# What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

Luís Nobre Gonçalves

http://matagalatlante.org/UiTlecture.pdf

What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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The financial crisis is ravaging the economy and opinion-makers are calling for innovation as a solution. Many have forgotten that innovation is nothing but a side-effect of the old, well-established, classic scientific method.

This lecture is an attempt to remember what the scientific method is and how it works. A problem related with circle packing is used as a demonstrative example. Some applications in Materials Science are explored.

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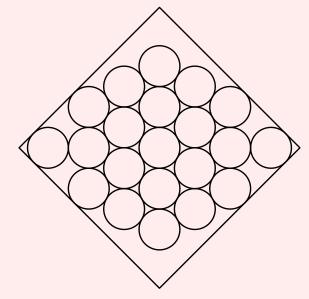
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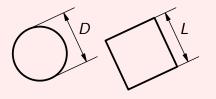
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## Definitions



$$F = \frac{NA_{\bigcirc}}{A_{\square}} = \frac{N\pi \left(\frac{D}{2}\right)^2}{L^2(N,D)}$$

N is the the number of circles

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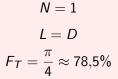
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## Target fraction of covered area (0,785)

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To learn from reality

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- ► To learn from reality
  - Avoid belief, bias and myth

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- To learn from reality
  - Avoid belief, bias and myth
- Sophisticated trial-and-error

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- Avoid belief, bias and myth
- Sophisticated trial-and-error
  - Everybody learns

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<ul> <li>Everybody learns</li> <li>Models should be simple, general and beautiful</li> </ul>	Answer 2 3, 5 1, 4, 9, 16, 25 3, 8, 15, 24, 23 6, 12, 18, 20 7, 14 10, 11, 17, 19 13, 22 26 Finish Go beyond 3D
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## Models

### Models are

- mental representations
- visualizations of uninitiated actions
- expectations about the unknown
- scenarios
- expressions

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### Model

Answer

## Models

### Models are

- mental representations
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- expressions
- ways to start, continue, assume, measure, facilitate, avoid common problems, interpret, classify, detect, solve, confirm, prove, explain, generalize, understand, use, teach and publish

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A scientist works to improve not just one model but several.

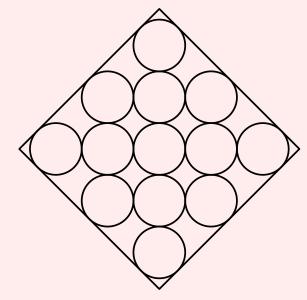
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### Answer

### Start at the beginning

### What's the best way to reach the answer?

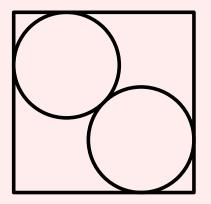
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### Answer



 $F_2 \approx 0,539$ 

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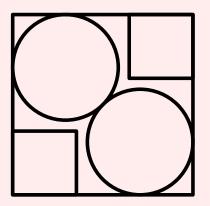
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 $F_2 \approx F_T - 25\%$ 

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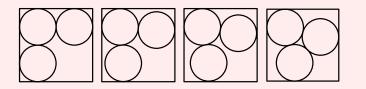
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 $F_3 pprox 0,610$ 

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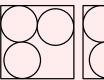
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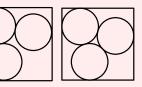
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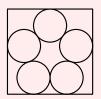
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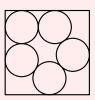






 $F_3\approx 0{,}610$ 







 $F_5 \approx 0,674$ 

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### Start organizing the results

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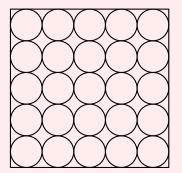
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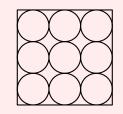
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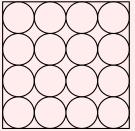
### Perfect squares











 $F_{\Box} = F_T$ 

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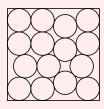
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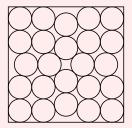
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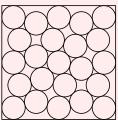
### Perfect squares -1 or -2











 $F_8\approx 0{,}731 \quad F_3\approx 0{,}610 \quad F_{15}\approx 0{,}762$ 

 $F_{24} \approx 0,775$   $F_{23} \approx 0,764$ 

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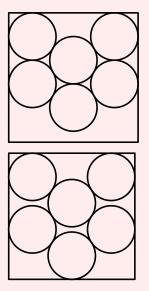
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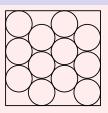
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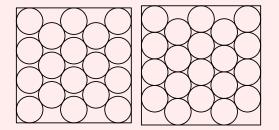


