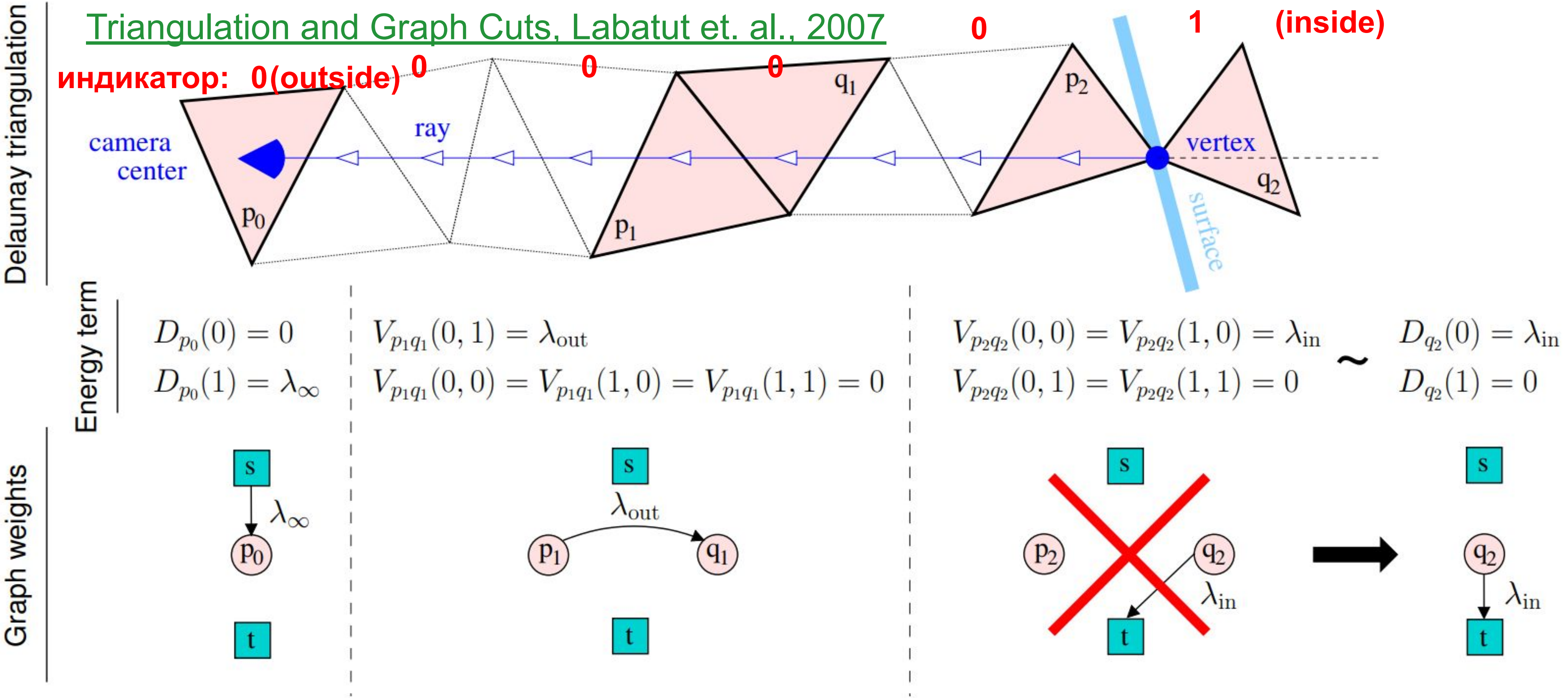
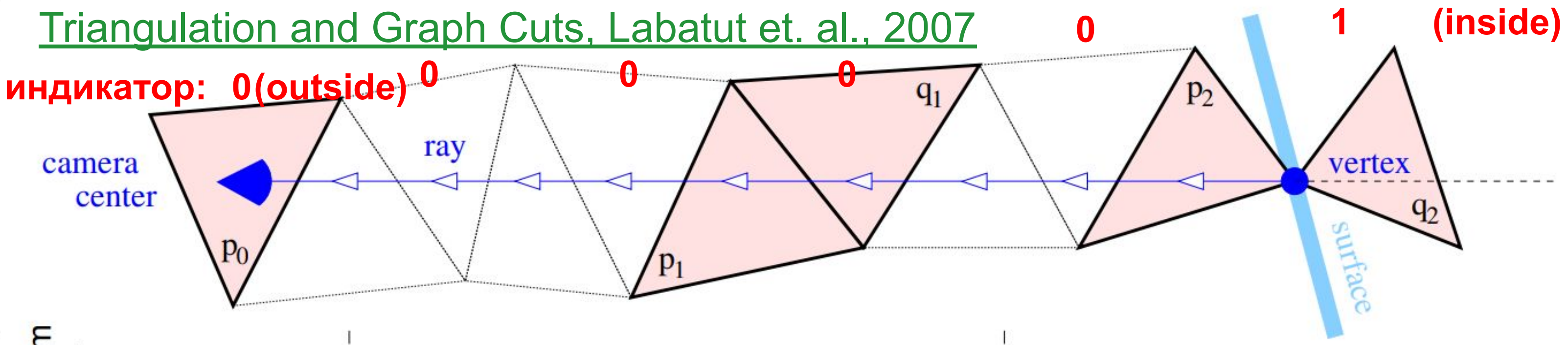


$$E(\mathcal{S}) = E_{\text{vis}}(\mathcal{S}) + \lambda_{\text{photo}}\, E_{\text{photo}}(\mathcal{S}) + \lambda_{\text{area}}\, E_{\text{area}}(\mathcal{S})$$

что из нашего функционала мы обсудили?

1) Efficient Multi-View Reconstruction of Large-Scale Scenes using Interest Points, Delaunay Triangulation and Graph Cuts, Labatut et. al., 2007

Delaunay triangulation



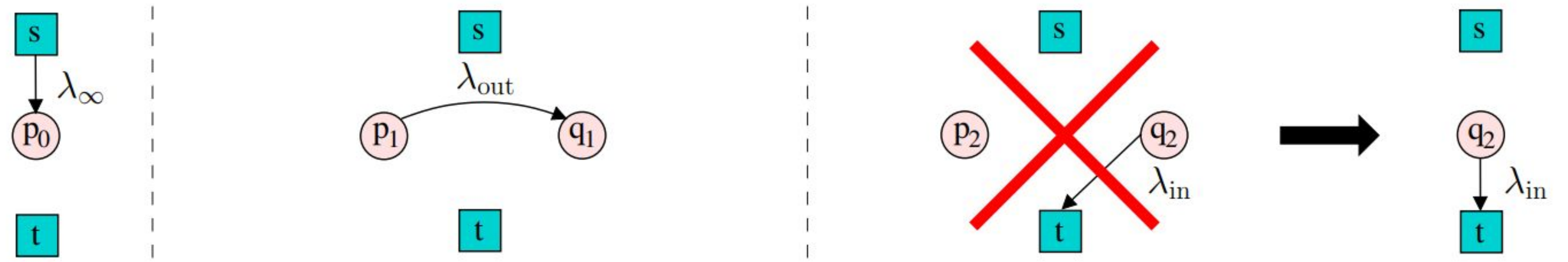
Energy term

$$D_{p_0}(0) = 0 \qquad D_{p_0}(1) = \lambda_\infty$$

$$V_{p_1q_1}(0,1) = \lambda_{\text{out}} \qquad V_{p_1q_1}(0,0) = V_{p_1q_1}(1,0) = V_{p_1q_1}(1,1) = 0$$

