Optimal disc and sphere packings

Daria Pchelina
LIP, équipe MC2

SIESTE seminar
16/10/2024

Optimal coin packings

Given infinite number of identical coins (),
how to place them on an infinite plane without overlap to maximize the covered surface?

coin packing: 

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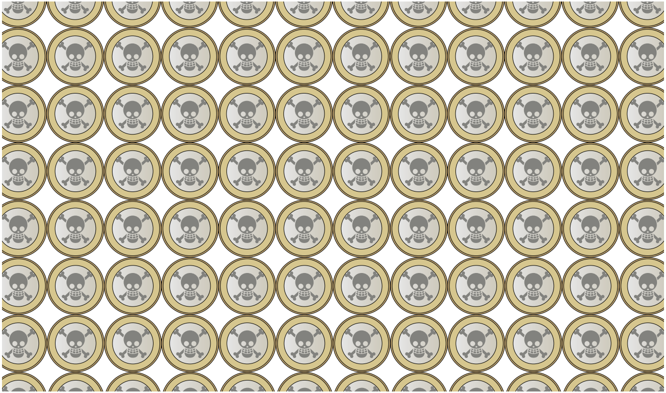
coin packing:
78%



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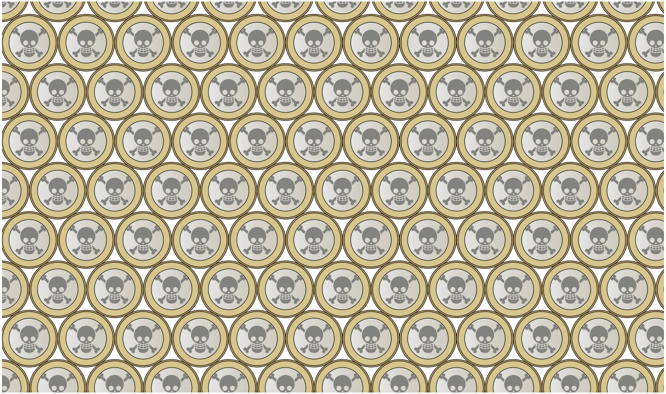
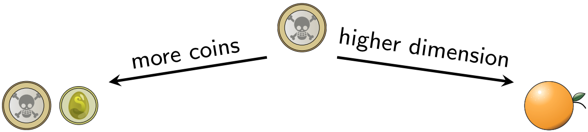
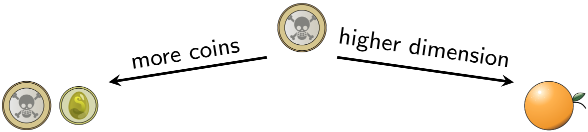
hexagonal coin packing:
90%

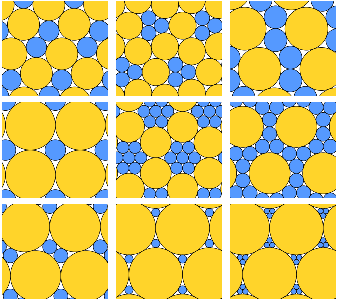


1910–1940

The hexagonal coin packing is optimal.


more coins
higher dimension





(proved optimal in 2000-2022)

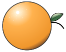
Kepler conjecture, 1611

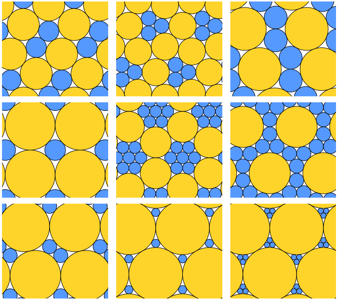
The “cannonball” packing is optimal:

(proved in 1998–2014)

more coins

higher dimension





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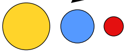

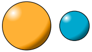

$\mathbb{R}^8, \mathbb{R}^{24}$

(Viazovska, Fields Medal 2022)

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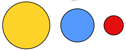

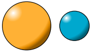

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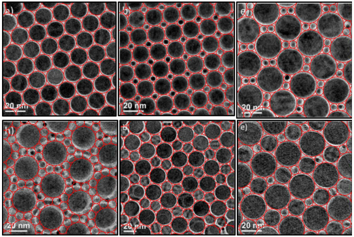
Nanomaterials and packings

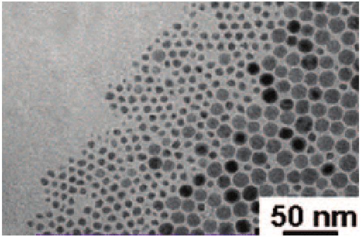
combine different types of nanoparticles
self-assembly

new material



Paik et al 2015

phase separation



Cheon et al 2006

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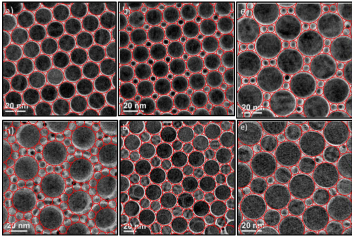

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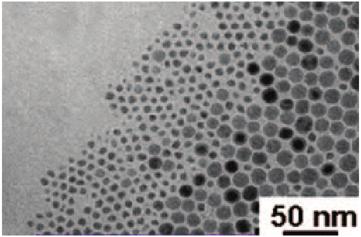
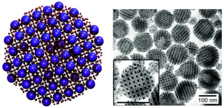


Cheon et al 2006

Also in 3D:

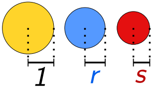


Wu, Fan, Yin 2022

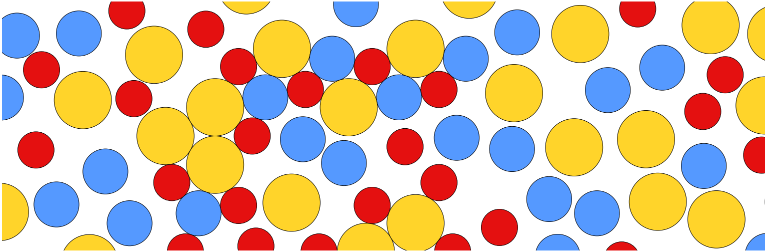
Chemists' question : **which sizes and concentrations allow for new materials?**

Definitions

Discs:



Packing P:
(in $\mathbb{R}^2$)



Disc packings

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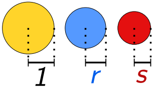
Discs: 

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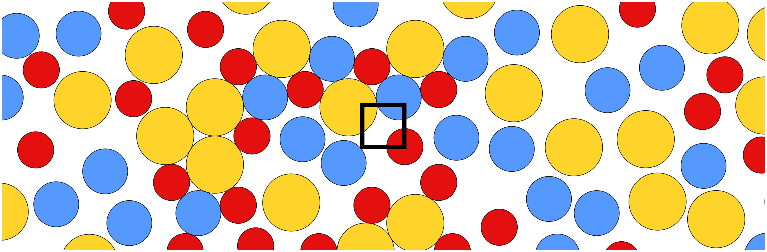

Density:

$$\delta(P) := \limsup_{n\to\infty} \frac{area([-n,n]^2 \cap P)}{area([-n,n]^2)}$$

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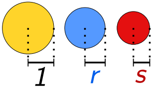

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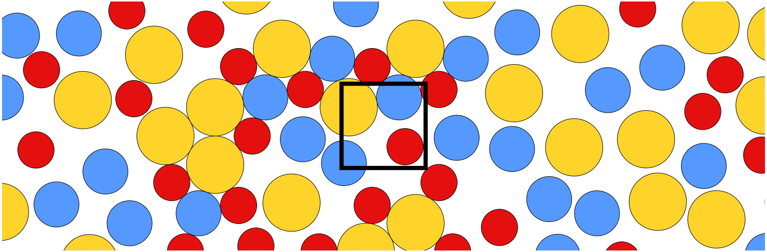

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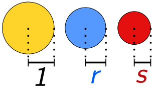

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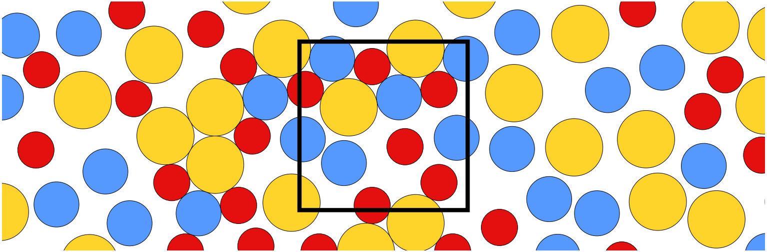

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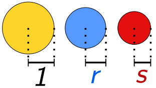

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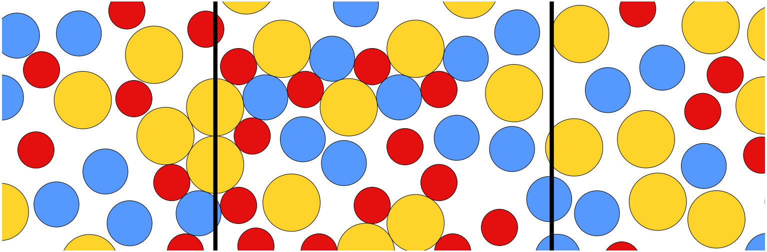

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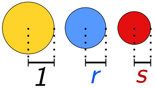

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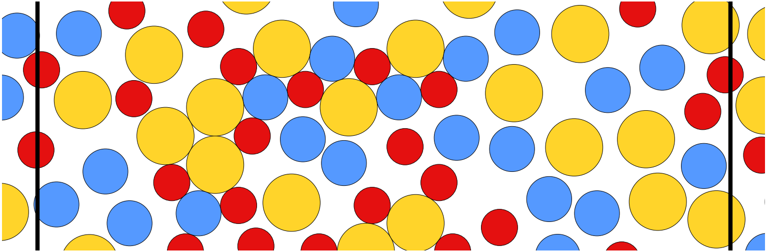

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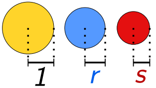

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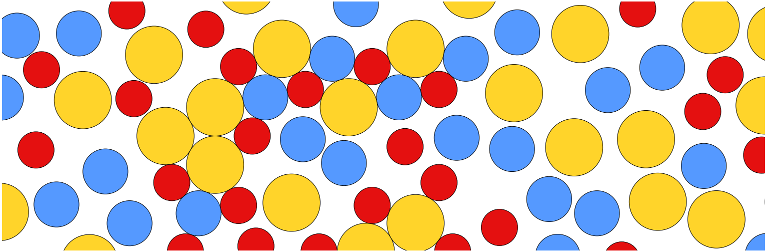

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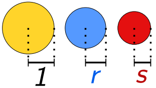
Discs: 

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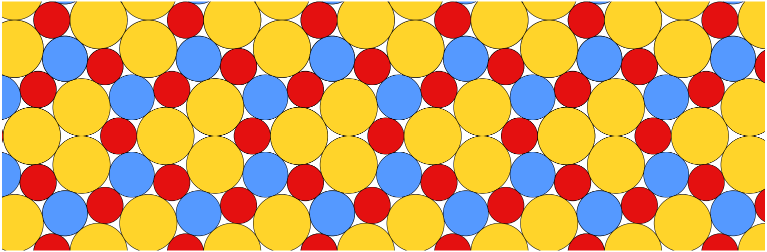

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Main Question

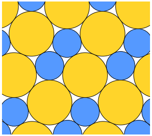
Given a finite set of discs (e.g., ),
what is the maximal density δ^* of a packing?

