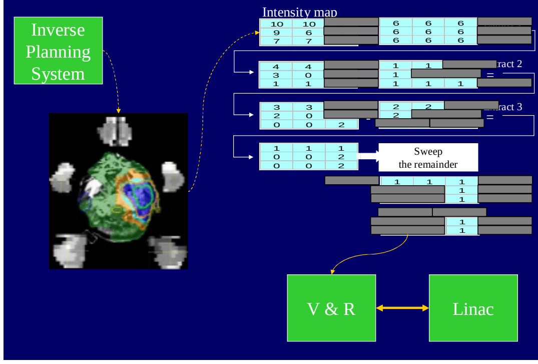
Simplifying IMRT Plans
Through Efficient Segmentation

R. Alfredo C. Siochi, PhD

Holden Comprehensive Cancer Center
Department of Radiation Oncology
University of Iowa Hospitals & Clinics

Leaf Sequencing Overview



Processes affecting the number of segments in IMRT

- Intensity map creation
- Segmentation of the map
- Corrections

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Creating the Intensity Map

- Aim the Beams
- Use the appropriate optimization
- Set the Number of Levels (intensity resolution)
- Set the leaf position resolution

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Aim the Beams

- Better avoidance of critical structures
- Lower integral dose
- Fewer beams may be needed
- Possibly simpler intensity maps

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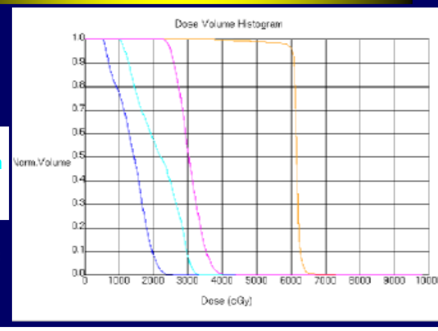
7 Equally Spaced Beams

7 Equally Spaced

Parotid
Brain stem
Cord
PTV

Segments: 90



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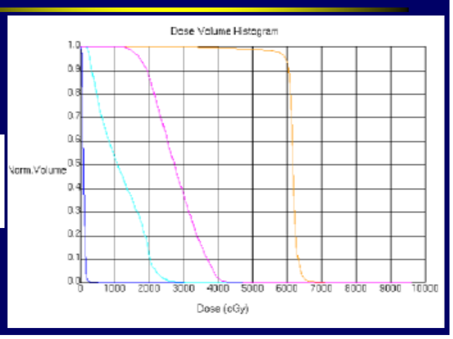
4 Aimed non-coplanar Beams

4 Aimed non-coplanar

Parotid
Brain stem
Cord
PTV

Segments: 62



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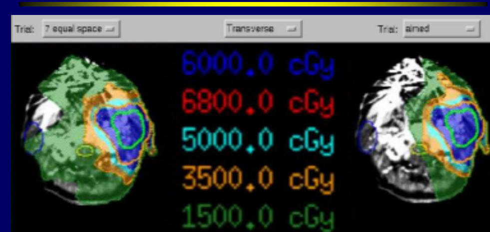
Aimed vs Equi-spaced Integral Dose



Aimed Beams can yield a lower integral dose.

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Effect of Inverse Plan Algorithm

- Modulation Scaling Factor
- "= MLC MU/compensator MU"
- Gradient Search: lower MSF, simpler maps
- Simulated Annealing: complex maps, many peaks and valleys, high MSF
- Lower MSF = fewer segments

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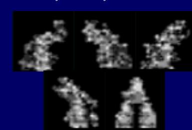
Effect of Optimization Algorithm on Intensity Maps

Indexed Dose
MSF average = 1.55
Courtesy University of North Carolina



Simulated Annealing
MSF average = 3.33
Courtesy Univ. Califonia, San Francisco

Gradient search
MSF average = 1.64
Courtesy DKFZ, Heidelberg, Germany

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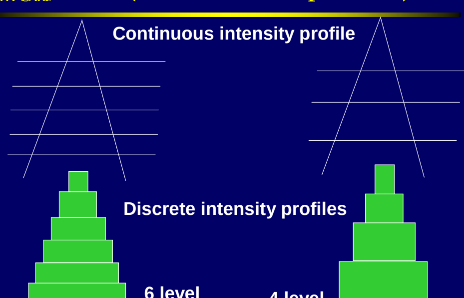
Intensity Resolution (number of map levels)



More levels require more segments

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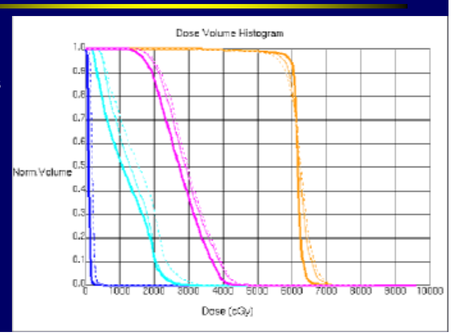
Fewest Levels with Clinically sufficient Quality

Thick: continuous
Thin: 15 Levels
Dashed: 7 Levels



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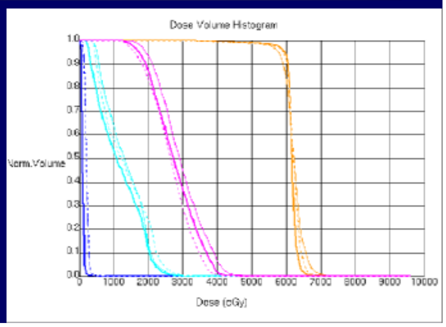
Fewest Levels with Clinically sufficient Quality

Thick: continuous
Thin: 15 Levels
Dashed: 7 Levels adjusted (DMPO)