$$V_{p_2q_2}(0,0) = V_{p_2q_2}(1,0) = \lambda_{\text{in}} \qquad V_{p_2q_2}(0,1) = V_{p_2q_2}(1,1) = 0 \quad \sim \quad D_{q_2}(0) = \lambda_{\text{in}} \qquad D_{q_2}(1) = 0$$

Graph weights



$$E(\mathcal{S}) = E_{\text{vis}}(\mathcal{S}) + \boxed{\lambda_{\text{photo}}\, E_{\text{photo}}(\mathcal{S})} + \lambda_{\text{area}}\, E_{\text{area}}(\mathcal{S})$$

как добавить photoconsistency?

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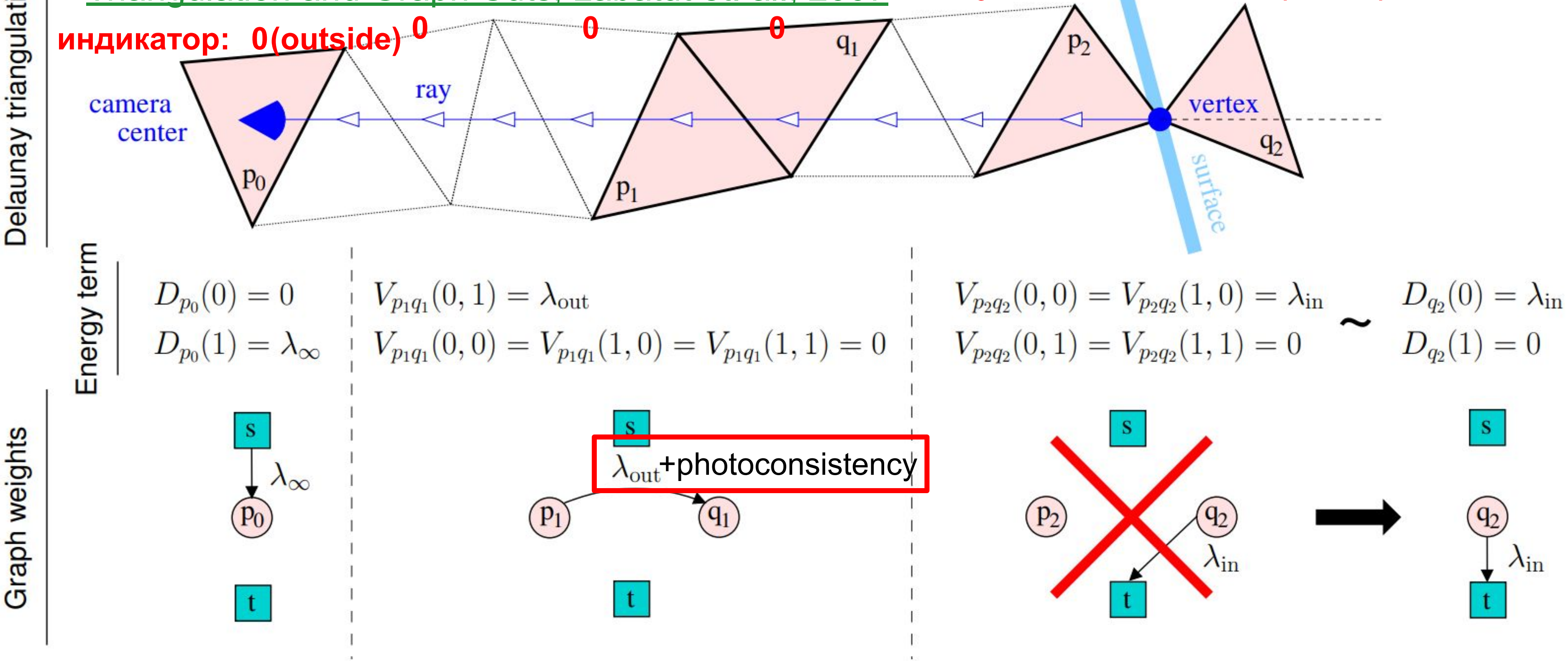
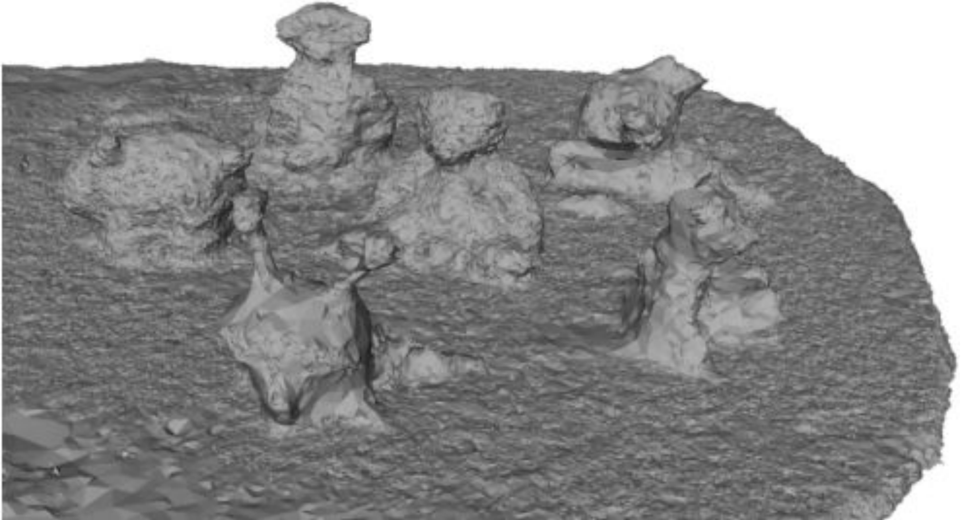


$$\mathrm{E}(\mathcal{S}) = \mathrm{E}_{\text{vis}}(\mathcal{S}) + \boxed{\lambda_{\text{photo}}\,\mathrm{E}_{\text{photo}}(\mathcal{S})} + \lambda_{\text{area}}\,\mathrm{E}_{\text{area}}(\mathcal{S})$$

photoconsistency можно привнести добавкой на ребра

1) [Efficient Multi-View Reconstruction of Large-Scale Scenes using Interest Points, Delaunay Triangulation and Graph Cuts, Labatut et. al., 2007]



