Muffin Problems

November 20, 2020
Five Muffins, Three Students

How can you divide and distribute 5 muffins to 3 students so that every student gets $\frac{5}{3}$ where nobody gets a tiny sliver?
Alan Frank came up with the problem and it was circulating in some math newsgroups around 2010, though I did not know this.
Five Muffins, Three Students, Proc by Picture

<table>
<thead>
<tr>
<th>Person</th>
<th>Color</th>
<th>What they Get</th>
</tr>
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<tbody>
<tr>
<td>Alice</td>
<td>RED</td>
<td>$1 + \frac{2}{3} = \frac{5}{3}$</td>
</tr>
<tr>
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<td>BLUE</td>
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<tr>
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<td>$1 + \frac{1}{3} + \frac{1}{3} = \frac{5}{3}$</td>
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Smallest Piece: $\frac{1}{3}$
Can We Do Better?

The smallest piece in the above solution is \( \frac{1}{3} \).

Is there a procedure with a larger smallest piece?

Work on it with your Breakout Rooms Group
YES WE CAN!
YES WE CAN!

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Smallest Piece: $\frac{5}{12}$
Can We Do Better?

The smallest piece in the above solution is \( \frac{5}{12} \).
Can We Do Better?

The smallest piece in the above solution is \( \frac{5}{12} \).

Is there a procedure with a larger smallest piece?
Can We Do Better?

The smallest piece in the above solution is $\frac{5}{12}$.

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Work on it with your Breakout Rooms Group.
5 Muffins, 3 People–Can’t Do Better Than $\frac{5}{12}$

NO WE CAN’T!
5 Muffins, 3 People—Can’t Do Better Than $\frac{5}{12}$

**NO WE CAN’T!**

There is a procedure for 5 muffins, 3 students where each student gets $\frac{5}{3}$ muffins, smallest piece $N$. We want $N \leq \frac{5}{12}$. 
5 Muffins, 3 People—Can’t Do Better Than $\frac{5}{12}$

NO WE CAN’T!
There is a procedure for 5 muffins, 3 students where each student gets $\frac{5}{3}$ muffins, smallest piece $N$. We want $N \leq \frac{5}{12}$.

**Case 0:** Some muffin is uncut. Cut it ($\frac{1}{2}, \frac{1}{2}$) and give both $\frac{1}{2}$-sized pieces to whoever got the uncut muffin. (Note $\frac{1}{2} > \frac{5}{12}$.) Reduces to other cases.
*(Henceforth: All muffins are cut into $\geq 2$ pieces.)*
NO WE CAN’T!
There is a procedure for 5 muffins, 3 students where each student gets $\frac{5}{3}$ muffins, smallest piece $N$. We want $N \leq \frac{5}{12}$.

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(Henceforth: All muffins are cut into $\geq 2$ pieces.)

**Case 1:** Some muffin is cut into $\geq 3$ pieces. Then $N \leq \frac{1}{3} < \frac{5}{12}$.
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NO WE CAN’T!
There is a procedure for 5 muffins, 3 students where each student gets \( \frac{5}{3} \) muffins, smallest piece \( N \). We want \( N \leq \frac{5}{12} \).

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(\textbf{Henceforth:} All muffins are cut into \( \geq 2 \) pieces.)

**Case 1:** Some muffin is cut into \( \geq 3 \) pieces. Then \( N \leq \frac{1}{3} < \frac{5}{12} \). 

(\textbf{Henceforth:} All muffins are cut into 2 pieces.)

**Case 2:** All muffins are cut into 2 pieces. 10 pieces, 3 students: \textbf{Someone} gets \( \geq 4 \) pieces. He has some piece

\[
\leq \frac{5}{3} \times \frac{1}{4} = \frac{5}{12}
\]

Great to see \( \frac{5}{12} \).
General Problem

\[ f(m, s) \] be the smallest piece in the best procedure (best in that the smallest piece is maximized) to divide \( m \) muffins among \( s \) students so that everyone gets \( \frac{m}{s} \).
General Problem

$f(m, s)$ be the smallest piece in the best procedure (best in that the smallest piece is maximized) to divide $m$ muffins among $s$ students so that everyone gets $\frac{m}{s}$.