Segments:
7 Levels: 62
15 Levels:124



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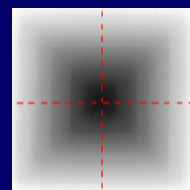
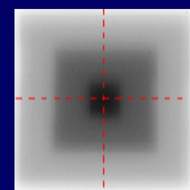
Limiting leaf resolution -Film





5 mm grid 1 cm grid

5 level and 3 level pyramid at 5 cm depth, 100 cm SAD

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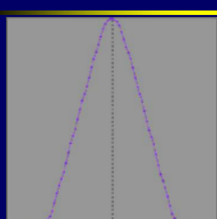
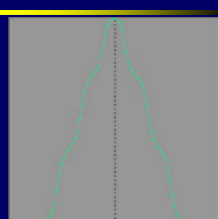
Limiting leaf resolution - Profile





5 mm grid 1 cm grid

Using a 2 mm grid and more intensity levels could more than double the number of segments compared to a 5 mm grid, without improving the profile

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Segmenting the Map

- **Many different combinations of segments can produce the desired intensity map**
- **Some configurations are more efficient than others**

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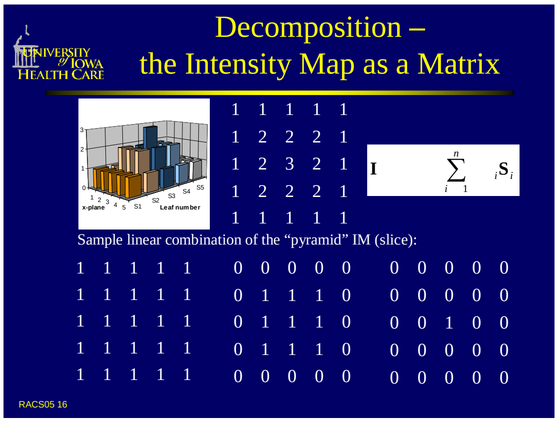
Decomposition –
the Intensity Map as a Matrix
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1 1 1 1 1
1 2 2 2 1
1 2 3 2 1
1 2 2 2 1
1 1 1 1 1
Sample linear combination of the "pyramid" IM (slice):
1 1 1 1 1 0 0 0 0 0 0 0 0 0 0
1 1 1 1 1 0 1 1 1 0 0 0 0 0 0
1 1 1 1 1 0 1 1 1 0 0 0 1 0 0
1 1 1 1 1 0 1 1 1 0 0 0 0 0 0
1 1 1 1 1 0 0 0 0 0 0 0 0 0 0
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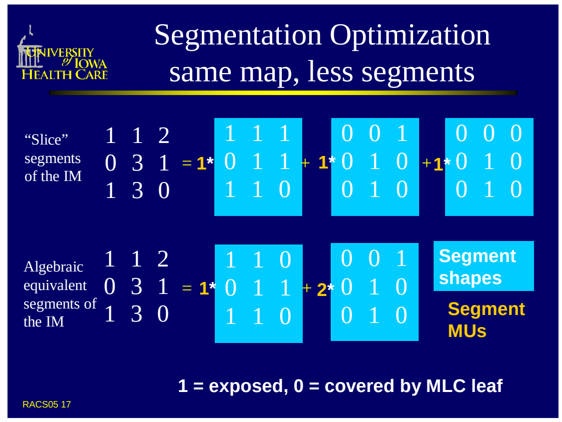
Segmentation Optimization
same map, less segments
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"Slice" segments of the IM
1 1 2
0 3 1
1 3 0
= 1*
1 1 1
0 1 1
1 1 0
+ 1*
0 0 1
0 1 0
0 1 0
+1*
0 0 0
0 1 0
0 1 0
Algebraic equivalent segments of the IM
1 1 2
0 3 1
1 3 0
= 1*
1 1 0
0 1 1
1 1 0
+ 2*
0 0 1
0 1 0
0 1 0
Segment shapes
Segment MUs
1 = exposed, 0 = covered by MLC leaf
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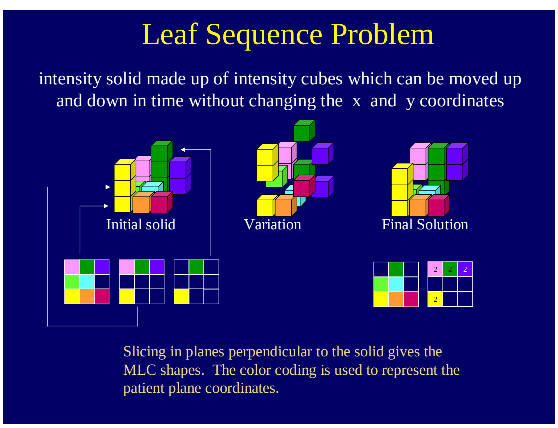
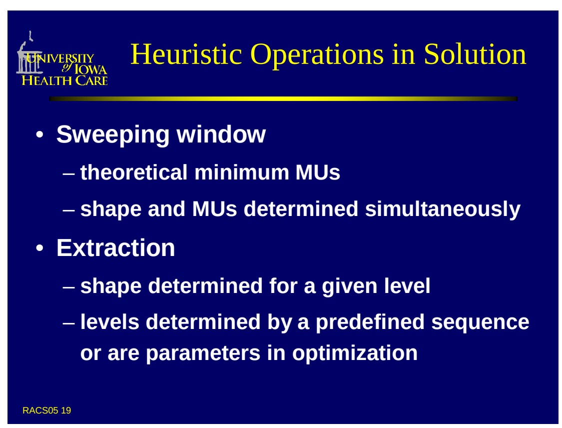

Leaf Sequence Problem
intensity solid made up of intensity cubes which can be moved up and down in time without changing the x and y coordinates
Initial solid
Variation
Final Solution
Slicing in planes perpendicular to the solid gives the MLC shapes. The color coding is used to represent the patient plane coordinates.