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## Squeezed horizontaly







 $F_6\approx 0{,}664 \quad F_{12}\approx 0{,}738$ 

 $F_{18}\approx 0{,}755 \quad F_{20}\approx 0{,}780$ 

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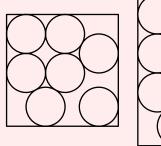
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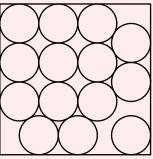
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References

### One free circle





$$F_7 \approx 0,670 \qquad F_{14} \approx 0,736$$

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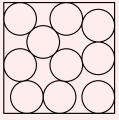
Definitions 1 ( $F_T \approx 0.785$ ) Scientific Method Models

#### Answer

2 3, 5 1, 4, 9, 16, 25 3, 8, 15, 24, 23 6, 12, 18, 20 **7**, 14 10, 11, 17, 19 13, 22 26 Finish Go beyond 3D Summary

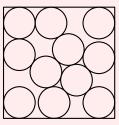
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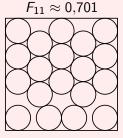
## Unclassified



 $F_{10} \approx 0.682$ 

 $F_{17} \approx 0,707$ 





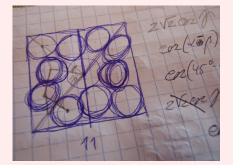
What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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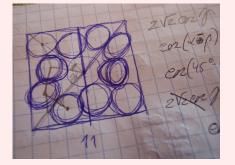
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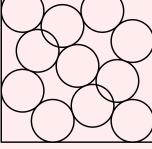


#### Introduction

Definitions 1 ( $F_T \approx 0,785$ ) Scientific Method Models

#### Answer





- Make a simulation (it's cheaper than a real experiment)
- Constraints matter
- Different causes may have the same effect

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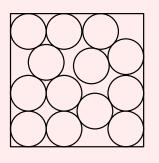
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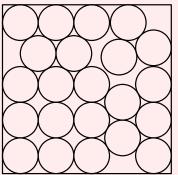
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### Five free circles





 $F_{13} \approx 0.733$   $F_{22} \approx 0.772$ 

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# **NO IDEA**

	Observe	the	big	picture	
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Pay attention to extremes

What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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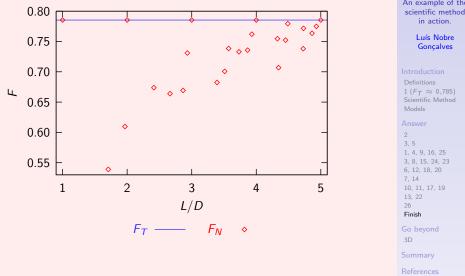
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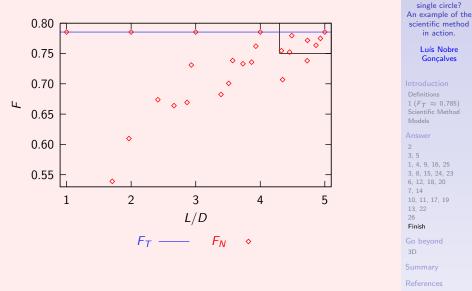
## Big picture



What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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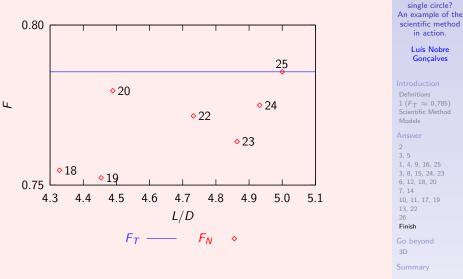
## Big picture



What is the

smallest number of circles that can cover more area of a square than a

### Extreme



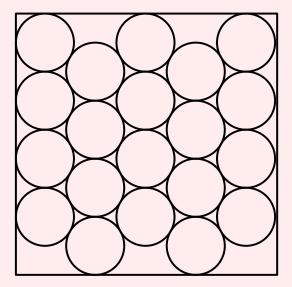
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Do you see a pattern?

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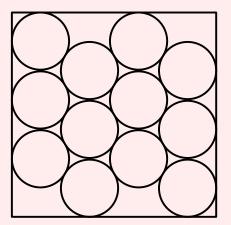
Definitions 1 ( $F_T \approx 0.785$ ) Scientific Method Models

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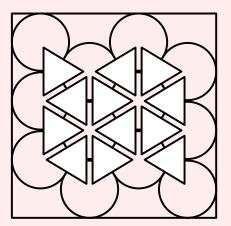
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Confirm.