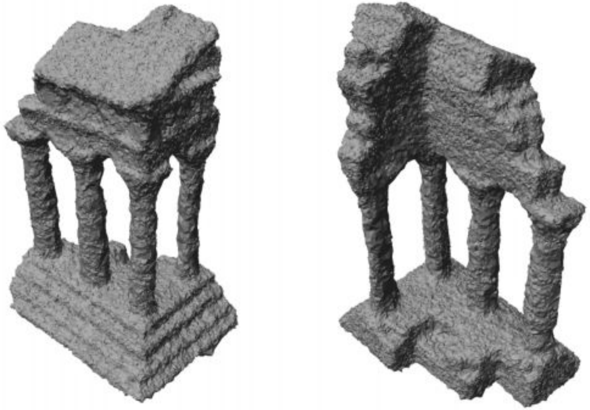
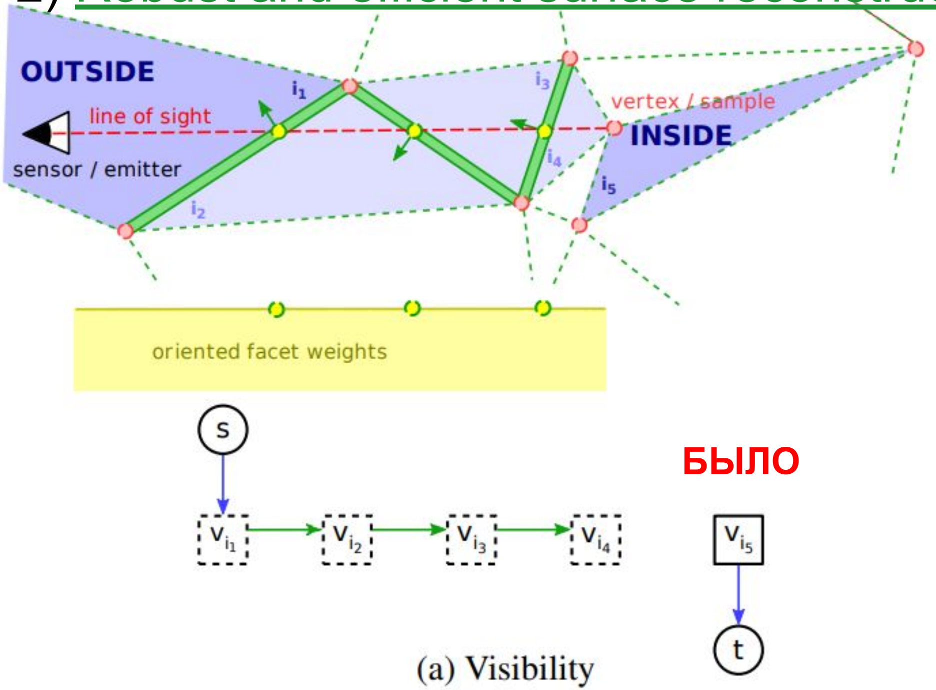


Figure 4. Some images of the temple dataset and our results

2) Robust and efficient surface reconstruction from range data, Labatut et. al., 2009



(a) Visibility

2) Robust and efficient surface reconstruction from range data, Labatut et. al., 2009

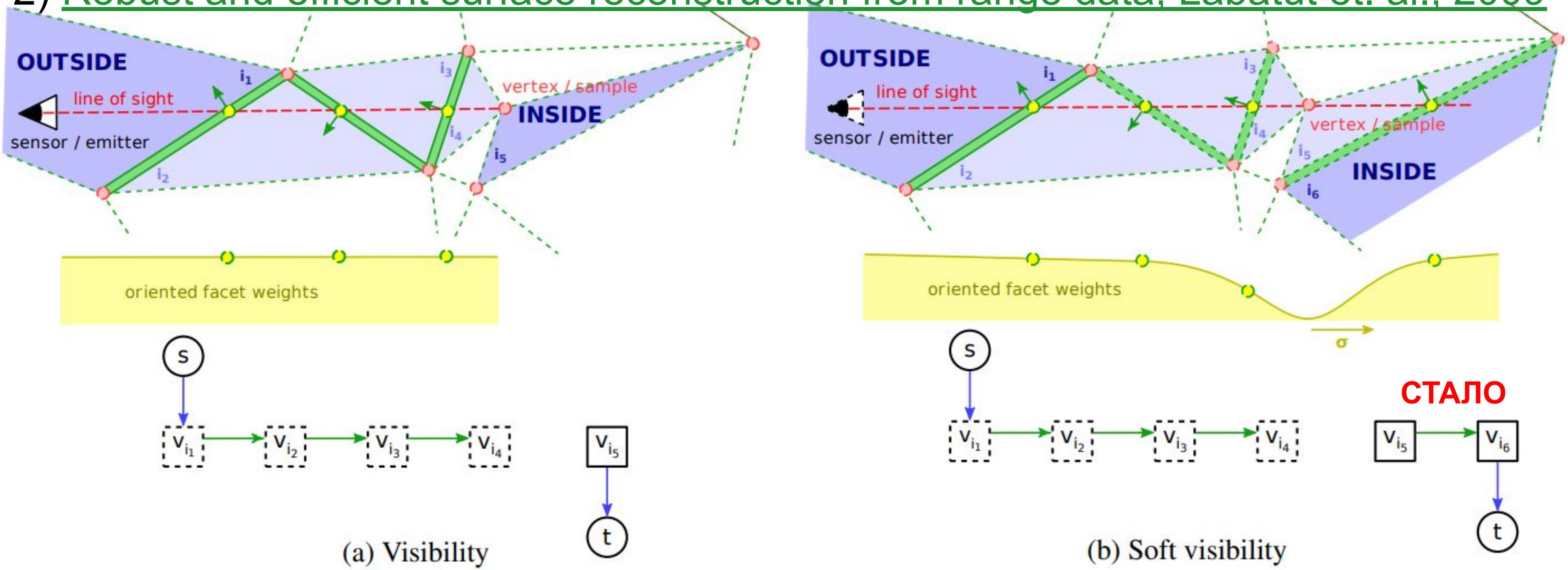


Figure 4: ***Visibility and soft visibility.*** How a single line of sight (pink) of a vertex of the triangulation (red) from a sample point to a laser (or to a sensor) contributes to the weights assigned to the origin tetrahedron, to the facets it crosses and to the final tetrahedron (blue).