Heuristic Operations in Solution
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• Sweeping window
– theoretical minimum MUs
– shape and MUs determined simultaneously
• Extraction
– shape determined for a given level
– levels determined by a predefined sequence or are parameters in optimization
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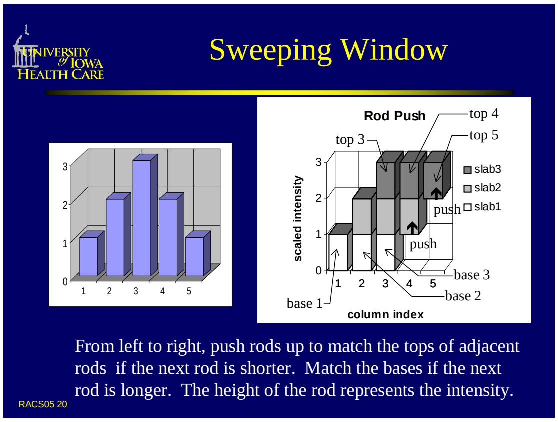
Sweeping Window
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Rod Push
top 4
top 5
top 3
scaled intensity
slab3
slab2
slab1
push
push
base 3
base 2
base 1
column index
From left to right, push rods up to match the tops of adjacent rods if the next rod is shorter. Match the bases if the next rod is longer. The height of the rod represents the intensity.
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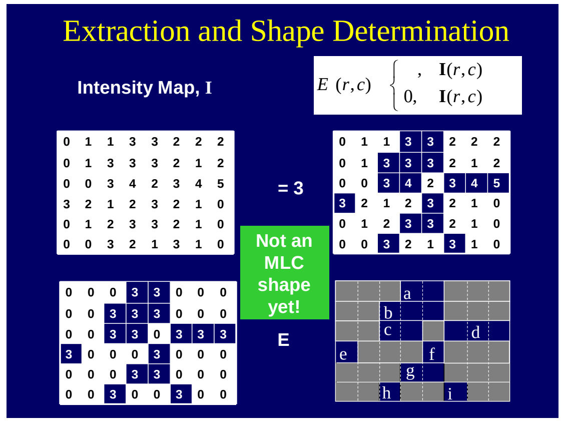
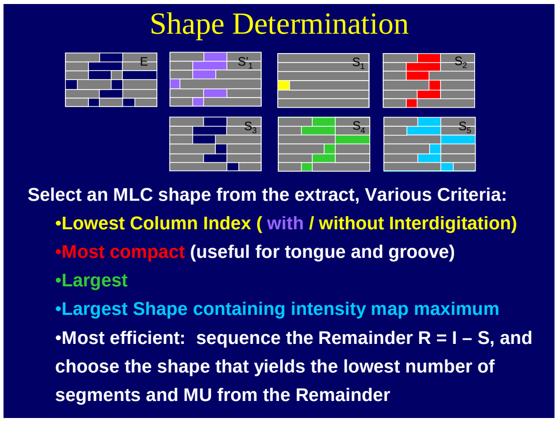
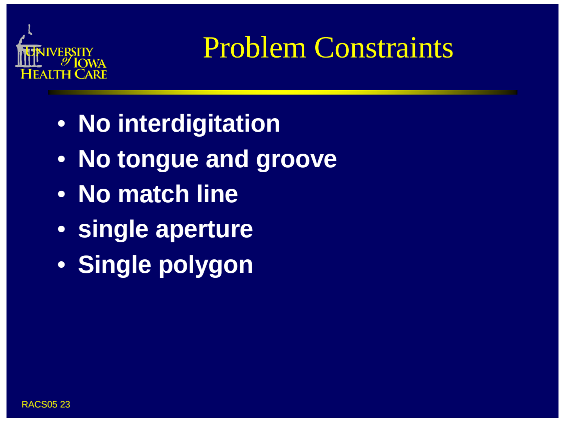

Extraction and Shape Determination
Intensity Map, I
E (r,c) { , I(r,c) / 0, I(r,c)
0 1 1 3 3 2 2 2
0 1 3 3 3 2 1 2
0 0 3 4 2 3 4 5
3 2 1 2 3 2 1 0
0 1 2 3 3 2 1 0
0 0 3 2 1 3 1 0
= 3
Not an MLC shape yet!
E
0 0 0 3 3 0 0 0
0 0 3 3 3 0 0 0
0 0 3 3 0 3 3 3
3 0 0 0 3 0 0 0
0 0 0 3 3 0 0 0
0 0 3 0 0 3 0 0
a
b
c
d
e
f
g
h
i