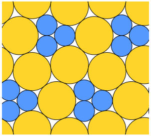
$$\delta^* := \sup_P \delta(P)$$

Optimal 2-disc packings

Theorem (Heppes 2000, 2003, Kennedy 2005, Bedaride and Fernique 2022)

Each of the following packings is optimal (densest) for discs of radii 1 and r:


$r \approx 0.63$ $\delta^* \approx 91.1\%$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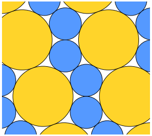
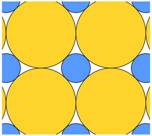
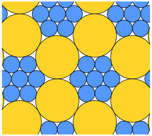
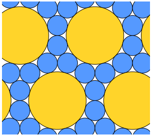

$r \approx 0.53$ $\delta^* \approx 91.4\%$


$r \approx 0.41$ $\delta^* \approx 92\%$


$r \approx 0.38$ $\delta^* \approx 92\%$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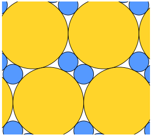
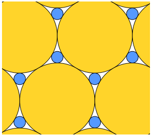
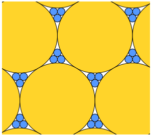

$r \approx 0.28$ $\delta^* \approx 93.2\%$


$r \approx 0.15$ $\delta^* \approx 95\%$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Disc packings

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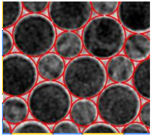

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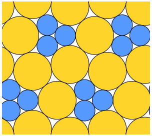

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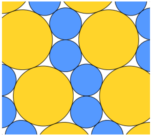

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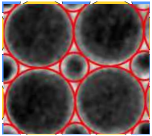

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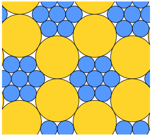

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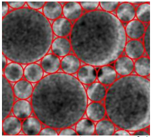

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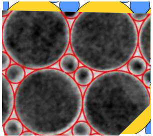

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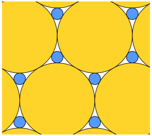

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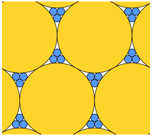

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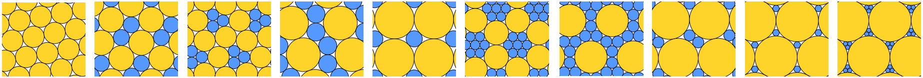
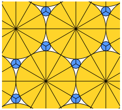
Connelly conjecture

Triangulated packings:



Conjecture (Connelly 2018)

If a finite set of discs allows **saturated** triangulated packings then one of them is optimal.



triangulated
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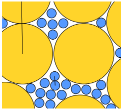
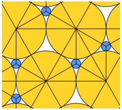


non triangulated
saturated



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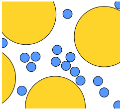

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Connelly conjecture

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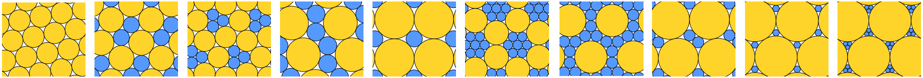

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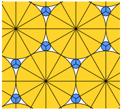

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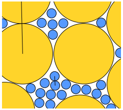

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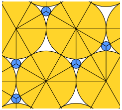

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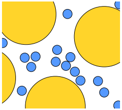
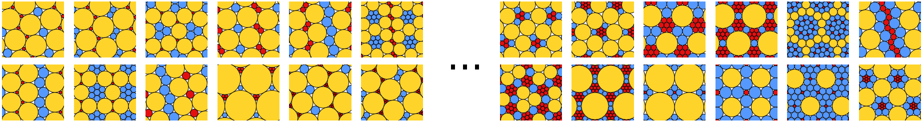
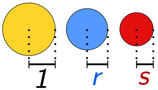


non triangulated
non saturated

Theorem (Fernique, Hashemi, Sizova 2019)

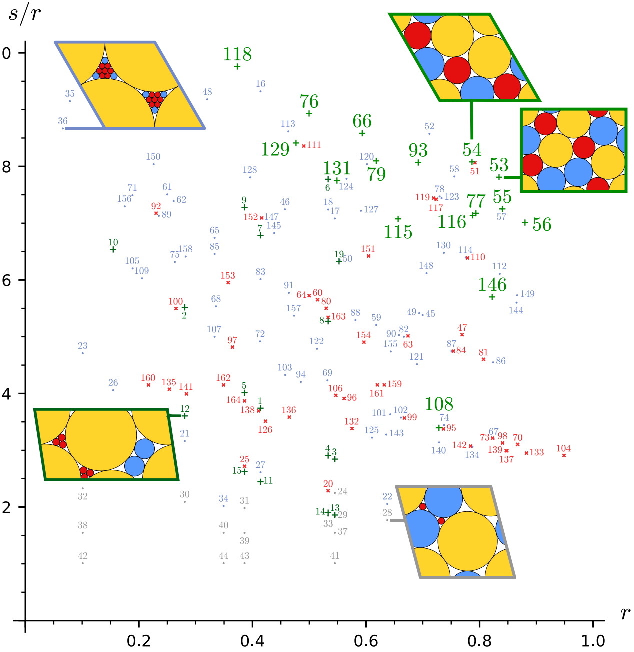
Discs of radii 1, r *and* s*: there are 164 pairs* (r, s) *allowing triangulated packings.*





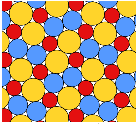
164 (r, s) allowing triangulated packings:

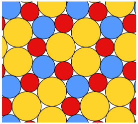
- 15 cases: non saturated
- 16+16 cases: a **ternary** or **binary** triangulated packing is densest
- 45 cases: a binary **non** triangulated packing is denser

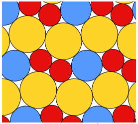


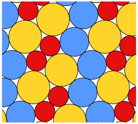
Theorem (Fernique, P 2023)

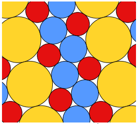
Each of the following packings is optimal for discs of radii 1, r and s:

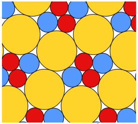

$r\approx0.8$ $s\approx0.7$ $\delta^*\approx90.9\%$

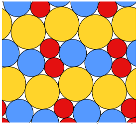

$r\approx0.8$ $s\approx0.6$ $\delta^*\approx90.9\%$

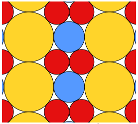

$r\approx0.8$ $s\approx0.6$ $\delta^*\approx91\%$

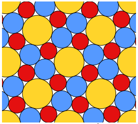

$r\approx0.8$ $s\approx0.6$ $\delta^*\approx90.9\%$

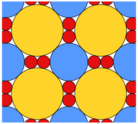

$r\approx0.6$ $s\approx0.5$ $\delta^*\approx91.2\%$

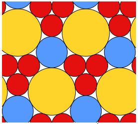

$r\approx0.5$ $s\approx0.4$ $\delta^*\approx91.5\%$

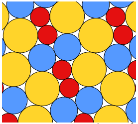

$r\approx0.8$ $s\approx0.6$ $\delta^*\approx91\%$

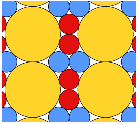

$r\approx0.6$ $s\approx0.5$ $\delta^*\approx91.3\%$

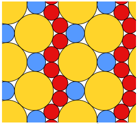

$r\approx0.7$ $s\approx0.5$ $\delta^*\approx91.1\%$

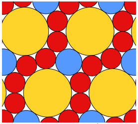

$r\approx0.7$ $s\approx0.2$ $\delta^*\approx93.2\%$

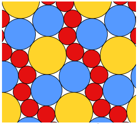

$r\approx0.7$ $s\approx0.5$ $\delta^*\approx91.5\%$


$r\approx0.8$ $s\approx0.6$ $\delta^*\approx91\%$


$r\approx0.4$ $s\approx0.4$ $\delta^*\approx92.2\%$

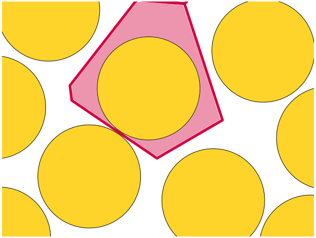

$r\approx0.5$ $s\approx0.4$ $\delta^*\approx91.8\%$


$r\approx0.5$ $s\approx0.4$ $\delta^*\approx91.7\%$

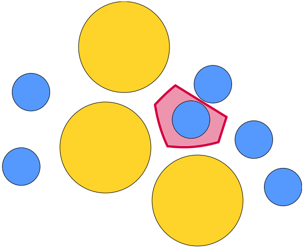

$r\approx0.8$ $s\approx0.5$ $\delta^*\approx91.2\%$

FM-triangulation

1-disc packing



multi-size disc packing

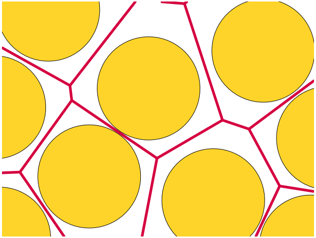


Voronoi cell of a disc in a packing: set of points closer to this disc than to any other