What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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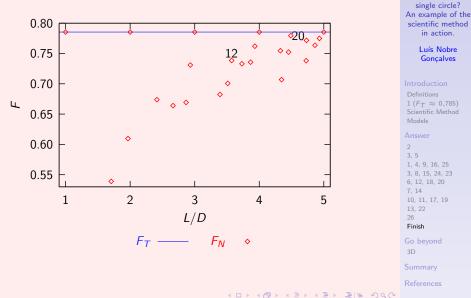
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### Both 20 and 12 are local maxima



What is the

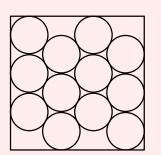
smallest number of circles that can cover more area of a square than a

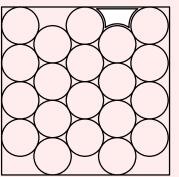
- Why are our efforts insufficient upto now?
- Don't go on without knowing why.

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Summary

### Boundary effects





What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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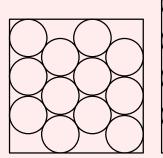
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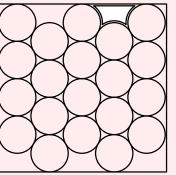
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## Boundary effects



Big voids at the boundary: +1Circles: +8



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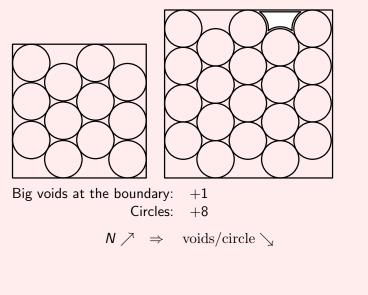
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### Boundary effects



What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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### Using only this pattern, can we expect to succeed?

What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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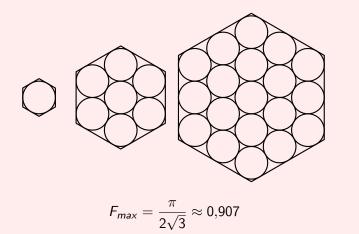
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### Hexagonal configuration



What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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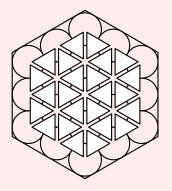
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### Hexagonal configuration



$$F_{max} = rac{\pi}{2\sqrt{3}} pprox 0,907$$

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### Could we have skipped the initial work?

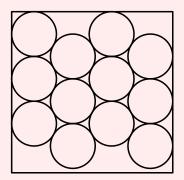
What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action. Luís Nobre Gonçalves Definitions Models 2 1, 4, 9, 16, 25 3, 8, 15, 24, 23 6, 12, 18, 20 7.14 26

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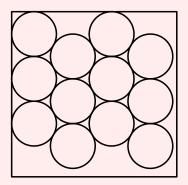
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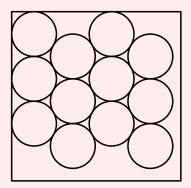
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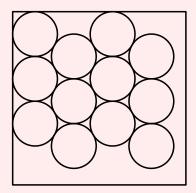
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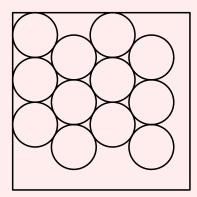
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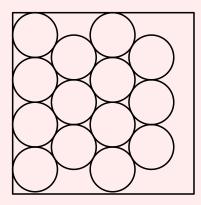
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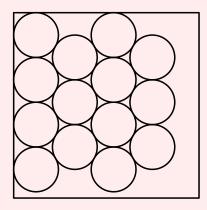
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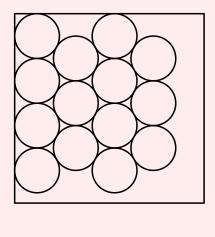
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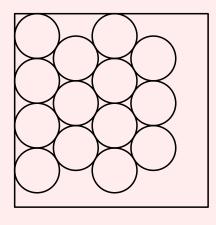
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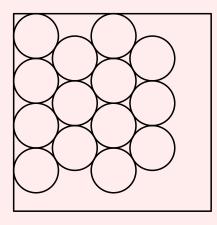
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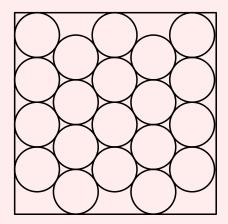
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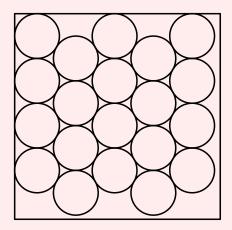
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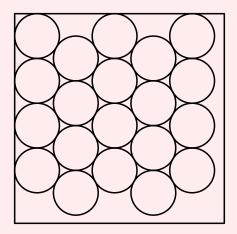
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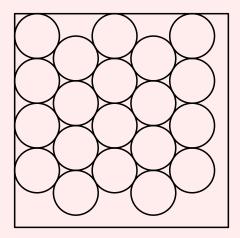
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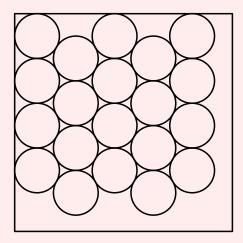
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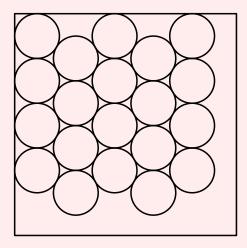
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What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action. Luís Nobre Gonçalves