Shape Determination
E
S'1
S1
S2
S3
S4
S5
Select an MLC shape from the extract, Various Criteria:
•Lowest Column Index (with / without Interdigitation)
•Most compact (useful for tongue and groove)
•Largest
•Largest Shape containing intensity map maximum
•Most efficient: sequence the Remainder R = I – S, and choose the shape that yields the lowest number of segments and MU from the Remainder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Problem Constraints
• No interdigitation
• No tongue and groove
• No match line
• single aperture
• Single polygon
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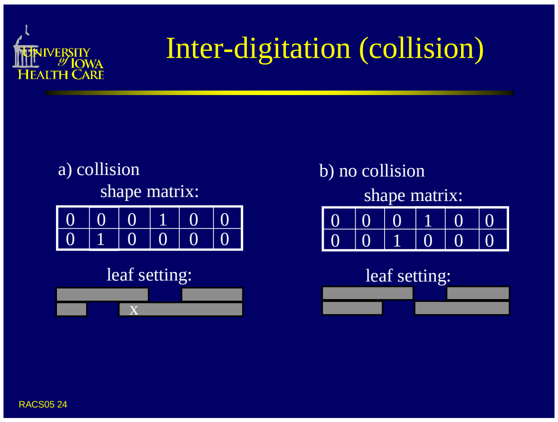
Inter-digitation (collision)
a) collision
shape matrix:
0 0 0 1 0 0
0 1 0 0 0 0
leaf setting:
x
b) no collision
shape matrix:
0 0 0 1 0 0
0 0 1 0 0 0
leaf setting:
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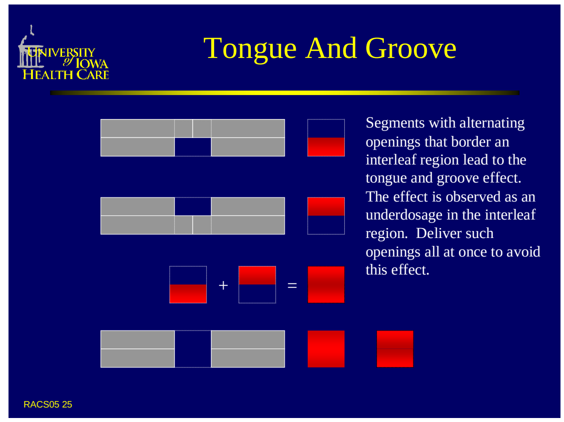
Tongue And Groove
Segments with alternating openings that border an interleaf region lead to the tongue and groove effect. The effect is observed as an underdosage in the interleaf region. Deliver such openings all at once to avoid this effect.
+
=
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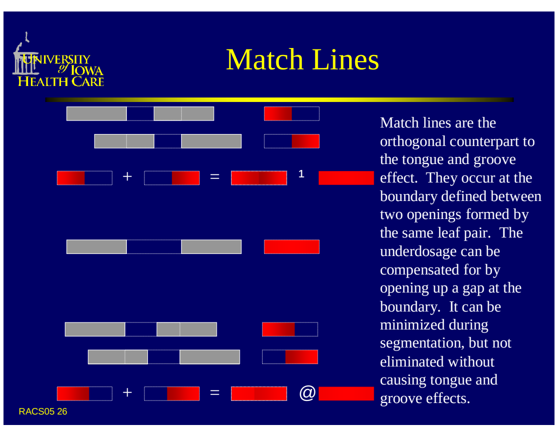
Match Lines
Match lines are the orthogonal counterpart to the tongue and groove effect. They occur at the boundary defined between two openings formed by the same leaf pair. The underdosage can be compensated for by opening up a gap at the boundary. It can be minimized during segmentation, but not eliminated without causing tongue and groove effects.
+
=
1
@
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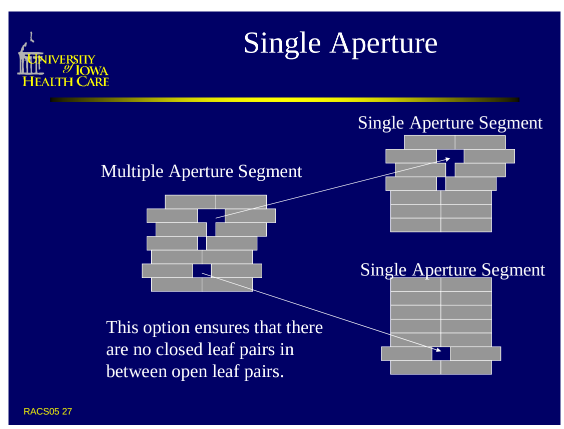
Single Aperture
Single Aperture Segment
Multiple Aperture Segment
Single Aperture Segment
This option ensures that there are no closed leaf pairs in between open leaf pairs.
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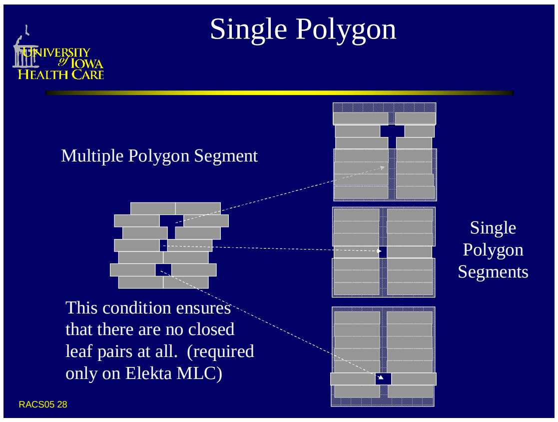
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Single Polygon
Multiple Polygon Segment
Single Polygon Segments
This condition ensures that there are no closed leaf pairs at all. (required only on Elekta MLC)
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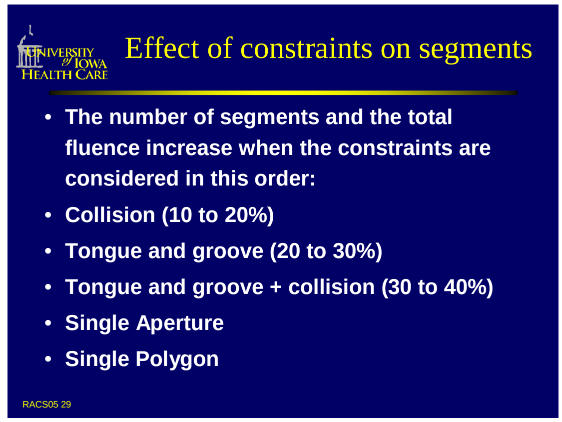
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Effect of constraints on segments
• The number of segments and the total fluence increase when the constraints are considered in this order:
• Collision (10 to 20%)
• Tongue and groove (20 to 30%)
• Tongue and groove + collision (30 to 40%)
• Single Aperture
• Single Polygon
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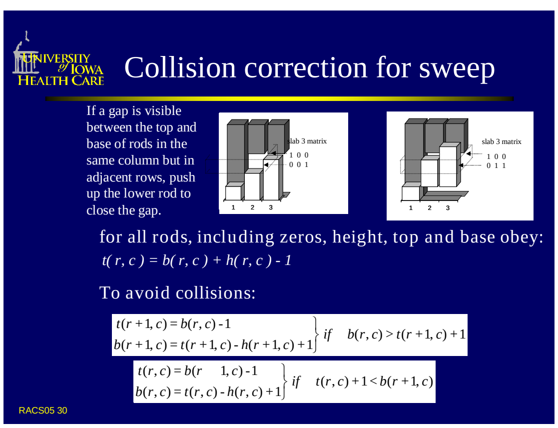
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Collision correction for sweep
If a gap is visible between the top and base of rods in the same column but in adjacent rows, push up the lower rod to close the gap.
slab 3 matrix
1 0 0
0 0 1
1 2 3
slab 3 matrix
1 0 0
0 1 1
1 2 3
for all rods, including zeros, height, top and base obey:
$t(r,c) = b(r,c) + h(r,c) - 1$
To avoid collisions:
$\left.\begin{array}{l} t(r+1,c) = b(r,c) - 1 \\ b(r+1,c) = t(r+1,c) - h(r+1,c) + 1 \end{array}\right\} \; if \quad b(r,c) > t(r+1,c) + 1$
$\left.\begin{array}{l} t(r,c) = b(r \quad 1,c) - 1 \\ b(r,c) = t(r,c) - h(r,c) + 1 \end{array}\right\} \; if \quad t(r,c) + 1 < b(r+1,c)$
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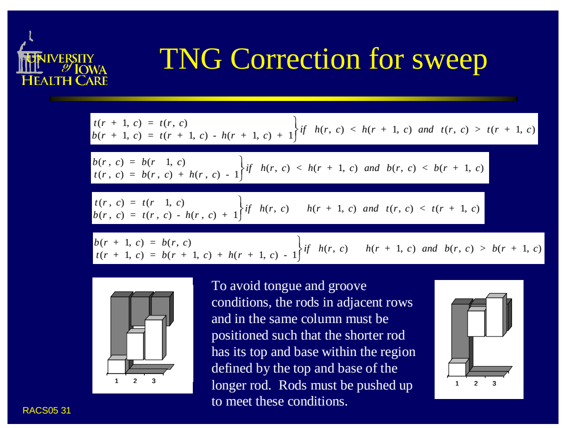
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TNG Correction for sweep
$\left.\begin{array}{l} t(r+1,c) = t(r,c) \\ b(r+1,c) = t(r+1,c) - h(r+1,c) + 1 \end{array}\right\} if \; h(r,c) < h(r+1,c) \; and \; t(r,c) > t(r+1,c)$
$\left.\begin{array}{l} b(r,c) = b(r \quad 1,c) \\ t(r,c) = b(r,c) + h(r,c) - 1 \end{array}\right\} if \; h(r,c) < h(r+1,c) \; and \; b(r,c) < b(r+1,c)$
$\left.\begin{array}{l} t(r,c) = t(r \quad 1,c) \\ b(r,c) = t(r,c) - h(r,c) + 1 \end{array}\right\} if \; h(r,c) \quad h(r+1,c) \; and \; t(r,c) < t(r+1,c)$
$\left.\begin{array}{l} b(r+1,c) = b(r,c) \\ t(r+1,c) = b(r+1,c) + h(r+1,c) - 1 \end{array}\right\} if \; h(r,c) \quad h(r+1,c) \; and \; b(r,c) > b(r+1,c)$
To avoid tongue and groove conditions, the rods in adjacent rows and in the same column must be positioned such that the shorter rod has its top and base within the region defined by the top and base of the longer rod. Rods must be pushed up to meet these conditions.
1 2 3
1 2 3
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Collision and TNG for Extraction