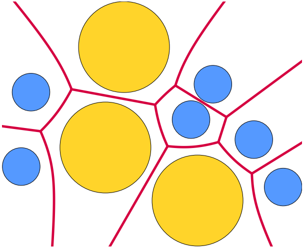
Disc packings

FM-triangulation

1-disc packing



multi-size disc packing

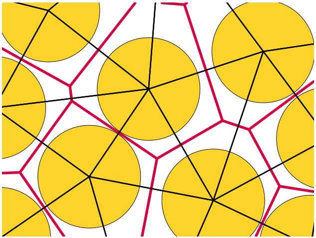


Voronoi cell of a disc in a packing: set of points closer to this disc than to any other

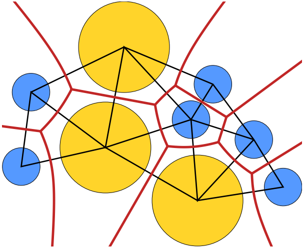
Voronoi diagram of a packing: partition of the plane into Voronoi cells

FM-triangulation

1-disc packing



multi-size disc packing



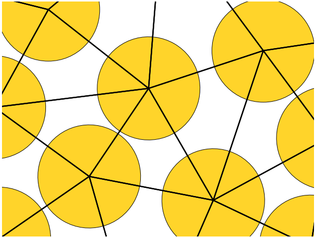
Voronoi cell of a disc in a packing: set of points closer to this disc than to any other

Voronoi diagram of a packing: partition of the plane into Voronoi cells

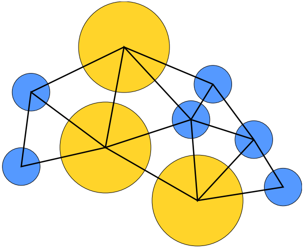
FM-triangulation of a packing: dual graph of the Voronoi diagram

FM-triangulation

1-disc packing



multi-size disc packing



Voronoi cell of a disc in a packing: set of points closer to this disc than to any other

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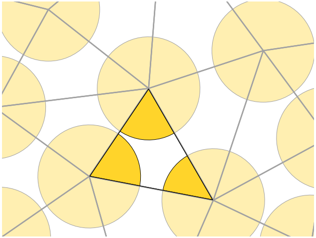
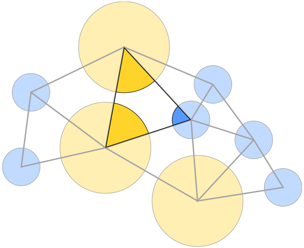
FM-triangulation

1-disc packing



multi-size disc packing



Voronoi cell of a disc in a packing: set of points closer to this disc than to any other

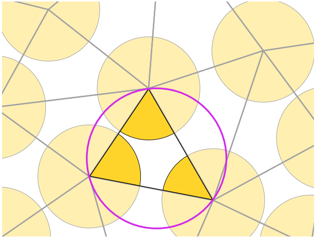
Voronoi diagram of a packing: partition of the plane into Voronoi cells

FM-triangulation of a packing: dual graph of the Voronoi diagram

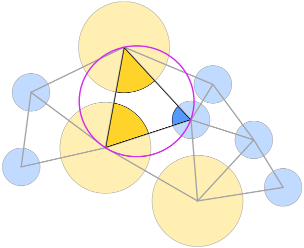
Density of a triangle Δ in a packing $=$ its proportion covered by discs $\delta_\Delta = \frac{area(\Delta \cap P)}{area(\Delta)}$

FM-triangulation

1-disc packing



multi-size disc packing



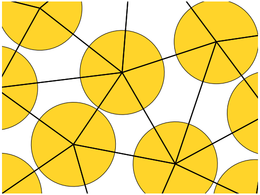
Voronoi cell of a disc in a packing: set of points closer to this disc than to any other

Voronoi diagram of a packing: partition of the plane into Voronoi cells

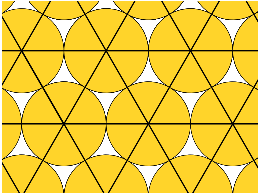
FM-triangulation of a packing: dual graph of the Voronoi diagram

Density of a triangle Δ in a packing $=$ its proportion covered by discs $\quad \delta_\Delta = \frac{area(\Delta \cap P)}{area(\Delta)}$

Local density redistribution

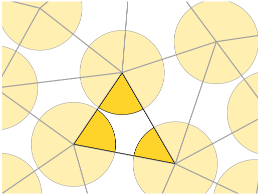


P of density $\delta(P)$



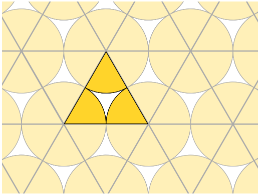
P^* of density $\delta^* = \frac{\pi}{2\sqrt{3}}$

Local density redistribution



P of density $\delta(P)$

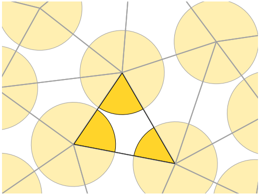
$\forall\Delta,\ \ \delta(\Delta) \leq \delta($$) = \delta^*$



P^* of density $\delta^* = \frac{\pi}{2\sqrt{3}}$

$\delta($$) = \delta^*$

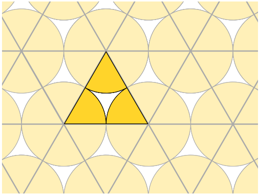
Local density redistribution



P of density $\delta(P)$

$\forall\Delta,\ \delta(\Delta) \leq \delta($$) = \delta^*$

$\delta(P) \leq \delta^*$



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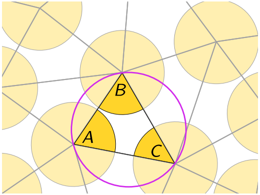
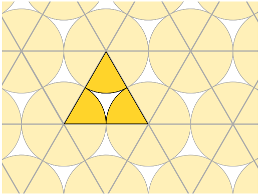
Local density redistribution



P of density $\delta(P)$

$\forall\Delta,\ \delta(\Delta) \leq \delta($  $) = \delta^*$

$\delta(P) \leq \delta^*$



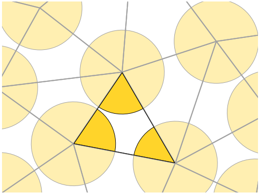
P^* of density $\delta^* = \frac{\pi}{2\sqrt{3}}$

$\delta($  $) = \delta^*$

Proof:

- the smallest angle of any Δ is at least $\frac{\pi}{6}$ $\qquad 2 > R = \frac{|AB|}{2\sin\widehat{C}} \geq \frac{1}{\sin\widehat{C}} \implies \widehat{C} > \frac{\pi}{6}$
- thus the largest angle is between $\frac{\pi}{3}$ and $\frac{2\pi}{3}$
- density of a triangle Δ: $\delta(\Delta) = \frac{\pi/2}{area(\Delta)}$
- the area of a triangle ABC with the largest angle $\hat{A}$: $\frac{|AB|\cdot|AC|\cdot\sin\widehat{A}}{2} \geq \frac{2\cdot 2\cdot\frac{\sqrt{3}}{2}}{2} = \sqrt{3}$
- thus the density of ABC is less or equal to $\frac{\pi/2}{\sqrt{3}} = \delta^*$

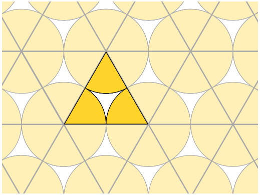
Local density redistribution



P of density $\delta(P)$

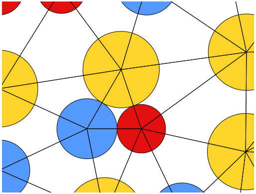
$\forall\Delta,\ \delta(\Delta) \leq \delta($$) = \delta^*$

$\delta(P) \leq \delta^*$

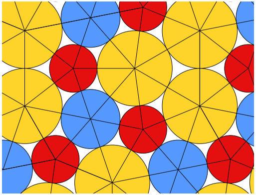


P^* of density $\delta^* = \frac{\pi}{2\sqrt{3}}$

$\delta($$) = \delta^*$

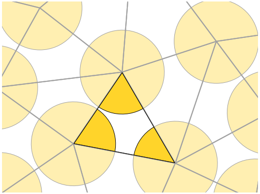


P of density $\delta(P)$



P^* of density δ^*

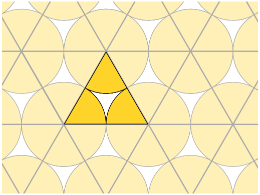
Local density redistribution



P of density $\delta(P)$

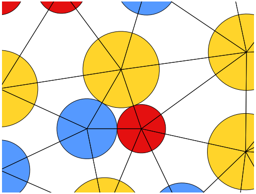
$\forall \Delta,\ \delta(\Delta) \leq \delta(\triangle) = \delta^*$

$\delta(P) \leq \delta^*$



P^* of density $\delta^* = \frac{\pi}{2\sqrt{3}}$

$\delta(\triangle) = \delta^*$

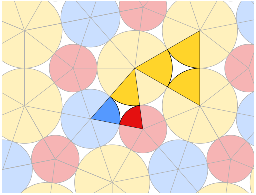


P of density $\delta(P)$

Triangles in P^* have different densities:

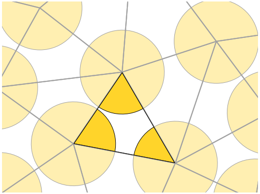
$\delta(\triangle) < \delta^* < \delta(\triangle)$

Hopeless to bound the density by δ^* in each triangle...