2) Robust and efficient surface reconstruction from range data, Labatut et. al., 2009

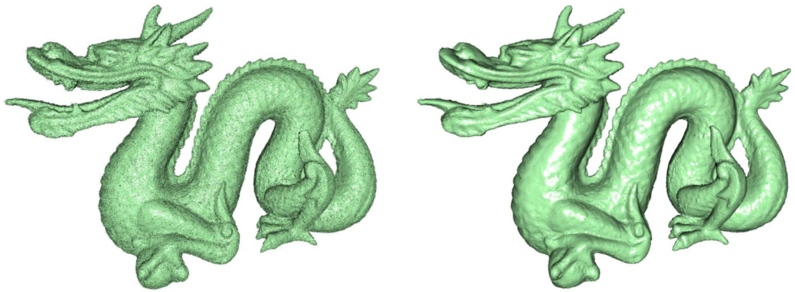


Figure 6: ***Stanford dragon (visibility vs. soft visibility).*** On the left, no tolerance is used and the reconstruction is bumpy and overly complex (1,176K vertices, 2,322K triangles). On the right, a reconstruction with tolerance generates a smoother and much coarser mesh (304K vertices, 580K triangles).

2) Robust and efficient surface reconstruction from range data, Labatut et. al., 2009

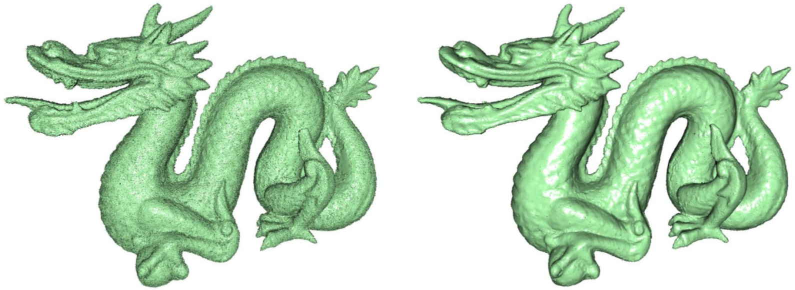


Figure 6: ***Stanford dragon (visibility vs. soft visibility).*** On the left, no tolerance is used and the reconstruction is bumpy and overly complex (1,176K vertices, 2,322K triangles). On the right, a reconstruction with tolerance generates a smoother and much coarser mesh (304K vertices, 580K triangles).

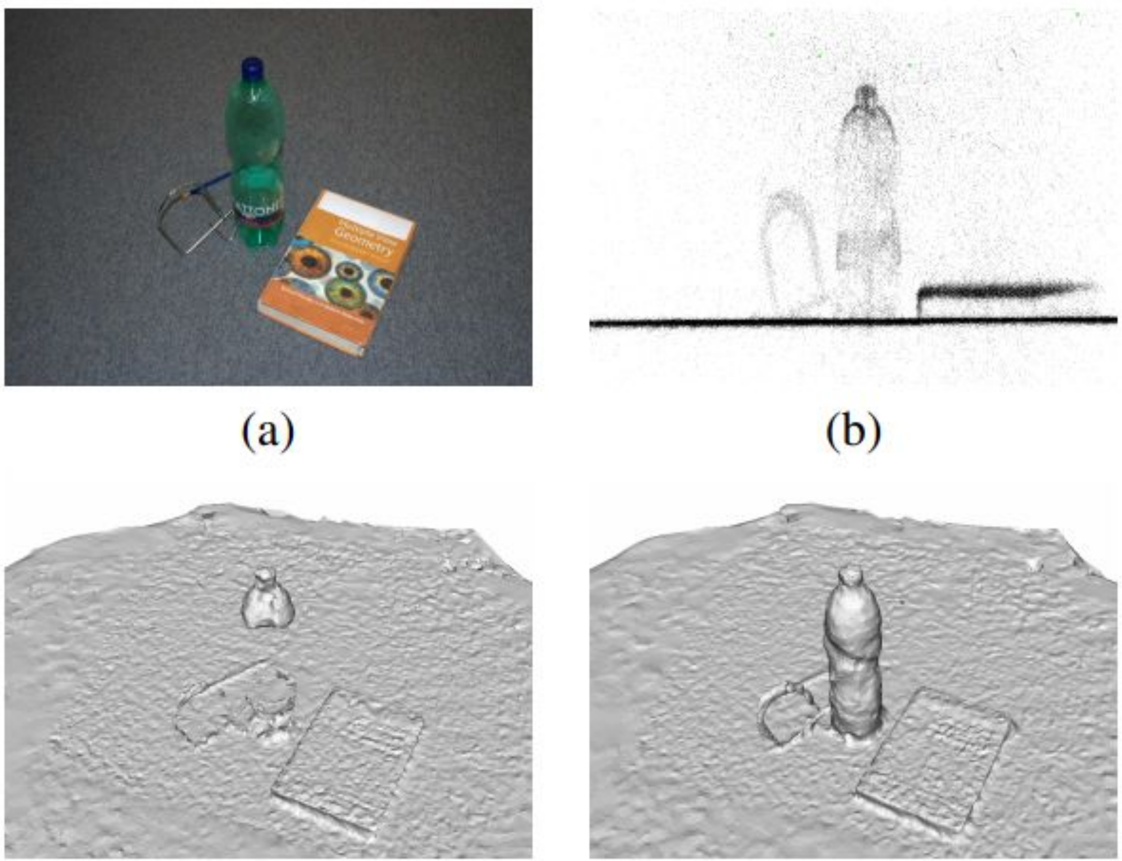
Figure 7: ***Stanford happy buddha.*** 380K vertices, 738K triangles. Setting the tolerance parameter σ too high might create unwanted holes (inside the square).

2) Robust and efficient surface reconstruction from range data, Labatut et. al., 2009

1) Visibility rays - из любого источника (LIDAR или плотные карты глубины).
2) Более мягкое указание пересечения поверхности (глубже под поверхность заглядываем + пропускная способность тем меньше чем ближе к поверхности).
3) Другой surface term про две смежные описывающие сферы (вместо медленного photoconsistency term и тяготеющего к излишним упрощениям area term).
4) Учитываем степень уверенности на базе угла наблюдения поверхности (нормаль)
5) Медленно работает:

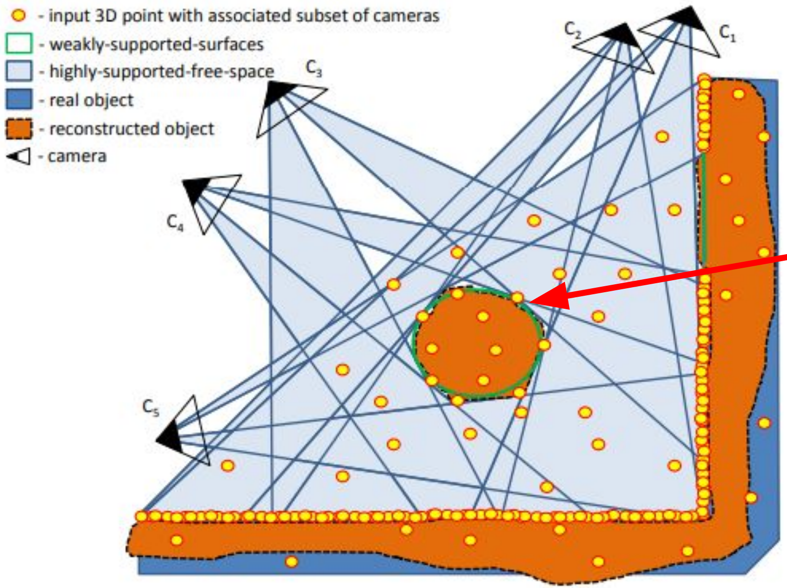
	Model	#Points	#Tets	Delaunay	Visibility	Quality	Min. s-t cut	Overall	
133M	Sheep (Fig. 8)	153K	966K	2s	3s	1s	3s	10s	$\ll$ 1m
306M	Bunny (Fig. 12)	362K	2,252K	10s	11s	2s	7s	31s	$<$ 1m
1.6G	Dragon (Fig. 6)	1,770K	11,383K	38s	68s	15s	59s	180s	3m
1.7G	Angel (Fig. 1)	2,008K	12,637K	41s	86s	16s	48s	190s	3m 10s
2.0G	Armadillo (Fig. 3)	2,247K	14,519K	47s	58s	13s	177s	295s	4m 55s
2.4G	Buddha (Fig. 7)	2,644K	17,167K	62s	120s	14s	74s	271s	4m 31s
-	Elephant (Fig. 2)	4,413K	27,487K	98s	274s	35s	-	-	
6.5G	Elephant (Fig. 2) / 64-bits	4,413K	27,487K	93s	189s	32s	102s	417s	6m 57s
9.9G	Soufflot (Fig. 14) / 64-bits	6,592K	42,062K	176s	416s	40s	521s	1154s	19m 14s

3) Multi-View Reconstruction Preserving Weakly-Supported Surfaces, Jancosek et. al., 2011



(a) (b) (c) (d)

3) Multi-View Reconstruction Preserving Weakly-Supported Surfaces, Jancosek et. al., 2011



Очень мало точек на поверхности бутылки

Figure 2. **Weakly-supported surfaces.** A highly-supported-free-space is the part of the space which is between the surfaces densely sampled by the input 3D points and the associated cameras. Weakly-supported surfaces (green) are the surfaces of the real object which are weakly sampled by the input 3D points and are close to the border of the union of the highly-supported-free-space cones.

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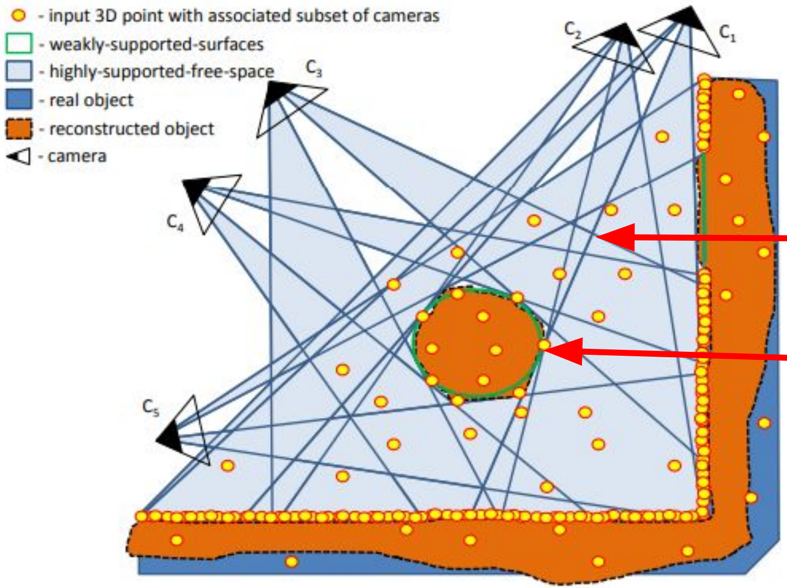

Очень **много лучей** пробивает пустоты

Очень **мало лучей** пробивает бутылку

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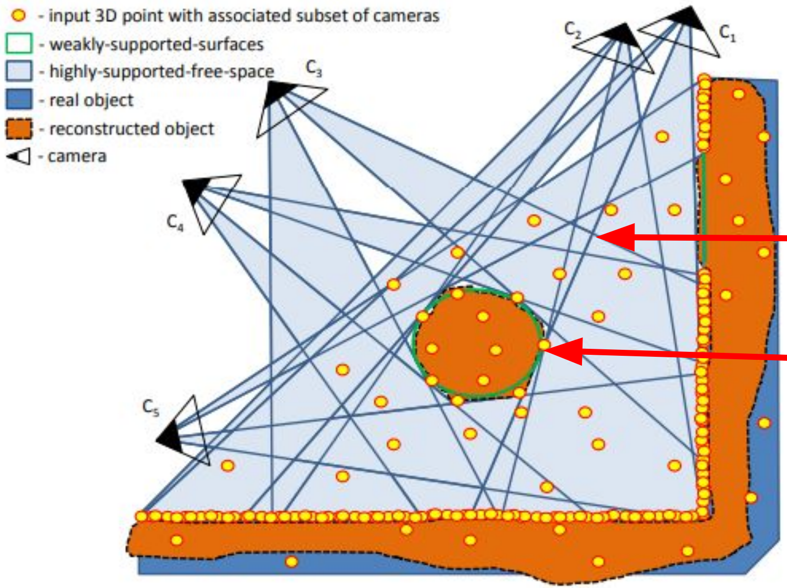