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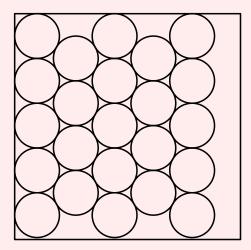
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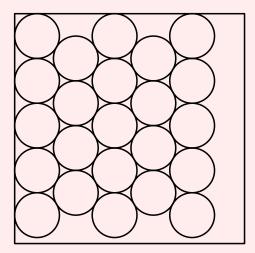
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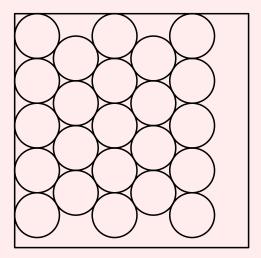
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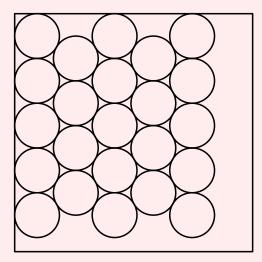
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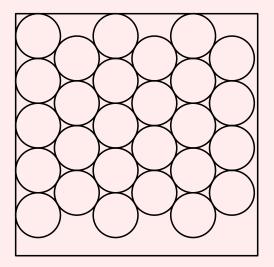
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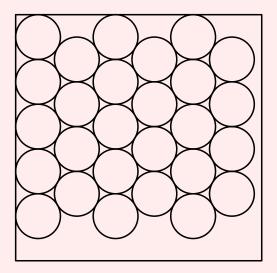
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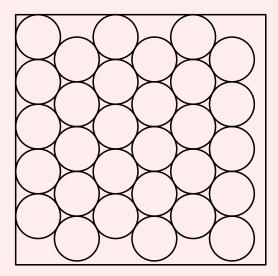
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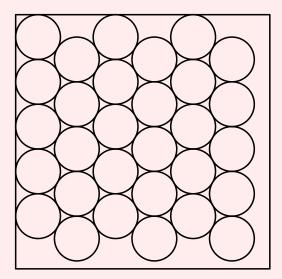
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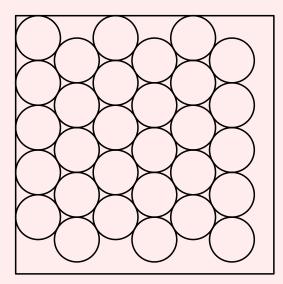
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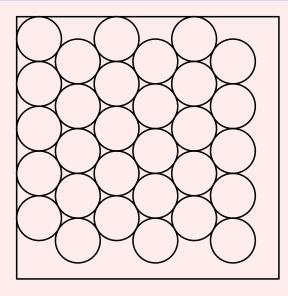
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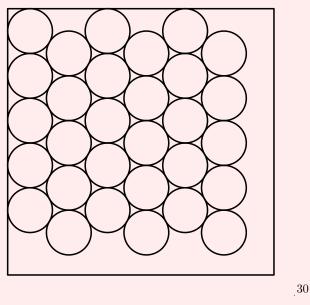
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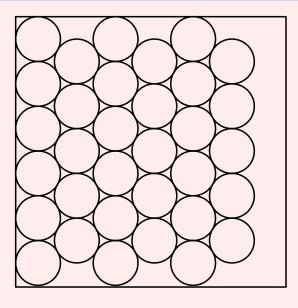