P^* of density δ^*

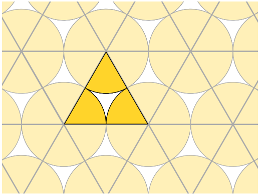
Local density redistribution



P of density $\delta(P)$

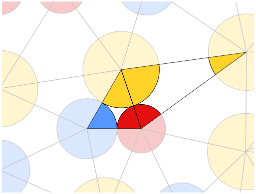
$\forall\Delta,\ \ \delta(\Delta) \leq \delta($  $) = \delta^*$

$\delta(P) \leq \delta^*$



P^* of density $\delta^* = \frac{\pi}{2\sqrt{3}}$

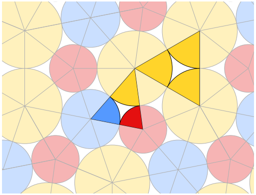
$\delta($  $) = \delta^*$



P of density $\delta(P) \leq \delta'(P)$

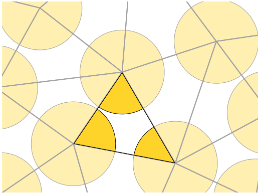
redistributed density δ':

dense triangles
share their density
with neighbors



P^* of density δ^*

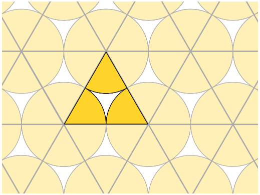
Local density redistribution



P of density $\delta(P)$

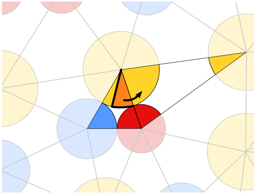
$\forall\Delta,\ \delta(\Delta) \leq \delta($$) = \delta^*$

$\delta(P) \leq \delta^*$



P^* of density $\delta^* = \frac{\pi}{2\sqrt{3}}$

$\delta($$) = \delta^*$



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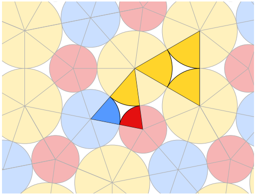
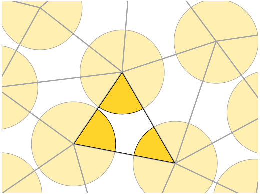


P^* of density δ^*

Local density redistribution



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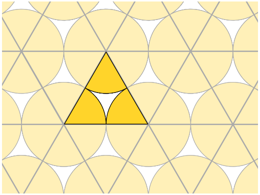
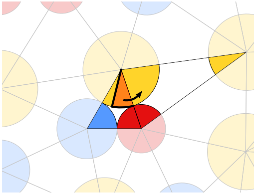
$\delta(P) \leq \delta^*$



P^* of density $\delta^* = \frac{\pi}{2\sqrt{3}}$

$\delta($$) = \delta^*$



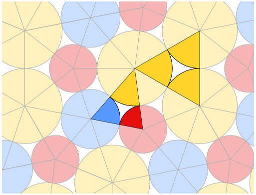
P of density $\delta(P) \leq \delta'(P)$

$\forall\Delta,\ \delta'(\Delta) \leq \delta^*$

$\delta(P) \leq \delta'(P) \leq \delta^*$

redistributed density δ':

dense triangles
share their density
with neighbors



P^* of density δ^*

Verifying inequalities on compact sets

How to check $\delta'(\Delta) \leq \delta^*$ on each possible triangle Δ? (there is a continuum of them)

Verifying inequalities on compact sets

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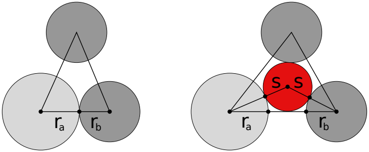
FM-triangulation properties + saturation ⇒ uniform bound on edge length

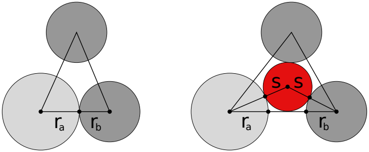


$$r_a + r_b \leq c \leq r_a + r_b + 2s$$

Verifying inequalities on compact sets

How to check $\delta'(\Delta) \leq \delta^*$ on each possible triangle Δ? (there is a continuum of them)

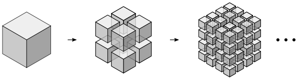
FM-triangulation properties + saturation $\Rightarrow$ uniform bound on edge length



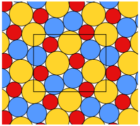
$$r_a + r_b \leq c \leq r_a + r_b + 2s$$

- Interval arithmetic: to verify $\delta'(\Delta_{a,b,c}) \leq \delta^*$ for all $(a,b,c) \in [\underline{a}, \overline{a}] \times [\underline{b}, \overline{b}] \times [\underline{c}, \overline{c}]$,
  we verify $[\underline{\delta}, \overline{\delta}] \leq \delta^*$ where $[\underline{\delta}, \overline{\delta}] = \delta'(\Delta_{[\underline{a},\overline{a}],[\underline{b},\overline{b}],[\underline{c},\overline{c}]})$

- If $\delta^* \in [\underline{\delta}, \overline{\delta}]$, recursive subdivision:



Our proof worked for these cases: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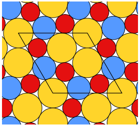
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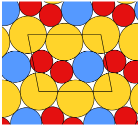
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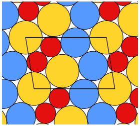
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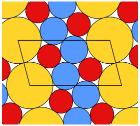
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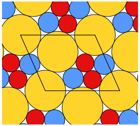
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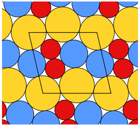
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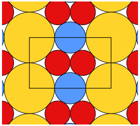
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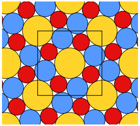
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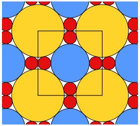
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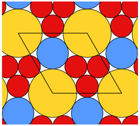
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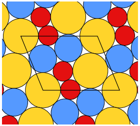
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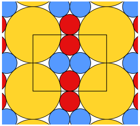
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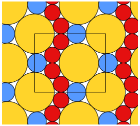
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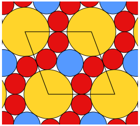
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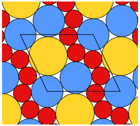
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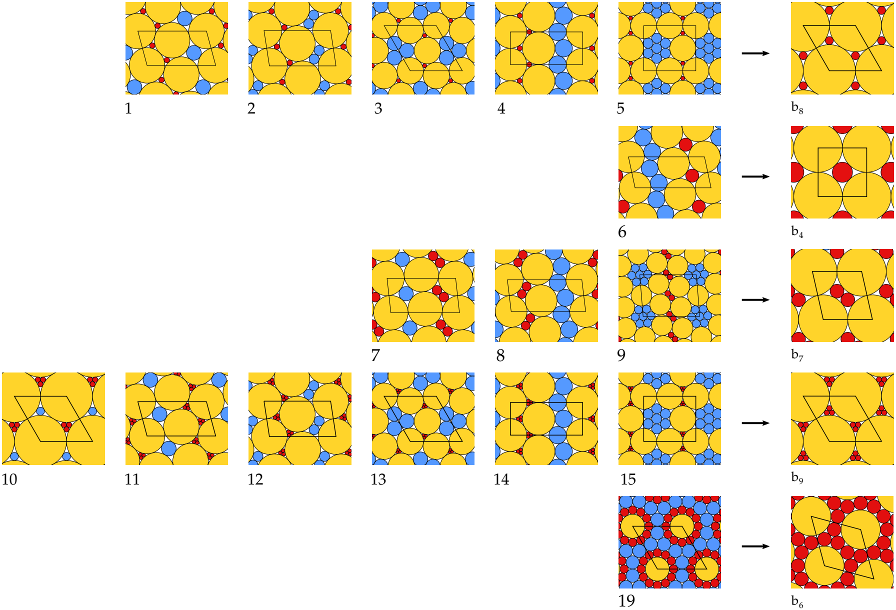
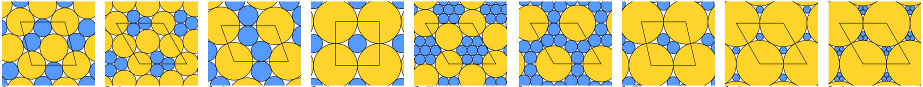
And these:



45 counter examples: *flip-and-flow* method

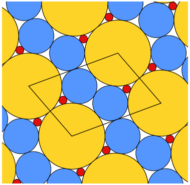


b1 b2 b3 b4 b5 b6 b7 b8 b9

When the ratio of two discs is close enough to the ratio in a dense binary packing, we can pack these discs in a similar manner (non triangulated) and still get high density

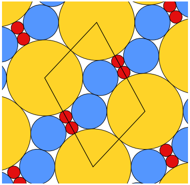
ternary triangulated packing

20



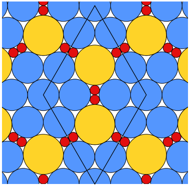
$\delta \leq 0.931369$ $s \approx 0.121445$

136



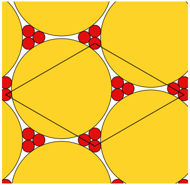
$\delta \leq 0.924522$ $s \approx 0.166169$

142

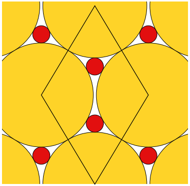


$\delta \leq 0.917352$ $s \approx 0.240205$

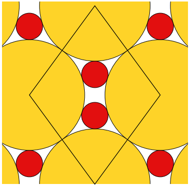
counter example using only 2 discs



$\delta \geq 0.937371$ $s \approx 0.121445$

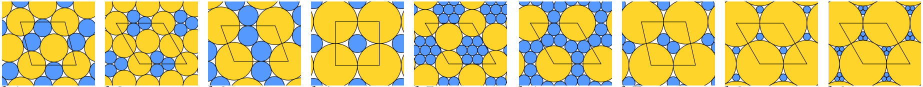


$\delta \geq 0.939305$ $s \approx 0.166169$



$\delta \geq 0.918420$ $s \approx 0.240205$

45 counter examples: *flip-and-flow* method


b1 b2 b3 b4 b5 b6 b7 b8 b9

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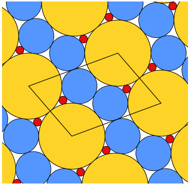
ternary triangulated packing

20



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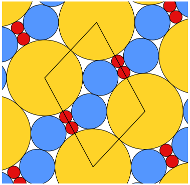