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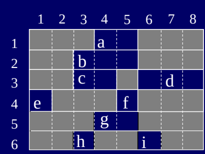
$$\mathbf{S}_e(r,c) = \begin{cases} {}_e, & \mathbf{I}(r,c) \quad {}_e \\ 0, & \mathbf{I}(r,c) \quad {}_e \end{cases}$$



Collision correction picks openings a, b, c, f, g, and h from S_e by performing an analysis of the openings that intersect pairs of columns, in this case 3 and 4.

Tongue and groove correction: if D = I - S ,
iterate between collision correction and elimination of cells that do not obey :

$$\mathbf{D}_e(r,c) \quad \mathbf{D}_e(r+1,c), \text{ if } \mathbf{S}_e(r,c) = 0 \text{ and } \mathbf{S}_e(r+1,c) > 0$$
$$\mathbf{D}_e(r,c) \quad \mathbf{D}_e(r-1,c), \text{ if } \mathbf{S}_e(r,c) = 0 \text{ and } \mathbf{S}_e(r-1,c) > 0$$

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Various Segmentation Algorithms

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- Sweeping window (Bortfeld et al)
- Slice (or close in)
- Areal reduction:
  - Count sequence (Galvin et al)
  - Power of 2 sequence (Xia and Verhey)
  - Half Max, Mean, Median sequence (Que)
- Optimization
  - Solid paradigm (IMFAST) (Siochi)
  - Segment shape optimization (Dai and Zhu)
  - Graph theory (Luan et al, Chen et al)

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Level selection methods

- Iterative
  - one extract at a time (ignores effect on subsequent extract selections)
  - Difference map of current round becomes intensity map of next round
  - Power of 2: level = power of 2 closest to half of the maximum value in the current intensity map
  - Counting: level = n, 1+2+…+n just >= maximum in map
  - Que: Half Maximum, Mean, Mode of map is the level
  - Shape Optimization: try all levels from 1 to maximum
  - Slice: Minimum in map
- Configurations: Optimization method in IMFAST (exhaustive parameter search, takes into account effect of prior extract selections)