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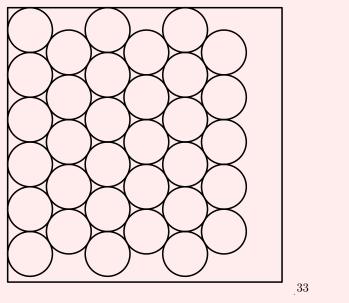


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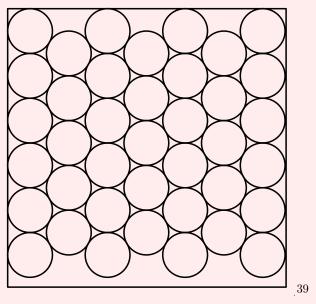
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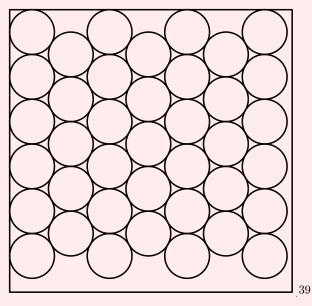
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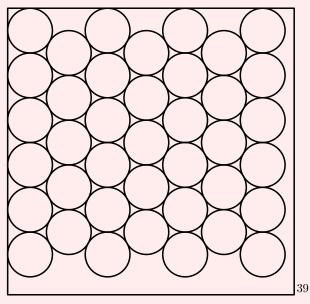
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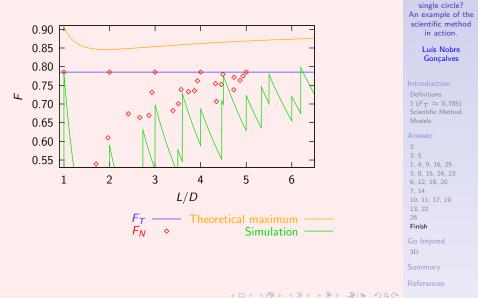
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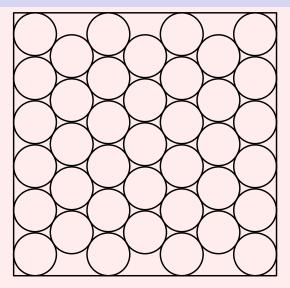
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39



 $F_{39}\approx 0{,}811$ 

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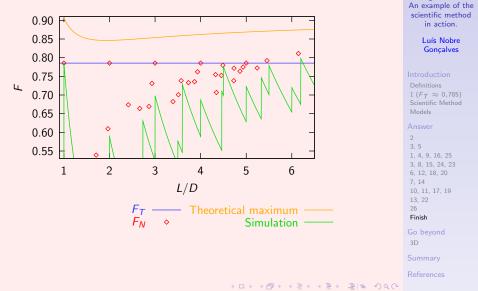
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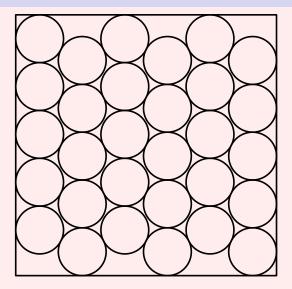
References

# Optimize



What is the

smallest number of circles that can cover more area of a square than a single circle? 30