$\delta \leq 0.924522$ $s \approx 0.166169$

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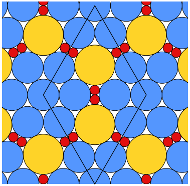
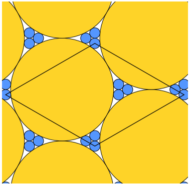
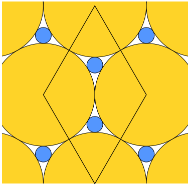


$\delta \leq 0.917352$ $s \approx 0.240205$

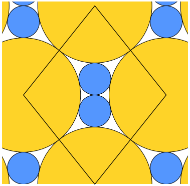
dense binary packing



$\delta \approx 0.962430$ $r \approx 0.101021$



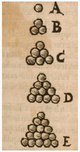
$\delta \approx 0.950308$ $r \approx 0.154701$

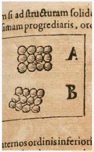


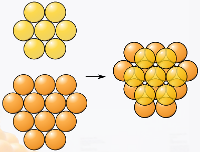
$\delta \approx 0.931901$ $r \approx 0.280776$

Kepler conjecture: ●-packings

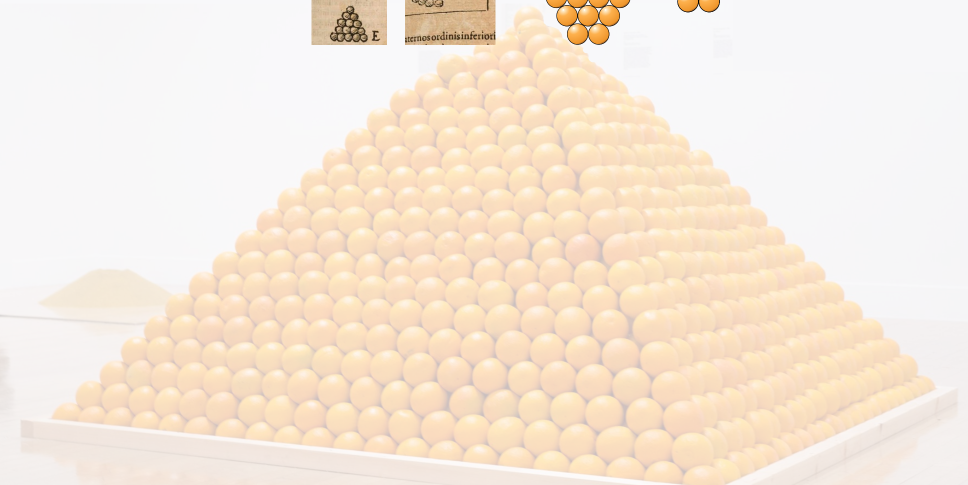
3D close ●-packing:





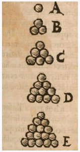


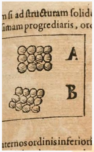
$$\delta^* = \frac{\pi}{3\sqrt{2}} \approx 74\%$$

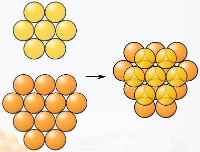


Kepler conjecture: -packings

3D close -packing:







$\delta^* = \frac{\pi}{3\sqrt{2}} \approx 74\%$

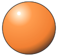
Kepler conjecture, 1611

Close packing is optimal.

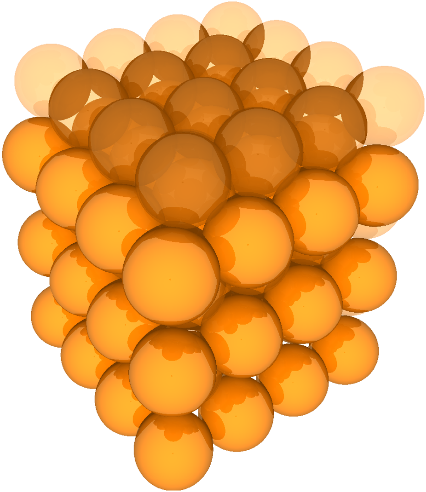
- close packing is optimal among lattice packings — Gauss, 1831
- 18th problem of the Hilbert's list — 1900
- 6 preprints by Hales and Ferguson — ArXiv 1998
  $>$ 180000 lines of code
- 13 reviewers, 4 years... "99% certain" — 1999–2003
- published proof: 300 pages, 3 computer programs — DCG 2006
- formal proof: Flyspeck project (HOL Light) — 2003–2014

Rock salt -packings

sphere

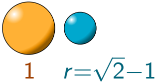


cannonball packing

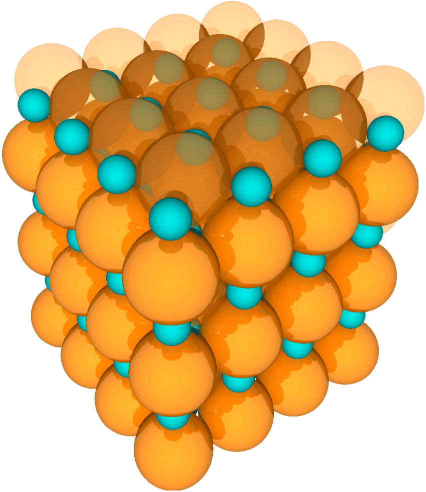


Rock salt -packings

rock salt spheres

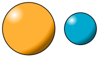


rock salt packing



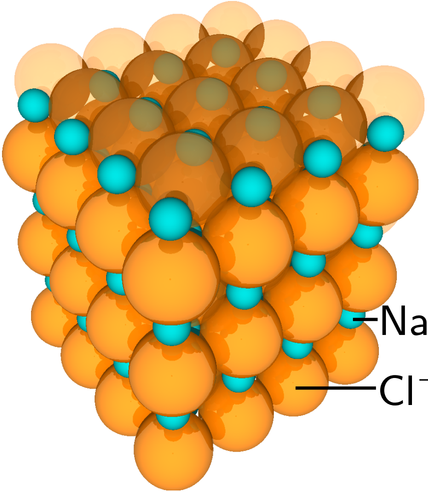
Rock salt -packings

rock salt spheres



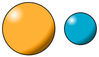
1 $r=\sqrt{2}-1$

rock salt packing



Rock salt ●●-packings

rock salt spheres



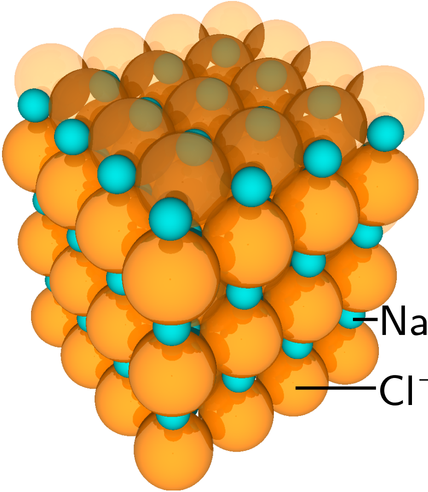
1 $r = \sqrt{2} - 1$

triangulated $\rightarrow$ simplicial
(contact graph is a "tetrahedration")

Fernique, 2019

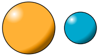
The only simplicial 2-sphere packings are rock salt packings.

rock salt packing



Rock salt -packings

rock salt spheres



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Fernique, 2019

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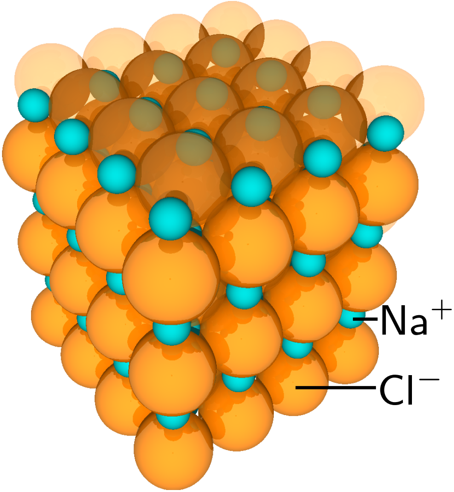
Salt conjecture **open problem**

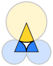
Rock salt packing is optimal $\delta^* \approx 79\%$

rock salt packing



Upper density bound for ○○-packings in 2D

Florian, 1960

The density of a packing never exceeds the density in the following triangle: 

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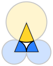
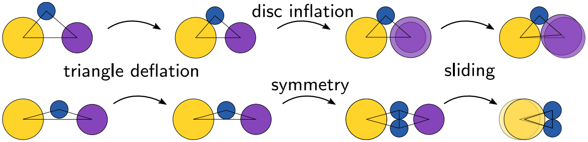
The density of a packing never exceeds the density in the following triangle: 

Proof:

- dimension reduction $(3 \to 1)$ — Fejes Tóth, Mólnar, 1958
  for any triangle, there is a denser triangle with at least two contacts between discs



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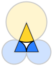

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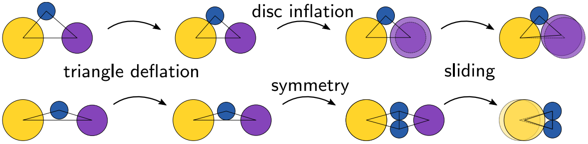
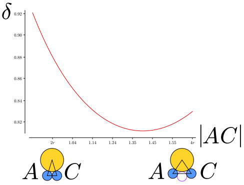
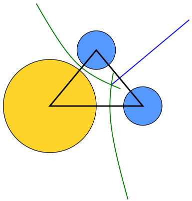


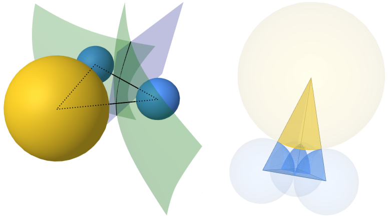
- analysis



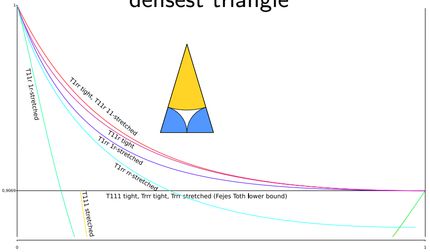
Upper density bound for ●●-packings

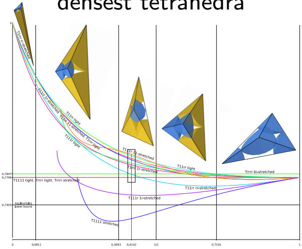
FM-triangulation (triangles) → FM-simplicial partition (tetrahedra)





densest triangle → densest tetrahedra

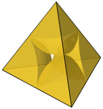




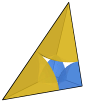
Upper density bound for -packings

Theorem, $r = \sqrt{2} - 1$ — in progress

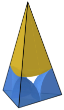
Each of the following tetrahedra is densest among the tetrahedra with the same spheres:



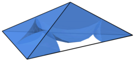
$\delta_{1111} \approx 0.7209$



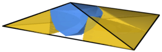
$\delta_{11rr} \approx 0.8105$



$\delta_{1rrr} \approx 0.8065$



$\delta_{rrrr} \approx 0.7847$

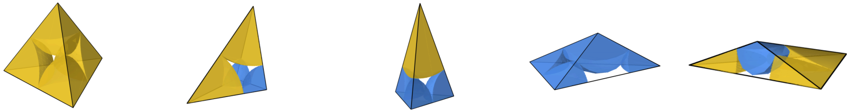


$\delta_{111r} \approx 0.8125$

Upper density bound for ●●-packings

Theorem, $r = \sqrt{2} - 1$ — in progress

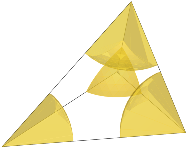
Each of the following tetrahedra is densest among the tetrahedra with the same spheres:



$\delta_{1111} \approx 0.7209$ $\delta_{11rr} \approx 0.8105$ $\delta_{1rrr} \approx 0.8065$ $\delta_{rrrr} \approx 0.7847$ $\delta_{111r} \approx 0.8125$

Proof:

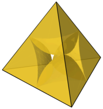
- dimension reduction ($6 \to 4$):
  tetrahedron deflation + sphere sliding



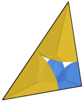
Upper density bound for -packings

Theorem, $r = \sqrt{2} - 1$ — in progress

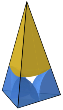
Each of the following tetrahedra is densest among the tetrahedra with the same spheres:



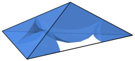
$\delta_{1111} \approx 0.7209$



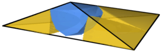
$\delta_{11rr} \approx 0.8105$



$\delta_{1rrr} \approx 0.8065$



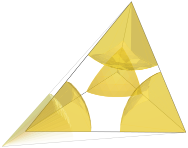
$\delta_{rrrr} \approx 0.7847$



$\delta_{111r} \approx 0.8125$

Proof:

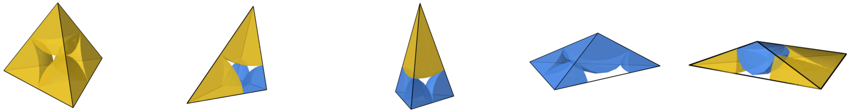
- dimension reduction $(6 \to 4)$:
  tetrahedron deflation + sphere sliding



Upper density bound for ●●-packings

Theorem, $r=\sqrt{2}-1$ — in progress

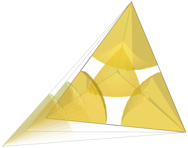
Each of the following tetrahedra is densest among the tetrahedra with the same spheres:



$\delta_{1111}\approx 0.7209$ $\delta_{11rr}\approx 0.8105$ $\delta_{1rrr}\approx 0.8065$ $\delta_{rrrr}\approx 0.7847$ $\delta_{111r}\approx 0.8125$

Proof:

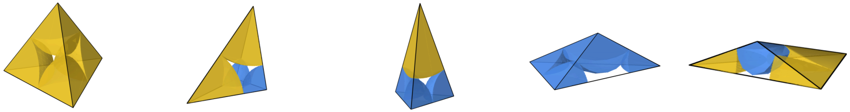
- dimension reduction ($6\to 4$):
  tetrahedron deflation + sphere sliding



Upper density bound for -packings

Theorem, $r = \sqrt{2} - 1$ — in progress

Each of the following tetrahedra is densest among the tetrahedra with the same spheres:



$\delta_{1111} \approx 0.7209$ $\delta_{11rr} \approx 0.8105$ $\delta_{1rrr} \approx 0.8065$ $\delta_{rrrr} \approx 0.7847$ $\delta_{111r} \approx 0.8125$

Proof:

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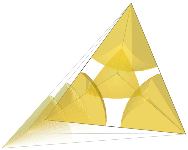


- computer-assisted proof for tetrahedra with 2 contacts:
  recursive subdivision + interval arithmetic
  $\approx$ 1000 lines of code

11h on 96 CPUs

Why the computations are so slow

interval arithmetic $+$ huge formulas $\rightarrow$ loss of precision

Why the computations are so slow

interval arithmetic + huge formulas → loss of precision

Example: to compute the support sphere radius, we need to solve $A\,r^2 + B\,r + C = 0$

$$
\begin{aligned}
A =& -4a^2b^2d^2+4a^2c^2d^2+4b^2c^2d^2-4c^4d^2-4c^2d^4+4a^2b^2e^2-4b^4e^2-4a^2c^2e^2+4b^2c^2e^2+4b^2d^2e^2+4c^2d^2e^2-4b^2e^4-4a^4f^2+4a^2b^2f^2+4a^2c^2f^2-4b^2c^2f^2+4a^2d^2f^2+4c^2d^2f^2+4a^2e^2f^2+4b^2e^2f^2-4d^2e^2f^2\\
& -4a^2f^4+4d^4r_x^2-8d^2e^2r_x^2+4e^4r_x^2-8d^2f^2r_x^2-8e^2f^2r_x^2+4f^4r_x^2-8b^2d^2r_xr_y+8c^2d^2r_xr_y+8b^2e^2r_xr_y-8c^2e^2r_xr_y-16a^2f^2r_xr_y+8b^2f^2r_xr_y+8c^2f^2r_xr_y+8d^2f^2r_xr_y+8e^2f^2r_xr_y-8f^4r_xr_y+4b^4r_y^2-8b^2c^2r_y^2+4c^4r_y^2\\
& -8b^2f^2r_y^2-8c^2f^2r_y^2+4f^4r_y^2-8a^2d^2r_xr_z+8c^2d^2r_xr_z+8a^2e^2r_xr_z-16b^2e^2r_xr_z+8c^2e^2r_xr_z+8d^2e^2r_xr_z-8e^4r_xr_z+8a^2f^2r_xr_z-8c^2f^2r_xr_z+8e^2f^2r_xr_z-8a^2b^2r_yr_z+8a^2c^2r_yr_z+8b^2c^2r_yr_z-8c^4r_yr_z-16c^2d^2r_yr_z\\
& +8b^2e^2r_yr_z+8c^2e^2r_yr_z+8a^2f^2r_yr_z+8c^2f^2r_yr_z-8e^2f^2r_yr_z+4a^4r_z^2-8a^2c^2r_z^2+4c^4r_z^2-8a^2e^2r_z^2-8c^2e^2r_z^2+4e^4r_z^2+8a^2d^2r_xr_w+8b^2d^2r_xr_w-16c^2d^2r_xr_w-8d^4r_xr_w-8a^2e^2r_xr_w+8b^2e^2r_xr_w+8d^2e^2r_xr_w\\
& +8a^2f^2r_xr_w-8b^2f^2r_xr_w+8d^2f^2r_xr_w+8a^2b^2r_yr_w-8b^4r_yr_w-8a^2c^2r_yr_w+8b^2c^2r_yr_w+8b^2d^2r_yr_w+8c^2d^2r_yr_w-16b^2e^2r_yr_w+8a^2f^2r_yr_w+8b^2f^2r_yr_w-8d^2f^2r_yr_w-8a^4r_zr_w+8a^2b^2r_zr_w+8a^2c^2r_zr_w-8b^2c^2r_zr_w\\
& +8a^2d^2r_zr_w+8c^2d^2r_zr_w+8a^2e^2r_zr_w+8b^2e^2r_zr_w-8d^2e^2r_zr_w-16a^2f^2r_zr_w+4a^4r_w^2-8a^2b^2r_w^2+4b^4r_w^2-8a^2d^2r_w^2-8b^2d^2r_w^2+4d^4r_w^2
\end{aligned}
$$