Очень **большие** пропускные способности

Очень **малые** пропускные способности

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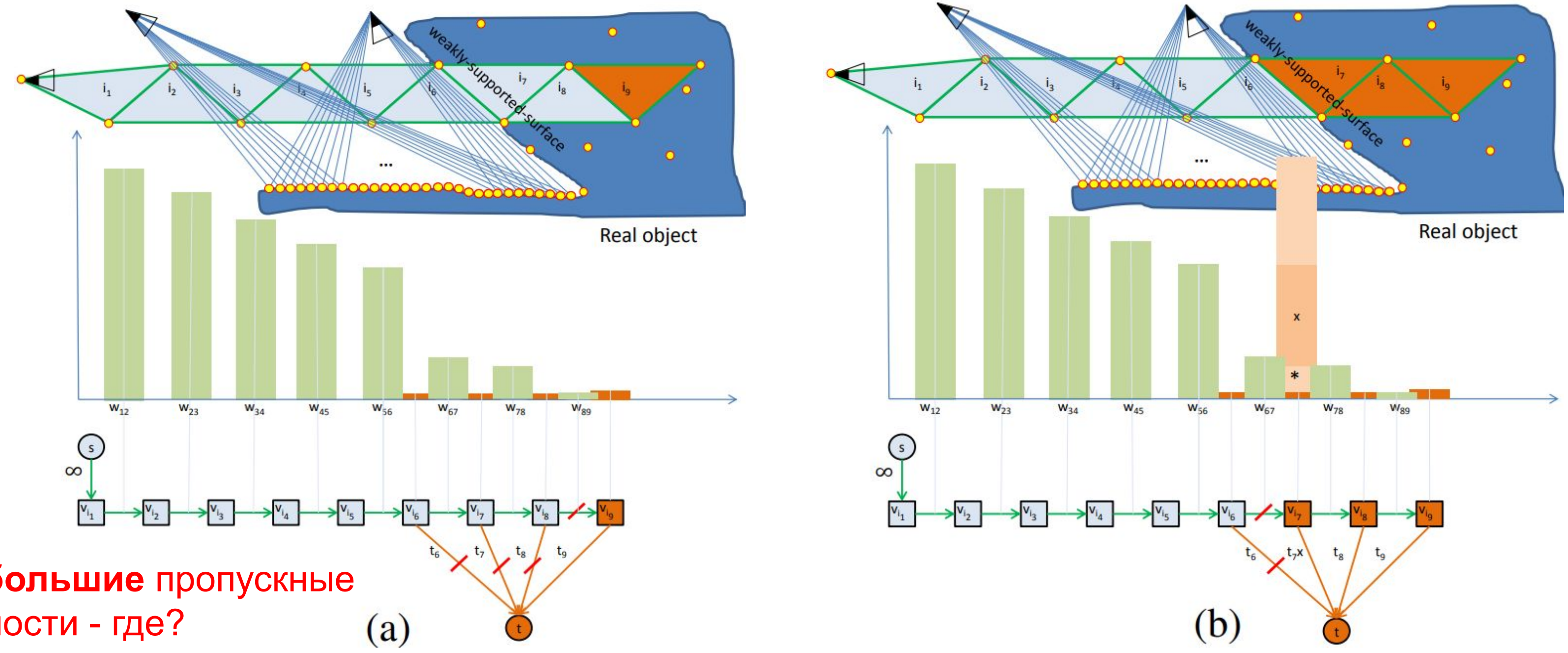
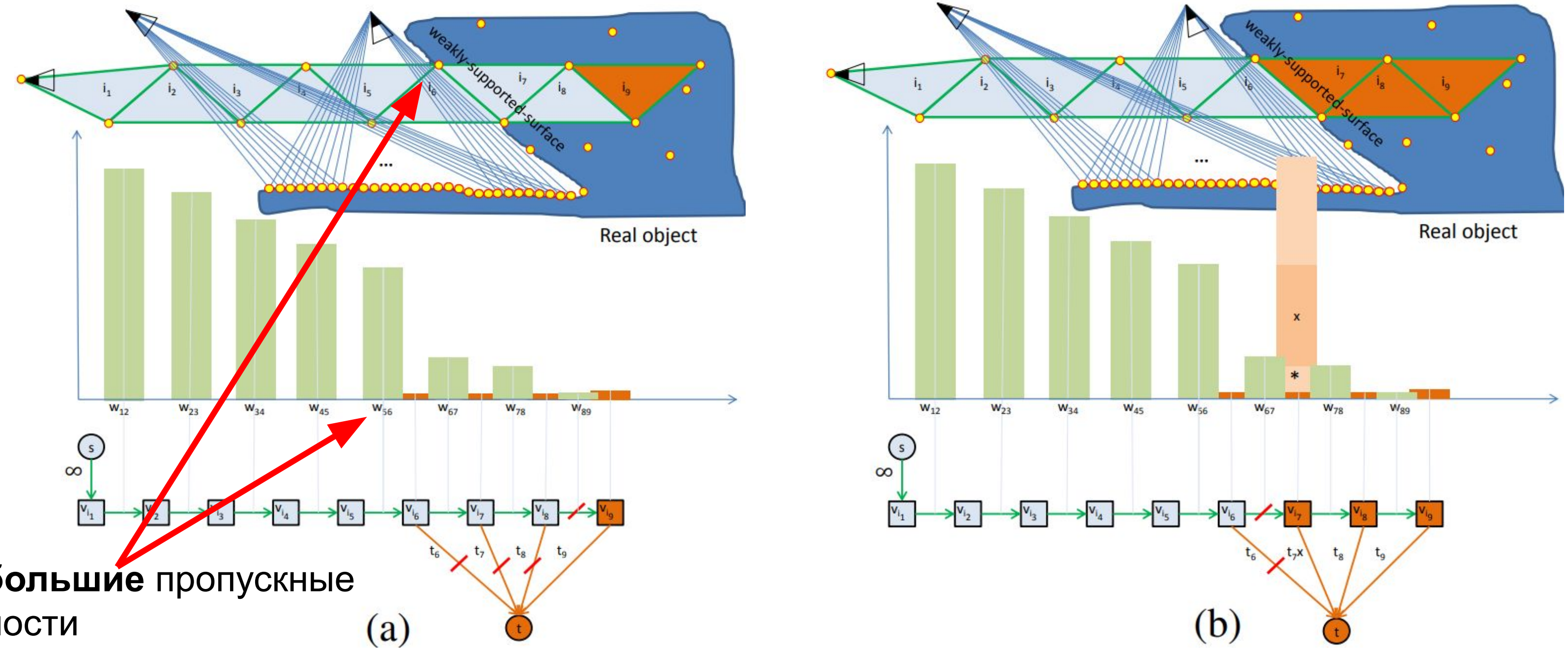


Очень **большие** пропускные способности - где?

Figure 6. **Representative example.** Light blue: source label (free space), brown: sink label (full space). (a,b) top: a part of the triangulation, bottom: the associated s-t graph, middle: the weights of the associated edges. (a) Minimal cut for weights computed by the base-line approach leads to a wrong solution (b) Multiplying t_7 by $(w_{56} - w_{78})$ leads to the correct solution.