 $F_{30} \approx 0,792$ 

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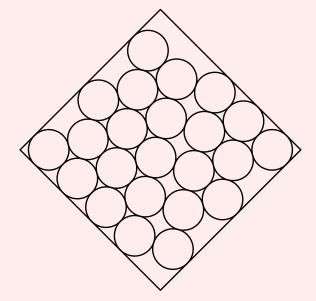
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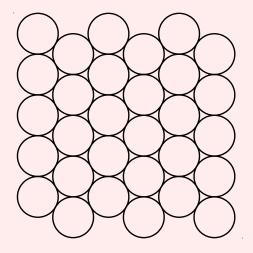
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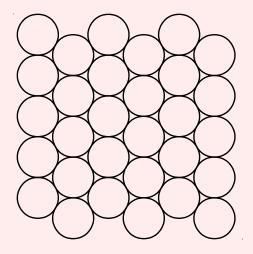
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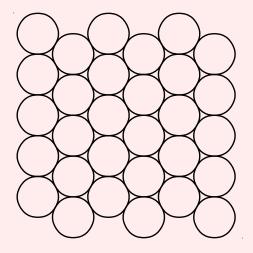
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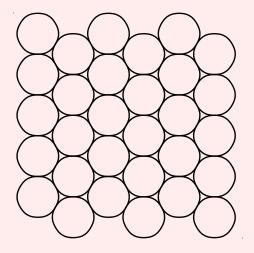
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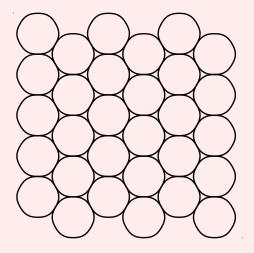
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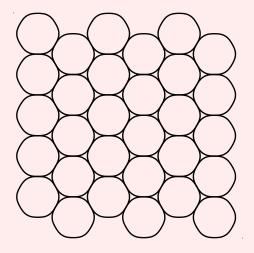
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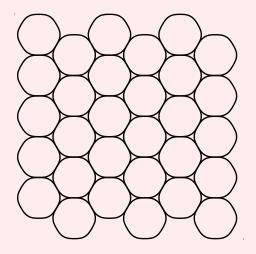
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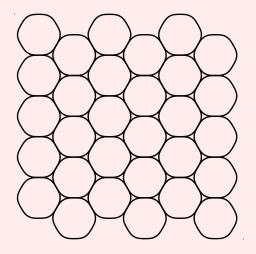
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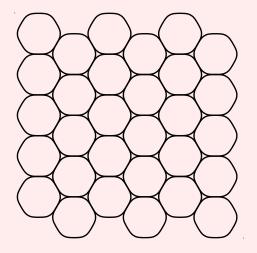
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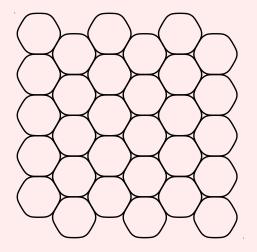
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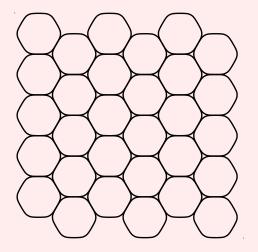
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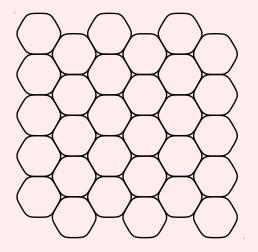
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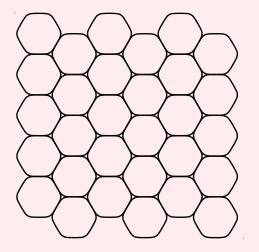
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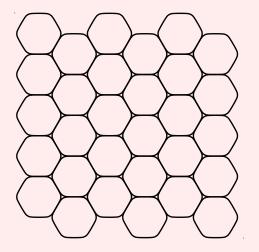
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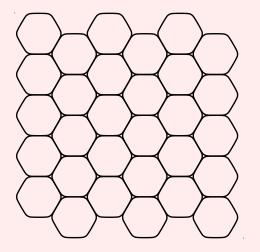
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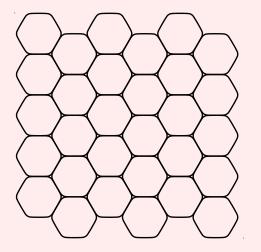
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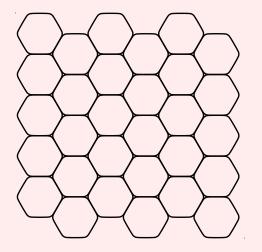
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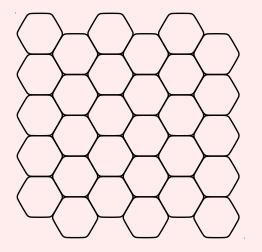
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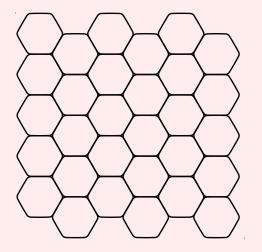
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### Answer

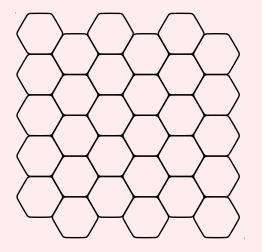
2 3, 5 1, 4, 9, 16, 25 3, 8, 15, 24, 23 6, 12, 18, 20 7, 14 10, 11, 17, 19 13, 22 26 Finish

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What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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### Answer

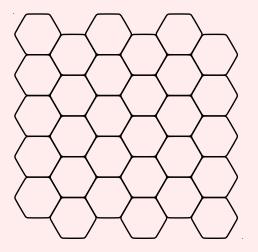
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The hexagonal configuration minimizes "free energy".