Various Algorithms: Segments

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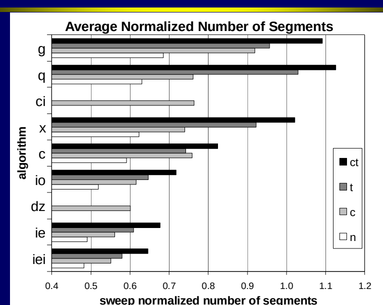

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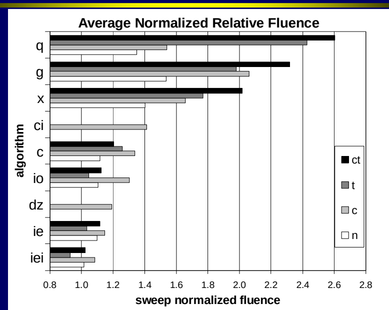
Various Algorithms: Fluence



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Segment Reduction

R. Alfredo C. Siochi: Modified IMFAST algorithm

TABLE V. The total number of segments and the total relative fluence for the various algorithms and constraints for the first head and neck case. iei is the modified IMFAST algorithm, ie is the partial modification, io is the original IMFAST (Ref. 3), dz is the algorithm of Dai and Zhu (Ref. 5), ci is the Corvus embedded version of IMFAST, 'c' is the algorithm of Crooks *et al.*,[7] 'x' is the algorithm of Xia and Verhey (Ref. 2), *q* is the algorithm of Que (Ref. 4), *g* is the algorithm of Galvin *et al.* (Ref. 1), and *b* is the algorithm of Bortfeld *et al.* (Ref. 8). The constraints are labeled *n* for no constraint, *c* for collision, *t* for tongue-and-groove, and *ct* for both collision and tongue-and-groove.

	Segments				Relative fluence			
Algorithm	*n*	*c*	*t*	*ct*	*n*	*c*	*t*	*ct*
iei	57	70	83	93	141	166	149	169
ie	59	71	84	95	152	173	175	194
io	63	78	91	101	155	198	172	189
dz	···	77	···	···	···	165	···	···
ci	···	103	···	···	···	211	···	···
c	72	101	109	118	156	200	210	198
x	74	91	128	141	187	235	267	314
q	77	94	141	160	179	217	366	391
g	82	115	134	163	204	291	305	390
b	124	132	142	143	138	144	158	161

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Optimization by Exhaustive Parameter SubSpace Searching

- Up to N extracts followed by rod pushing
- Unique sequence is defined by the extracts: ($_1$, $_2$, , $_n$) + Rod Push
- sum of extracts kept below some adjustable maximum to limit fluence

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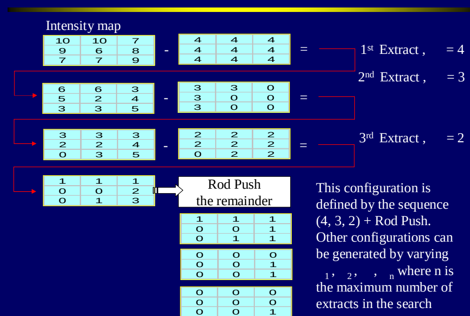
Example Configuration



This configuration is defined by the sequence (4, 3, 2) + Rod Push. Other configurations can be generated by varying $_1$, $_2$, , $_n$ where n is the maximum number of extracts in the search space.

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Leaf Sequencing Improvements

- **Variable Depth Recursion**
  - Method for finding the minimum number of treatment segments and MU
  - Checks the complexity of the remainder intensity map after a variable number of segment extractions
  - Faster than exhaustive parameter subspace search
- **Partial Synchronization**
  - remove only enough junctions to reduce the underdose to acceptable levels

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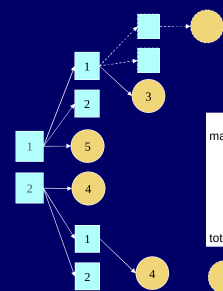
Variable Depth Recursion



A poor choice up front may not end up to be a poor choice down the road.
m1 = 1 layer of recursion
m2 = 2 layers of recursion

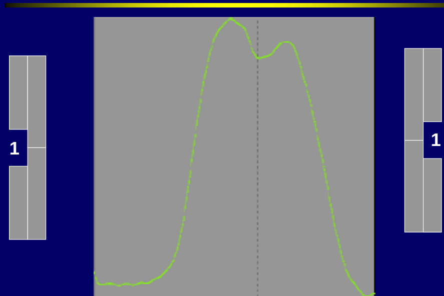
map #	m1 seg	m1 level	m2 seg	m2 level
	no interdig, no tng correct			
1	12	26	11	30
2	13	27	12	27
3	14	35	13	34
4	12	27	12	27
5	13	25	11	26
6	12	32	12	25
total	76	172	71	169

= complexity of remainder

= # levels extracted

Recursive: the algorithm itself is used to determine complexity

TNG Ratio – 1 to 1



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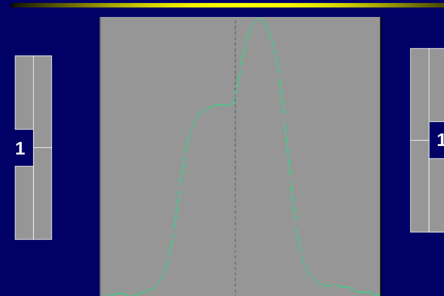
TNG Ratio – 1.5 to 1



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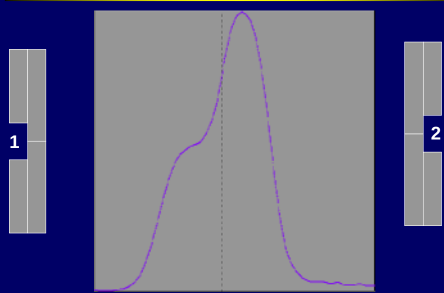
TNG Ratio – 2 to 1