3) Multi-View Reconstruction Preserving Weakly-Supported Surfaces, Jancosek et. al., 2011



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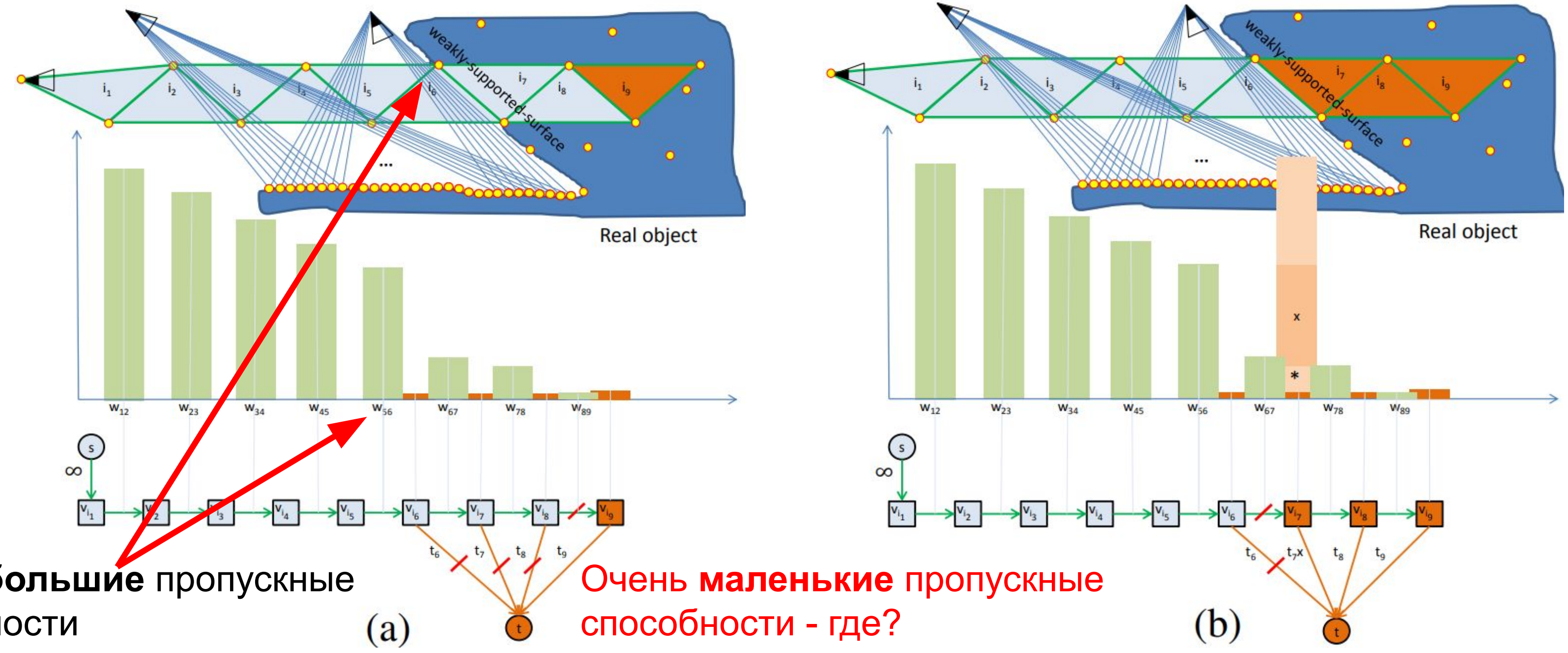

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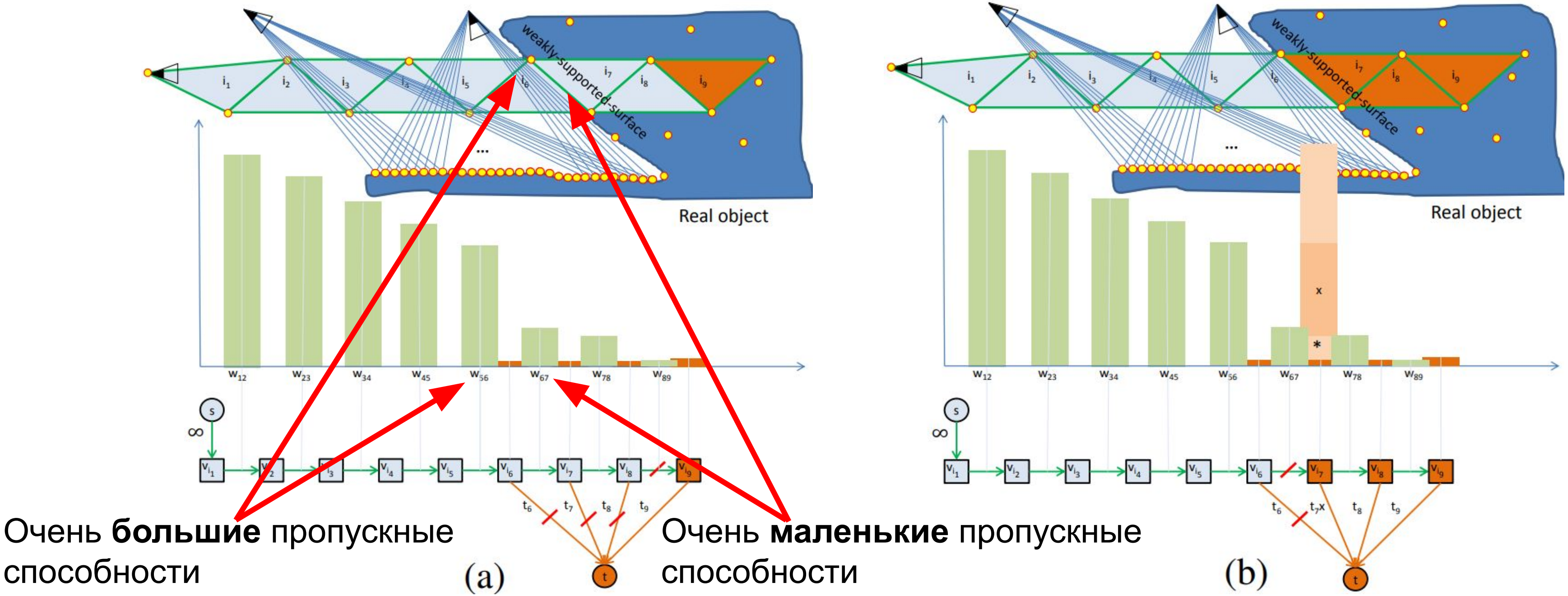