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## 2D foam

## red beryl

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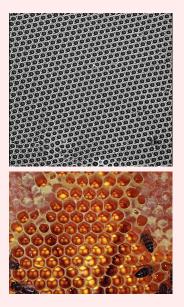
2 3, 5 1, 4, 9, 16, 25 3, 8, 15, 24, 23 6, 12, 18, 20 7, 14 10, 11, 17, 19 13, 22 26 Finish

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## bubble-raft

honeycomb

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## ommatidia

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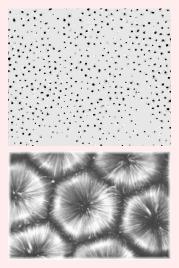
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giant's causeway



## dusty plasma

## Rayleigh-Bénard convection

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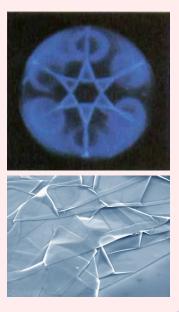
Answer

2 3, 5 1, 4, 9, 16, 25 3, 8, 15, 24, 23 6, 12, 18, 20 7, 14 10, 11, 17, 19 13, 22 26 Finish

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## hex. blue phase

graphene

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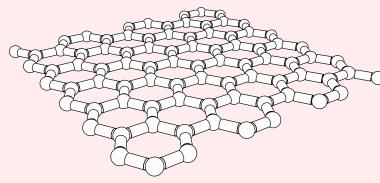
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## Graphene



Nobel Prize in Physics 2010. Very unusual electronic properties. Will be used in the "Subsea Sensors for Oil and Gas" project.

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## Ask the same question but in a different framing.

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# What is the smallest number of **spheres** that can **fill** more **volume** of a **cube** than a single **sphere**?

What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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## Cubic configurations

## Cubic

- Boby–centered–cubic (bcc)
- Face-centered-cubic (fcc)
- Clathrate type I ("dfcbcc")

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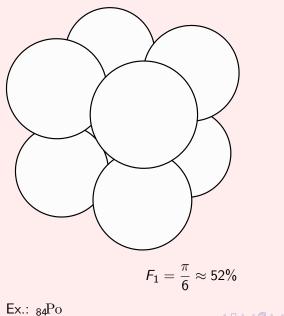
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## Cubic



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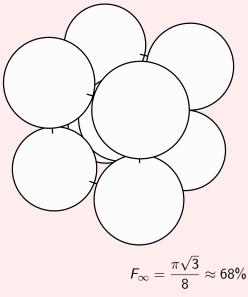
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## Boby-centered-cubic (bcc)



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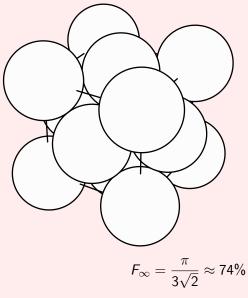
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Ex.: 26Fe



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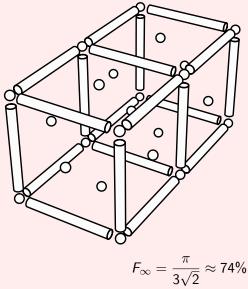
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Ex.: 29Cu

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Ex.: 29Cu

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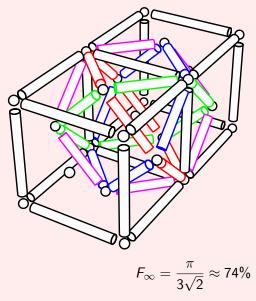
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2 3, 5 1, 4, 9, 16, 25 3, 8, 15, 24, 23 6, 12, 18, 20 7, 14 10, 11, 17, 19 13, 22 26 Finish

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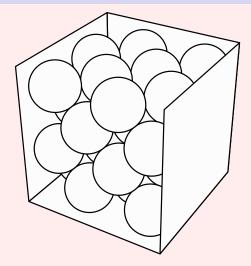
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Ex.: 29Cu



 $F_{31} \gtrsim 52\%$ 

Ex.: 79Au

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2 3, 5 1, 4, 9, 16, 25 3, 8, 15, 24, 23 6, 12, 18, 20 7, 14 10, 11, 17, 19 13, 22 26 Finish

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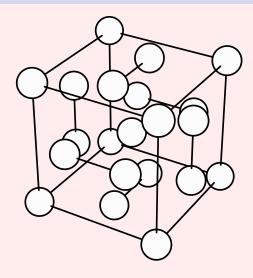
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## Clathrate