$$
\begin{aligned}
B =& -4c^2d^4r_x+4b^2d^2e^2r_x+4c^2d^2e^2r_x-4b^2e^4r_x+4a^2d^2f^2r_x+4c^2d^2f^2r_x+4a^2e^2f^2r_x+4b^2e^2f^2r_x-8d^2e^2f^2r_x-4a^2f^4r_x+4d^4r_x^3-8d^2e^2r_x^3+4e^4r_x^3-8d^2f^2r_x^3-8e^2f^2r_x^3+4f^4r_x^3+4b^2c^2d^2r_y-4c^4d^2r_y-4b^4e^2r_y\\
& +4b^2c^2e^2r_y+4a^2b^2f^2r_y+4a^2c^2f^2r_y-8b^2c^2f^2r_y+4c^2d^2f^2r_y+4b^2e^2f^2r_y-4a^2f^4r_y-4b^2d^2r_x^2r_y+4c^2d^2r_x^2r_y+4b^2e^2r_x^2r_y-4c^2e^2r_x^2r_y-8a^2f^2r_x^2r_y+4b^2f^2r_x^2r_y+4c^2f^2r_x^2r_y+4d^2f^2r_x^2r_y+4e^2f^2r_x^2r_y-4f^4r_x^2r_y\\
& -4b^2d^2r_xr_y^2+4c^2d^2r_xr_y^2+4b^2e^2r_xr_y^2-4c^2e^2r_xr_y^2-8a^2f^2r_xr_y^2+4b^2f^2r_xr_y^2+4c^2f^2r_xr_y^2+4d^2f^2r_xr_y^2+4e^2f^2r_xr_y^2-4f^4r_xr_y^2+4b^4r_y^3-8b^2c^2r_y^3+4c^4r_y^3-8b^2f^2r_y^3-8c^2f^2r_y^3+4f^4r_y^3+4a^2c^2d^2r_z-4c^4d^2r_z+4a^2b^2e^2r_z\\
& -8a^2c^2e^2r_z+4b^2c^2e^2r_z+4c^2d^2e^2r_z-4b^2e^4r_z-4a^4f^2r_z+4a^2c^2f^2r_z+4a^2e^2f^2r_z-4a^2d^2r_x^2r_z+4c^2d^2r_x^2r_z+4a^2e^2r_x^2r_z-8b^2e^2r_x^2r_z+4c^2e^2r_x^2r_z+4d^2e^2r_x^2r_z-4e^4r_x^2r_z+4a^2f^2r_x^2r_z-4c^2f^2r_x^2r_z+4e^2f^2r_x^2r_z\\
& -4a^2b^2r_y^2r_z+4a^2c^2r_y^2r_z+4b^2c^2r_y^2r_z-4c^4r_y^2r_z-8c^2d^2r_y^2r_z+4b^2e^2r_y^2r_z+4c^2e^2r_y^2r_z+4a^2f^2r_y^2r_z+4c^2f^2r_y^2r_z-4e^2f^2r_y^2r_z-4a^2d^2r_xr_z^2+4c^2d^2r_xr_z^2+4a^2e^2r_xr_z^2-8b^2e^2r_xr_z^2+4c^2e^2r_xr_z^2+4d^2e^2r_xr_z^2-4e^4r_xr_z^2\\
& +4a^2f^2r_xr_z^2-4c^2f^2r_xr_z^2+4e^2f^2r_xr_z^2-4a^2b^2r_yr_z^2+4a^2c^2r_yr_z^2+4b^2c^2r_yr_z^2-4c^4r_yr_z^2-8c^2d^2r_yr_z^2+4b^2e^2r_yr_z^2+4c^2e^2r_yr_z^2+4a^2f^2r_yr_z^2+4c^2f^2r_yr_z^2-4e^2f^2r_yr_z^2+4a^4r_z^3-8a^2c^2r_z^3+4c^4r_z^3-8a^2e^2r_z^3-8c^2e^2r_z^3\\
& +4e^4r_z^3-8a^2b^2d^2r_w+4a^2c^2d^2r_w+4b^2c^2d^2r_w-4c^2d^4r_w+4a^2b^2e^2r_w-4b^4e^2r_w+4b^2d^2e^2r_w-4a^4f^2r_w+4a^2b^2f^2r_w+4a^2d^2f^2r_w+4a^2d^2r_x^2r_w+4b^2d^2r_x^2r_w-8c^2d^2r_x^2r_w-4d^4r_x^2r_w-4a^2e^2r_x^2r_w+4b^2e^2r_x^2r_w\\
& +4d^2e^2r_x^2r_w+4a^2f^2r_x^2r_w-4b^2f^2r_x^2r_w+4d^2f^2r_x^2r_w+4a^2b^2r_y^2r_w-4b^4r_y^2r_w-4a^2c^2r_y^2r_w+4b^2c^2r_y^2r_w+4b^2d^2r_y^2r_w+4c^2d^2r_y^2r_w-8b^2e^2r_y^2r_w+4a^2f^2r_y^2r_w+4b^2f^2r_y^2r_w-4d^2f^2r_y^2r_w-4a^4r_z^2r_w+4a^2b^2r_z^2r_w+4a^2c^2r_z^2r_w\\
& -4b^2c^2r_z^2r_w+4a^2d^2r_z^2r_w+4c^2d^2r_z^2r_w+4a^2e^2r_z^2r_w+4b^2e^2r_z^2r_w-4d^2e^2r_z^2r_w-8a^2f^2r_z^2r_w+4a^2d^2r_xr_w^2+4b^2d^2r_xr_w^2-8c^2d^2r_xr_w^2-4d^4r_xr_w^2-4a^2e^2r_xr_w^2+4b^2e^2r_xr_w^2+4d^2e^2r_xr_w^2+4a^2f^2r_xr_w^2-4b^2f^2r_xr_w^2\\
& +4d^2f^2r_xr_w^2+4a^2b^2r_yr_w^2-4b^4r_yr_w^2-4a^2c^2r_yr_w^2+4b^2c^2r_yr_w^2+4b^2d^2r_yr_w^2+4c^2d^2r_yr_w^2-8b^2e^2r_yr_w^2+4a^2f^2r_yr_w^2+4b^2f^2r_yr_w^2-4d^2f^2r_yr_w^2-4a^4r_zr_w^2+4a^2b^2r_zr_w^2+4a^2c^2r_zr_w^2\\
& -4b^2c^2r_zr_w^2+4a^2d^2r_zr_w^2+4c^2d^2r_zr_w^2+4a^2e^2r_zr_w^2+4b^2e^2r_zr_w^2-4d^2e^2r_zr_w^2-8a^2f^2r_zr_w^2+4a^4r_w^3-8a^2b^2r_w^3+4b^4r_w^3-8a^2d^2r_w^3-8b^2d^2r_w^3+4d^4r_w^3
\end{aligned}
$$

$$
\begin{aligned}
C =& c^4d^4-2b^2c^2d^2e^2+b^4e^4-2a^2c^2d^2f^2-2a^2b^2e^2f^2+a^4f^4-2c^2d^4r_x^2+2b^2d^2e^2r_x^2+2c^2d^2e^2r_x^2-2b^2e^4r_x^2+2a^2d^2f^2r_x^2+2c^2d^2f^2r_x^2+2a^2e^2f^2r_x^2+2b^2e^2f^2r_x^2-4d^2e^2f^2r_x^2-2a^2f^4r_x^2+d^4r_x^4-2d^2e^2r_x^4+e^4r_x^4\\
& -2d^2f^2r_x^4-2e^2f^2r_x^4+f^4r_x^4+2b^2c^2d^2r_y^2-2c^4d^2r_y^2-2b^4e^2r_y^2+2b^2c^2e^2r_y^2+2a^2b^2f^2r_y^2+2a^2c^2f^2r_y^2-4b^2c^2f^2r_y^2+2c^2d^2f^2r_y^2+2b^2e^2f^2r_y^2-2a^2f^4r_y^2-2b^2d^2r_x^2r_y^2+2c^2d^2r_x^2r_y^2+2b^2e^2r_x^2r_y^2-2c^2e^2r_x^2r_y^2-4a^2f^2r_x^2r_y^2\\
& +2b^2f^2r_x^2r_y^2+2c^2f^2r_x^2r_y^2+2d^2f^2r_x^2r_y^2+2e^2f^2r_x^2r_y^2-2f^4r_x^2r_y^2+b^4r_y^4-2b^2c^2r_y^4+c^4r_y^4-2b^2f^2r_y^4-2c^2f^2r_y^4+f^4r_y^4+2a^2c^2d^2r_z^2-2c^4d^2r_z^2+2a^2b^2e^2r_z^2-4a^2c^2e^2r_z^2+2b^2c^2e^2r_z^2+2c^2d^2e^2r_z^2-2b^2e^4r_z^2\\
& -2a^4f^2r_z^2+2a^2c^2f^2r_z^2+2a^2e^2f^2r_z^2-2a^2d^2r_x^2r_z^2+2c^2d^2r_x^2r_z^2+2a^2e^2r_x^2r_z^2-4b^2e^2r_x^2r_z^2+2c^2e^2r_x^2r_z^2+2d^2e^2r_x^2r_z^2-2e^4r_x^2r_z^2+2a^2f^2r_x^2r_z^2-2c^2f^2r_x^2r_z^2+2e^2f^2r_x^2r_z^2-2a^2b^2r_y^2r_z^2+2a^2c^2r_y^2r_z^2+2b^2c^2r_y^2r_z^2\\
& -2c^4r_y^2r_z^2-4c^2d^2r_y^2r_z^2+2b^2e^2r_y^2r_z^2+2c^2e^2r_y^2r_z^2+2a^2f^2r_y^2r_z^2+2c^2f^2r_y^2r_z^2-2e^2f^2r_y^2r_z^2+a^4r_z^4-2a^2c^2r_z^4+c^4r_z^4-2a^2e^2r_z^4-2c^2e^2r_z^4+e^4r_z^4-4a^2b^2d^2r_w^2+2a^2c^2d^2r_w^2+2b^2c^2d^2r_w^2-2c^2d^4r_w^2+2a^2b^2e^2r_w^2\\
& -2b^4e^2r_w^2+2b^2d^2e^2r_w^2-2a^4f^2r_w^2+2a^2b^2f^2r_w^2+2a^2d^2f^2r_w^2+2a^2d^2r_x^2r_w^2+2b^2d^2r_x^2r_w^2-4c^2d^2r_x^2r_w^2-2d^4r_x^2r_w^2-2a^2e^2r_x^2r_w^2+2b^2e^2r_x^2r_w^2+2d^2e^2r_x^2r_w^2+2a^2f^2r_x^2r_w^2-2b^2f^2r_x^2r_w^2+2d^2f^2r_x^2r_w^2+2a^2b^2r_y^2r_w^2\\
& -2b^4r_y^2r_w^2-2a^2c^2r_y^2r_w^2+2b^2c^2r_y^2r_w^2+2b^2d^2r_y^2r_w^2+2c^2d^2r_y^2r_w^2-4b^2e^2r_y^2r_w^2+2a^2f^2r_y^2r_w^2+2b^2f^2r_y^2r_w^2-2d^2f^2r_y^2r_w^2-2a^4r_z^2r_w^2+2a^2b^2r_z^2r_w^2+2a^2c^2r_z^2r_w^2-2b^2c^2r_z^2r_w^2+2a^2d^2r_z^2r_w^2+2c^2d^2r_z^2r_w^2\\
& +2a^2e^2r_z^2r_w^2+2b^2e^2r_z^2r_w^2-2d^2e^2r_z^2r_w^2-4a^2f^2r_z^2r_w^2+a^4r_w^4-2a^2b^2r_w^4+b^4r_w^4-2a^2d^2r_w^4-2b^2d^2r_w^4+d^4r_w^4
\end{aligned}
$$

Why the computations are so slow

interval arithmetic + huge formulas → loss of precision

Example: to compute the support sphere radius, we need to solve $A\,r^2 + B\,r + C = 0$

Thanks to dimension reduction:

compute with fixed radii and edge lengths, then "simplify"