RACS05 44

Recent Results

- Combining Partial Synchronization with Recursive Optimization
  - Optimization involves the sweep and extraction
  - Sweep algorithm already modified
  - Extraction algorithm recently modified
- Initial results compared to full TNG sweep
  - 16 levels: -68% segments, -10% MU
  - 3 levels: -31% segments, -6% MU

RACS05 45

Correcting The Map

- Fluence correction by segment weighting
- Fluence correction by resegmentation

RACS05 46

Effective Intensity Map

$$I_e(r, c) = {}_i \; {}_i (\; L_i(P_i(r,c) + {}_i(r,c) + {}_i(r,c)) \;)$$

$P_i(r,c)$ = 1 for exposed cells (r,c) and 0 for cells under a leaf.

${}_i$ is the scattering contribution relative to a 10 cm x 10 cm field

${}_i$ is the contribution due to transmission through the MLC leaves

L_i is the number of intensity steps (levels) the segment receives

${}_i$ is the segment correction factor

I_e is the effective intensity map.

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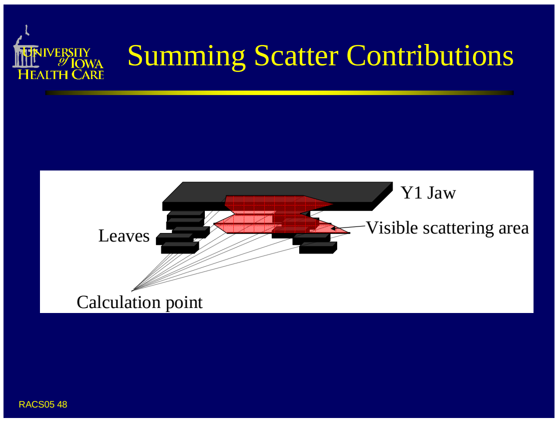
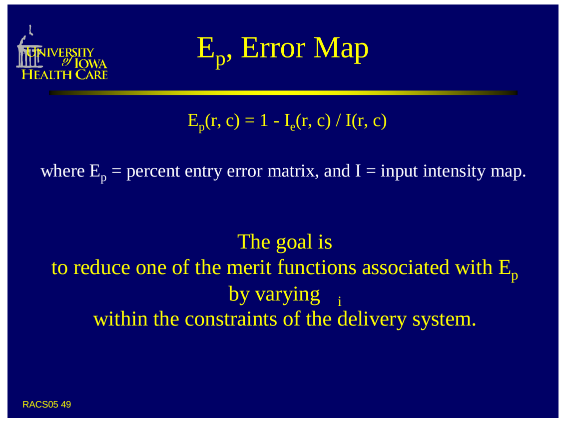

University of Iowa Health Care
Summing Scatter Contributions
Y1 Jaw
Visible scattering area
Leaves
Calculation point
RACS05 48


University of Iowa Health Care
E_p, Error Map
$E_p(r, c) = 1 - I_e(r, c) / I(r, c)$
where E_p = percent entry error matrix, and I = input intensity map.
The goal is
to reduce one of the merit functions associated with E_p
by varying $_i$
within the constraints of the delivery system.
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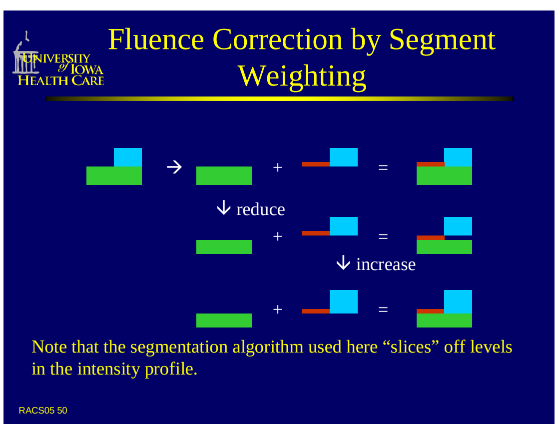
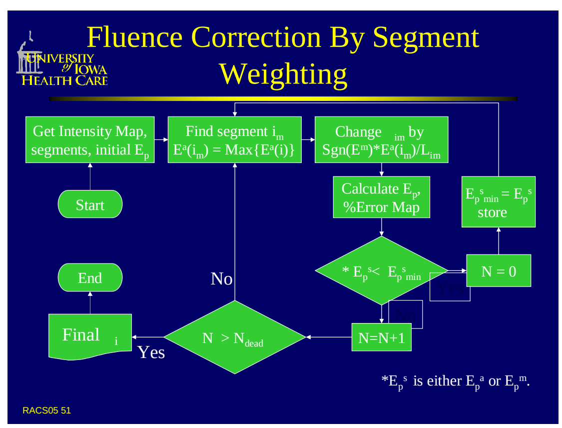
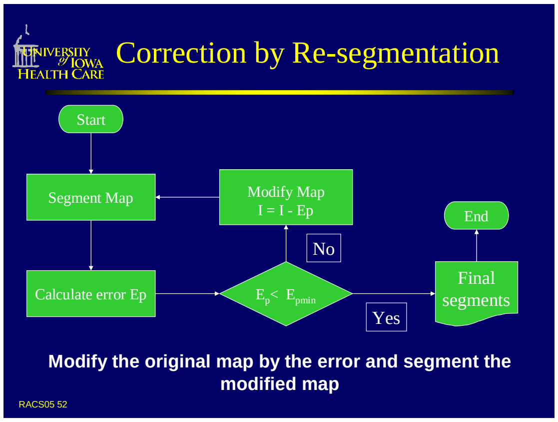
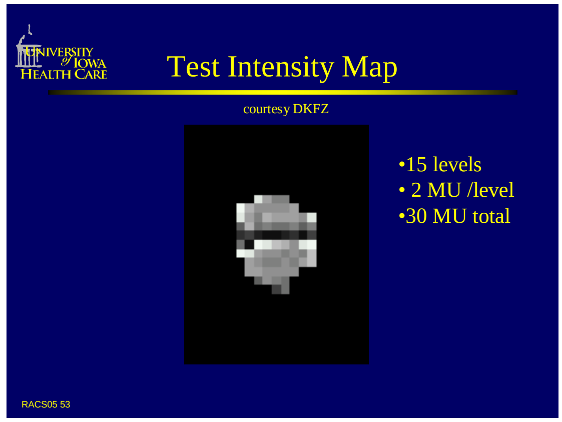
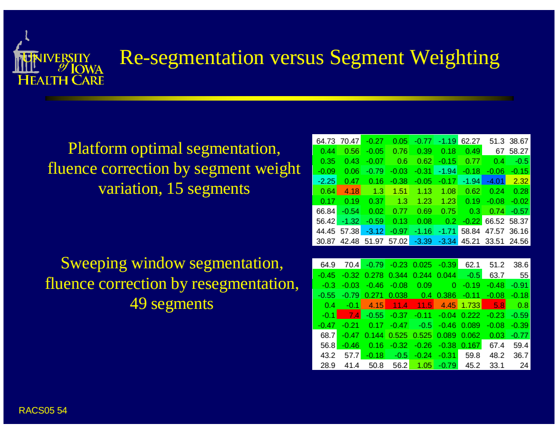