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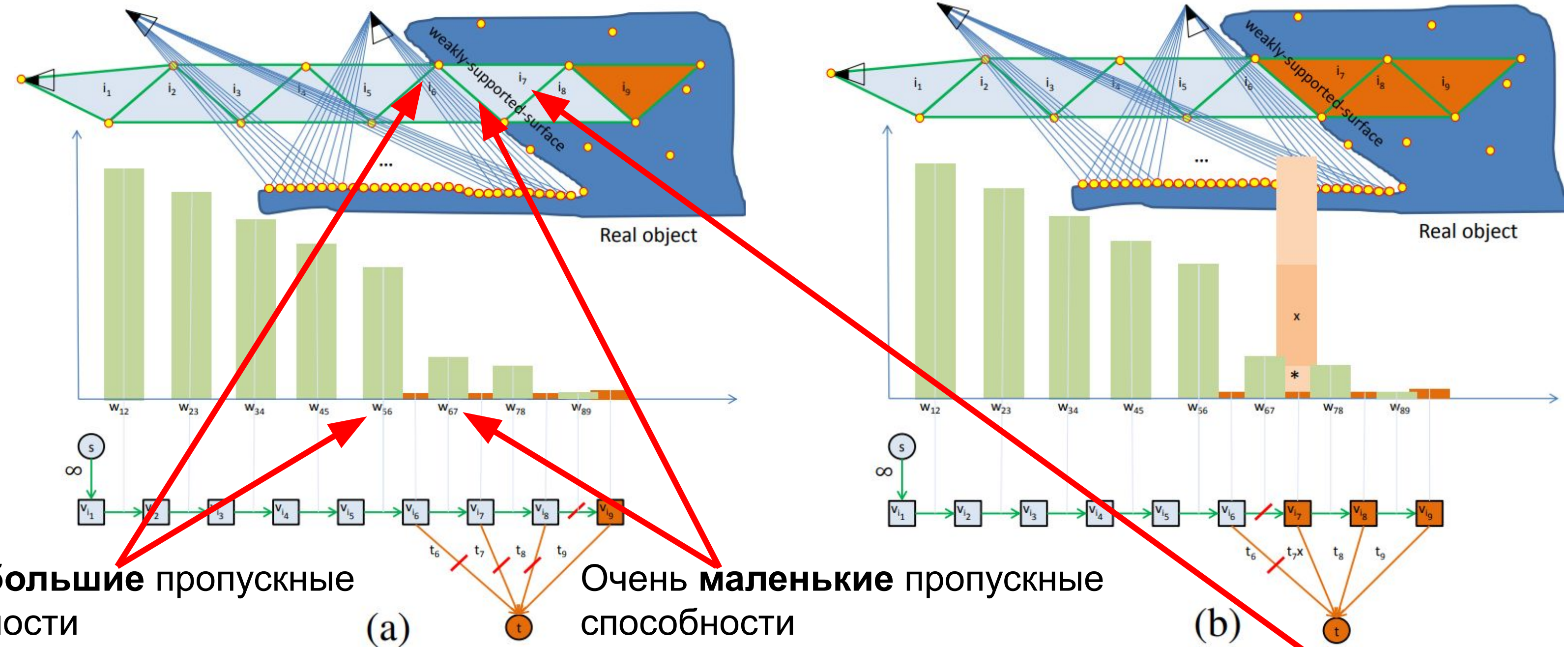

Очень **большие** пропускные способности

Очень **маленькие** пропускные способности

как попытаться спасти этот тетрагедрон? как ему помочь?

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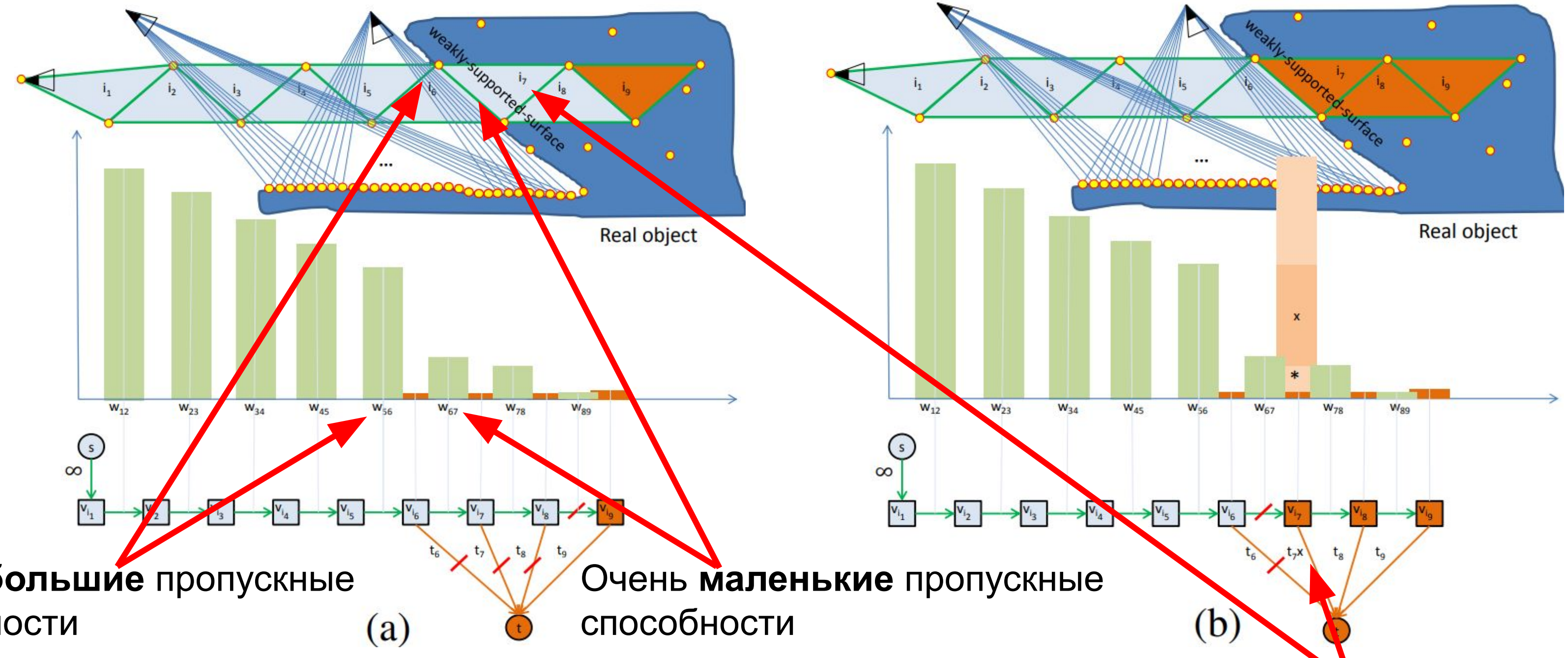

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поможем тетрагедрону домножив его пропускную способность к стоку на разность

3) Multi-View Reconstruction Preserving Weakly-Supported Surfaces, Jancosek et. al., 2011

Ссылки (реконструкция через **min-cut**)

Delaunay triangulation + graph min-cut:

1) Efficient Multi-View Reconstruction of Large-Scale Scenes using Interest Points, Delaunay Triangulation and Graph Cuts, Labatut et. al., 2007

2) Robust and efficient surface reconstruction from range data, Labatut et. al., 2009

3) Multi-View Reconstruction Preserving Weakly-Supported Surfaces, Jancosek et. al., 2011

Out-of-core adaptations:

- PHD Thesis: Large-scale and high-quality Multi-view stereo (p. 65 - section 5.3: Merging meshes from partition of bounding box), Vu, 2011
- Scalable Surface Reconstruction from Point Clouds with Extreme Scale and Density Diversity, Mostegel et.al., 2017

Пример реализации в OpenMVS: openMVS/libs/MVS/SceneReconstruct.cpp

Вопросы?

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polarnick239@gmail.com