We have shown $f(5, 3) = \frac{5}{12}$. 
FC Thm: If $m > s$ and $s$ does not divide $m$ then

$$f(m, s) \leq \text{FC}(m, s) = \max \left\{ \frac{1}{3}, \min \left\{ \frac{m}{s \lceil 2m/s \rceil}, 1 - \frac{m}{s \lfloor 2m/s \rfloor} \right\} \right\}.$$
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**Case 1:** Some muffin is cut into $\geq 3$ pieces. Some piece $\leq \frac{1}{3}$.

**Case 2:** Every muffin is cut into 2 pieces, so $2m$ pieces.
**FC Thm:** If $m > s$ and $s$ does not divide $m$ then

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Alice gets $\geq \left\lceil \frac{2m}{s} \right\rceil$ pieces. $\exists$ piece $\leq \frac{m}{s} \times \frac{1}{\lceil 2m/s \rceil} = \frac{m}{s \lceil 2m/s \rceil}$.  

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**Alice** gets $\leq \left\lfloor \frac{2m}{s} \right\rfloor$ pieces. $\exists$ piece $\geq \frac{m}{s} \left\lfloor \frac{1}{2m/s} \right\rfloor = \frac{m}{s \left\lfloor 2m/s \right\rfloor}$.

The other piece from that muffin is of size $\leq 1 - \frac{m}{s \left\lfloor 2m/s \right\rfloor}$.
THREE Students

We only look at when 3 does not divide the number of muffins. Here is what the FC theorem tells us:

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</tr>
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Try to find the protocol for EIGHT muffins, THREE students, everyone gets $\frac{8}{3}$, and smallest piece is $\frac{4}{9}$.

Solve in Breakout Rooms Groups
\[ f(8, 3) = \frac{4}{9} \]

By FC \( f(8, 3) \leq \frac{4}{9} \).
By FC $f(8, 3) \leq \frac{4}{9}$.

We show $f(8, 3) \geq \frac{4}{9}$. 
Let $f(8, 3) = \frac{4}{9}$.

By FC $f(8, 3) \leq \frac{4}{9}$.

We show $f(8, 3) \geq \frac{4}{9}$.

1. Divide 8 muffins $\{\frac{4}{9}, \frac{5}{9}\}$.
2. Give 2 students $\{\frac{5}{9}, \frac{5}{9}, \frac{5}{9}, \frac{4}{9}\}$.
3. Give 1 student $\{\frac{4}{9}, \frac{4}{9}, \frac{4}{9}, \frac{4}{9}, \frac{4}{9}, \frac{4}{9}\}$. 
FOUR Students

We only look at when 4 and $m$ have no common factors. Here is what the FC theorem tells us:

$$f(m, 4) \leq \frac{3}{8}, \frac{5}{12}, \frac{7}{16}, \frac{9}{20}$$
FOUR Students

We only look at when 4 and \( m \) have no common factors. Here is what the FC theorem tells us:

\[
\begin{array}{|c|c|}
\hline
m & f(m, 4) \leq \\
\hline
5 & 3/8 \\
7 & 5/12 \\
9 & 7/16 \\
11 & 9/20 \\
\hline
\end{array}
\]

Try to find the protocol for SEVEN muffins, FOUR students, everyone gets \( \frac{7}{4} \), and smallest piece is \( \frac{5}{12} \).

Solve in Breakout Rooms Groups
$f(7, 4) = \frac{5}{12}$

By FC $f(7, 4) \leq \frac{5}{12}$. 
By FC \( f(7, 4) \leq \frac{5}{12} \).

We show \( f(7, 4) \geq \frac{5}{12} \).
$f(7,4) = \frac{5}{12}$

By FC $f(7,4) \leq \frac{5}{12}$.

We show $f(7,4) \geq \frac{5}{12}$.

1. Divide 6 muffins $\{\frac{5}{12}, \frac{7}{12}\}$.
2. Divide 1 muffins $\{\frac{6}{12}, \frac{6}{12}\}$.
3. Give 2 students $\{\frac{7}{12}, \frac{7}{12}, \frac{7}{12}\}$.
4. Give 2 student $\{\frac{5}{12}, \frac{5}{12}, \frac{5}{12}, \frac{6}{12}\}$. 
The following is true:

- If $m \geq 4$ and $m \equiv 1, 2 \pmod{3}$ then $f(m, 3) = FC(m, 3)$.
- If $m \geq 5$ and $m \equiv 1, 3 \pmod{4}$ then $f(m, 4) = FC(m, 4)$. 
FC Conjecture

The following is true:

- If $m \geq 4$ and $m \equiv 1, 2 \pmod{3}$ then $f(m, 3) = \text{FC}(m, 3)$.
- If $m \geq 5$ and $m \equiv 1, 3 \pmod{4}$ then $f(m, 4) = \text{FC}(m, 4)$.