 $F_{\infty} = F_1$ 

smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

What is the

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2 3, 5 1, 4, 9, 16, 25 3, 8, 15, 24, 23 6, 12, 18, 20 7, 14 10, 11, 17, 19 13, 22 26 Finish

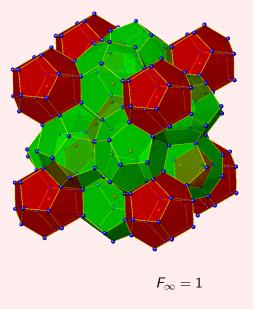
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## Methane Hydrate / Weaire-Phelan



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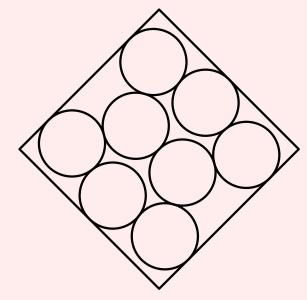
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- The SM is the business of questions
- Optimization is always present (together with a reason)
- Know the world

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- The SM is the business of questions
- Optimization is always present (together with a reason)
- Know the world

"Luck favors the prepared mind" [Louis Pasteur]

What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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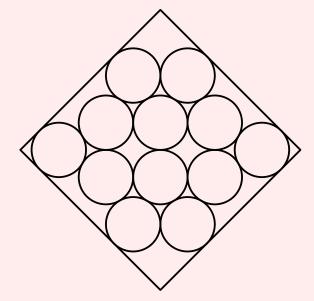
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### Answei

2 3, 5 1, 4, 9, 16, 25 3, 8, 15, 24, 23 6, 12, 18, 20 7, 14 10, 11, 17, 19 13, 22 26 Finish Go beyond 3D Summary References

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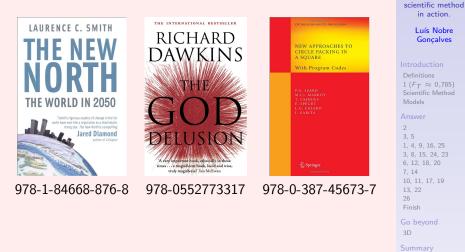
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## Books



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## Links

- Definition of "Scientific method" in the wikipedia
- The best known packings of equal circles in a square
- Erich's Packing Center
- What the bees know and what they do not know
- The rise of graphene
- Foam Physics
- Melting snow and ice : a call for action
- Clathrate gun hypothesis
- Avoiding Hydrates in the Petroleum Industry
- ► Ten Simple Rules for Doing Your Best Research
- "John Cleese on Creativity (video from a training)"
- Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa

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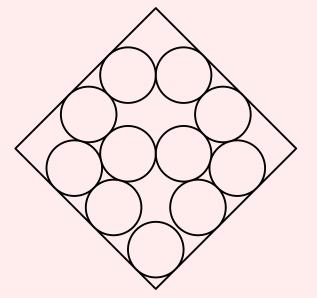
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## Appendix



What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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## Successes and pitfalls of the scientific method

What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action. Luís Nobre Gonçalves

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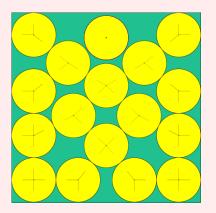
Acknowledgements

My quote

Vortex mill
Kevlar <sup>TM</sup>
Magnetotherapy

Cold fusion

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 $F \approx 0,734$ 

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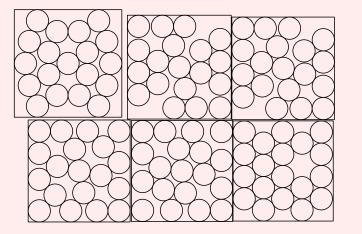
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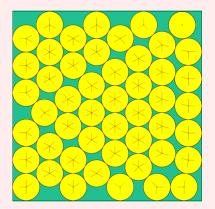
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Acknowledgements Further reading

## First non-square perfect square



 $F_{49} pprox 0,791$ 

What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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Acknowledgements Further reading

## Acknowledgements

What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action. Luís Nobre Gonçalves

Acknowledgements

Further reading

- ▶ ₽TEX Beamer class
- METAPOST
- GNUPLOT

- The first experimental scientist: Alhazen
- "Dialogue Concerning the Two Chief World Systems" by Galileo Galilei

What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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"The scientific method is the most powerful tool ever invented and, therefore, it is also the most dangerous tool. As soldiers face death in war, scientists face craziness in their jobs." What is the smallest number of circles that can cover more area of a square than a single circle? An example of the scientific method in action.

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