$r_x = r_y = r_z = r_w = 1, \;\; a = b = c = 2$:

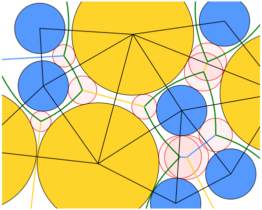
$$A_{1111} = 4\left(d^2 - e^2\right)^2 + 4\,f^4 + \left(\left(d^2 - 8\right)e^2 - 8\,d^2\right)f^2$$

$$B_{1111} = 8\left(d^2 - e^2\right)^2 + 8\,f^4 + 2\left(\left(d^2 - 8\right)e^2 - 8\,d^2\right)f^2$$

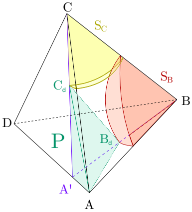
$$C_{1111} = d^2 e^2 f^2$$

Techniques

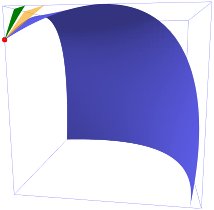
Geometry:



properties of triangulations

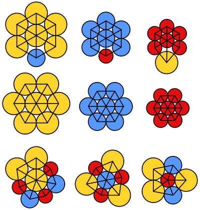


… and “tetrahedrizations”



differential geometry

Computer assistance:



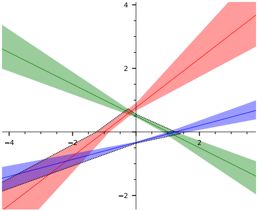
case analysis
Python, C++

$$\mathcal{A}_{1111} = 4\,\left(d^2 - e^2\right)^2 + 4\,f^4 + \left(\left(d^2 - 8\right)e^2 - 8\,d^2\right)f^2$$
$$\mathcal{B}_{1111} = 8\,\left(d^2 - e^2\right)^2 + 8\,f^4 + 2\left(\left(d^2 - 8\right)e^2 - 8\,d^2\right)f^2$$
$$\mathcal{C}_{1111} = d^2e^2f^2$$

$$\delta_{1111} = \frac{8\left(\begin{array}{r}\arctan\left(\frac{\sqrt{-4\,(d^2-e^2)^2-4\,f^4-((d^2-8)e^2-8\,d^2)f^2}}{(d+2)e^2+2\,d^2+(d^2+4\,d)e-2\,f^2}\right)\\ +\arctan\left(\frac{\sqrt{-4\,(d^2-e^2)^2-4\,f^4-((d^2-8)e^2-8\,d^2)f^2}}{(d+2)f^2+2\,d^2-2\,e^2+(d^2+4\,d)f}\right)\\ +\arctan\left(\frac{\sqrt{-4\,(d^2-e^2)^2-4\,f^4-((d^2-8)e^2-8\,d^2)f^2}}{(e+2)f^2-2\,d^2+2\,e^2+(e^2+4\,e)f}\right)\\ -\arctan\left(\frac{\sqrt{-4\,(d^2-e^2)^2-4\,f^4-((d^2-8)e^2-8\,d^2)f^2}}{2\,(d^2+e^2+f^2-32)}\right)\end{array}\right)}{\sqrt{-4\,\left(d^2-e^2\right)^2-4\,f^4-\left(\left(d^2-8\right)e^2-8\,d^2\right)f^2}}.$$

symbolic calculus
SageMath

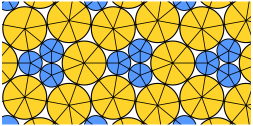
$\Longleftrightarrow$

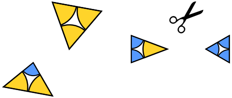


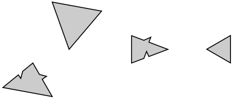
interval arithmetic
MPFI (RIF SageMath)
Boost (C++)

Open questions: packings and tilings

triangulated packings $\sim$ tilings by triangles with local rules



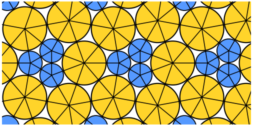


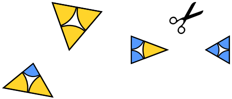


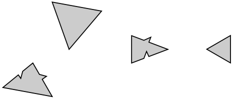
density = weighted proportion of tiles

Open questions: packings and tilings

triangulated packings $\sim$ tilings by triangles with local rules







density $=$ **weighted proportion of tiles**

Triangulated Packing Problem

Given k disc radii $\overbrace{r_1, \cdots, r_k}^{\text{algebraic numbers represented by polynomials and intervals}}$, is there a triangulated packing of density $\overbrace{> \frac{\pi}{2\sqrt{3}}}^{\text{excludes hexagonal packing}}$

$\forall\ r_1, \cdots, r_k$ with triangulated packings, one is periodic $\Rightarrow$ **decidable**
(Wang algorithm: search for a period)

$\exists\ r_1, \cdots, r_k$ whose triangulated packings are all aperiodic $\Rightarrow$ **undecidable?**

Open questions: packings and tilings

triangulated packings $\sim$ tilings by triangles with local rules

density = weighted proportion of tiles

Dense Packing Problem

Given k disc radii $\overbrace{r_1, \cdots, r_k}^{\text{algebraic numbers represented by polynomials and intervals}}$, is there a packing of density $\overbrace{> \frac{\pi}{2\sqrt{3}}}^{\text{excludes hexagonal packing}}$

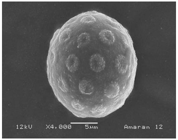
$\forall\ r_1, \cdots, r_k$ with dense packings, one is periodic $\Rightarrow$ **decidable**

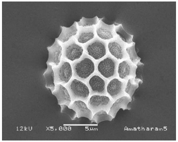
(interval arithmetic and subdivision until needed precision)

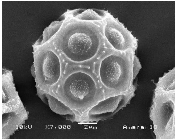
$\exists\ r_1, \cdots, r_k$ whose dense packings are all aperiodic $\Rightarrow$ **not possible!**

Other "spherical" questions: from pollen grains to kissing problem

Tammes 1930: configuration of pores on a pollen grain **spherical codes**







maximize the number of spherical caps of a given radius on a sphere

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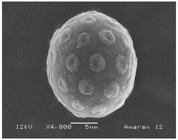

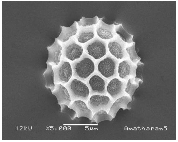

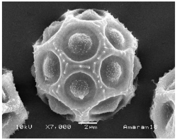

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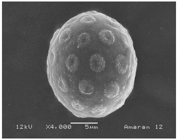

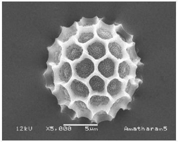

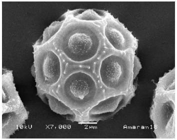

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solved for $n = 3, \ldots, 14$, and 24 (1943 – 2015)

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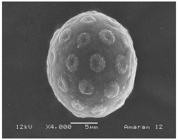 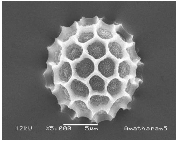  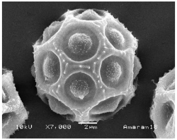

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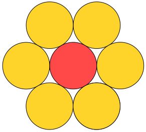
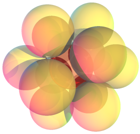
solved for $d = 2 : 6$, $3 :$

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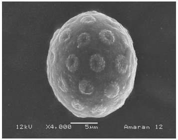

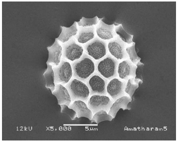

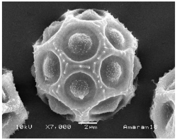

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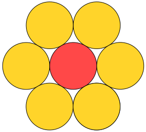
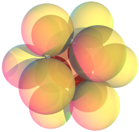

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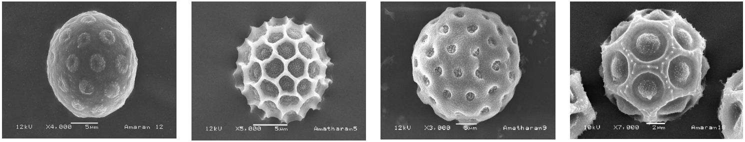

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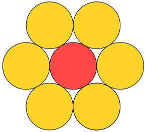
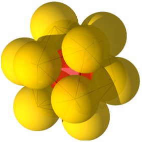
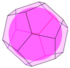


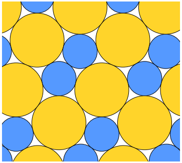


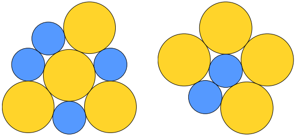


dodecahedral conjecture
smallest Voronoi cell in sphere packing
(proved in 2010)

Thank you for your attention!

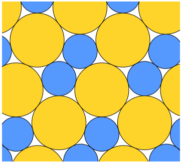
packing is triangulated $\Longleftrightarrow$ each disc has a "corona"

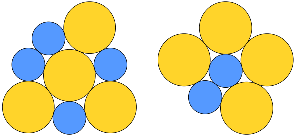




How to find triangulated packings

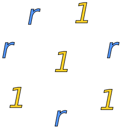
packing is triangulated $\Longleftrightarrow$ each disc has a "corona"





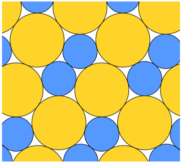
To find disc sizes with triangulated packings, we run trough all possible combinations of symbolic coronas of two discs (finite number):

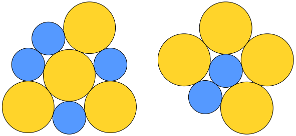
symbolic corona



(Fernique, Hashemi, Sizova 2019)

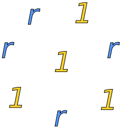
packing is triangulated $\iff$ each disc has a "corona"

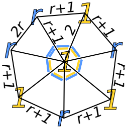




To find disc sizes with triangulated packings, we run trough all possible combinations of symbolic coronas of two discs (finite number):

symbolic corona $\longrightarrow$ value of r





$$6 \times \widehat{11r} + 1 \times \widehat{r1r} = 2\pi$$

$$r \approx 0.63$$

(Fernique, Hashemi, Sizova 2019)