University of Iowa Health Care
Fluence Correction by Segment Weighting
→ + =
↓ reduce
+ =
↓ increase
+ =
Note that the segmentation algorithm used here "slices" off levels in the intensity profile.
RACS05 50


University of Iowa Health Care
Fluence Correction By Segment Weighting
Get Intensity Map, segments, initial E_p
Find segment i_m $E^a(i_m) = Max\{E^a(i)\}$
Change $_{im}$ by $Sgn(E^m)*E^a(i_m)/L_{im}$
Start
Calculate E_p, %Error Map
$E^s_{p\,min} = E^s_p$ store
End
No
* $E_p^s < E^s_{p\,min}$
N = 0
Final $_i$
Yes
N > N_{dead}
N=N+1
*E_p^s is either E_p^a or E_p^m.
RACS05 51

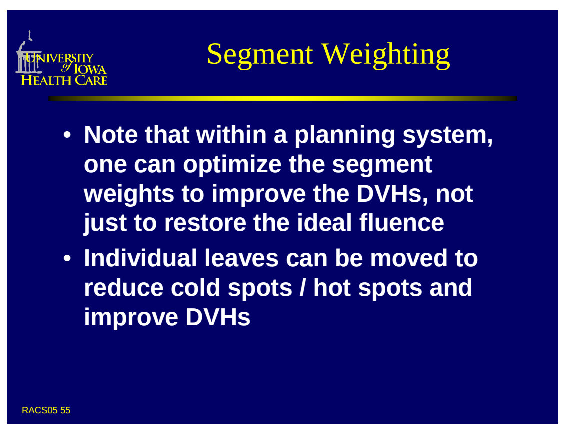






64.73	70.47	-0.27	0.05	-0.77	-1.19	62.27	51.3	38.67
0.44	0.56	-0.05	0.76	0.39	0.18	0.49	67	58.27
0.35	0.43	-0.07	0.6	0.62	-0.15	0.77	0.4	-0.5
-0.09	0.06	-0.79	-0.03	-0.31	-1.94	-0.18	-0.06	-0.15
-2.25	0.47	0.16	-0.38	-0.05	-0.17	-1.94	-4.01	2.32
0.64	4.18	1.3	1.51	1.13	1.08	0.62	0.24	0.28
0.17	0.19	0.37	1.3	1.23	1.23	0.19	-0.08	-0.02
66.84	-0.54	0.02	0.77	0.69	0.75	0.3	0.74	-0.57
56.42	-1.32	-0.59	0.13	0.08	0.2	-0.22	66.52	58.37
44.45	57.38	-3.12	-0.97	-1.16	-1.71	58.84	47.57	36.16
30.87	42.48	51.97	57.02	-3.39	-3.34	45.21	33.51	24.56

64.9	70.4	-0.79	-0.23	0.025	-0.39	62.1	51.2	38.6
-0.45	-0.32	0.278	0.344	0.244	0.044	-0.5	63.7	55
-0.3	-0.03	-0.46	-0.08	0.09	0	-0.19	-0.48	-0.91
-0.55	-0.79	0.271	0.038	0.4	0.386	-0.11	-0.08	-0.18
0.4	-0.1	4.15	11.4	11.5	4.45	1.733	5.8	0.8
-0.1	7.4	-0.55	-0.37	-0.11	-0.04	0.222	-0.23	-0.59
-0.47	-0.21	0.17	-0.47	-0.5	-0.46	0.089	-0.08	-0.39
68.7	-0.47	0.144	0.525	0.525	0.089	0.062	0.03	-0.77
56.8	-0.46	0.16	-0.32	-0.26	-0.38	0.167	67.4	59.4
43.2	57.7	-0.18	-0.5	-0.24	-0.31	59.8	48.2	36.7
28.9	41.4	50.8	56.2	1.05	-0.79	45.2	33.1	24



University of Iowa Health Care

Summary

- **Prepare the map carefully**
  - **Aim, proper optimization parameters, appropriate spatial and intensity resolution**
- **Optimize the segmentation**
  - **Proper settings/algorithm in sequencer**
- **Use segment weighting rather than re-segmentation**

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