FC Conjecture

If $m \geq s + 1$ and $s, m$ rel prime then $f(m, s) = \text{FC}(m, s)$.
FC Conjecture

The following is true:

- If \( m \geq 4 \) and \( m \equiv 1, 2 \pmod{3} \) then \( f(m, 3) = FC(m, 3) \).
- If \( m \geq 5 \) and \( m \equiv 1, 3 \pmod{4} \) then \( f(m, 4) = FC(m, 4) \).

FC Conjecture

If \( m \geq s + 1 \) and \( s, m \) rel prime then \( f(m, s) = FC(m, s) \).

Vote YES, NO, Unknown to Science (UN).
The following is true:

- If \( m \geq 4 \) and \( m \equiv 1, 2 \pmod{3} \) then \( f(m, 3) = \text{FC}(m, 3) \).
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\textbf{FC Conjecture}

If \( m \geq s + 1 \) and \( s, m \) rel prime then \( f(m, s) = \text{FC}(m, s) \).

\textbf{Vote} YES, NO, Unknown to Science (UN).

NO
FIVE Students

We only look at when 4 and $m$ have no common factors. Here is what the FC theorem tells us:

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I am sure you all could do protocols for $f(6, 5), f(7, 5), f(8, 5), f(9, 5)$ that match the bounds here. History I tried to find a protocol for $f(11, 5) \geq 11/25$. I could not. I found a protocol with $f(11, 5) \geq 13/30$. I showed that if there is a protocol it must BLAH. I showed there was NO such protocol with BLAH! and showed $f(11, 5) \leq 13/30$. 
We only look at when 4 and $m$ have no common factors. Here is what the FC theorem tells us:

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I am sure you all could do protocols for $f(6, 5)$, $f(7, 5)$, $f(8, 5)$, $f(9, 5)$ that match the bounds here.

**History** I tried to find a protocol for $f(11, 5) \geq \frac{11}{25}$. I could not. I found a protocol with $f(11, 5) \geq \frac{13}{30}$. 
FIVE Students

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I am sure you all could do protocols for \( f(6, 5) \), \( f(7, 5) \), \( f(8, 5) \), \( f(9, 5) \) that match the bounds here.

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I showed that if there is a protocol it must BLAH. I showed there was NO such protocol with BLAH! and showed \( f(11, 5) \leq \frac{13}{30} \).
Terminology: Buddy

Assume that in some protocol every muffin is cut into two pieces.

Let $x$ be a piece from muffin $M$. The other piece from muffin $M$ is the buddy of $x$.

Note that the buddy of $x$ is of size $1 - x$. 
There is a procedure for 11 muffins, 5 students where each student gets $\frac{11}{5}$ muffins, smallest piece $N$. We want $N \leq \frac{13}{30}$.

**Case 0:** Some muffin is uncut. Cut it ($\frac{1}{2}, \frac{1}{2}$) and give both halves to whoever got the uncut muffin. Reduces to other cases.
There is a procedure for 11 muffins, 5 students where each student gets \( \frac{11}{5} \) muffins, smallest piece \( N \). We want \( N \leq \frac{13}{30} \).

**Case 0:** Some muffin is uncut. Cut it \((\frac{1}{2}, \frac{1}{2})\) and give both halves to whoever got the uncut muffin. Reduces to other cases.

**Case 1:** Some muffin is cut into \( \geq 3 \) pieces. \( N \leq \frac{1}{3} < \frac{13}{30} \).

( Negation of Case 0 and Case 1: All muffins cut into 2 pieces.)
\[ f(11, 5) = \frac{13}{30}, \text{ Easy Case Based on Students} \]

**Case 2:** Some student gets \( \geq 6 \) pieces.

\[
N \leq \frac{11}{5} \times \frac{1}{6} = \frac{11}{30} < \frac{13}{30}.
\]
$f(11, 5) = \frac{13}{30}$, Easy Case Based on Students

**Case 2:** Some student gets $\geq 6$ pieces.

$$N \leq \frac{11}{5} \times \frac{1}{6} = \frac{11}{30} < \frac{13}{30}.$$ 

**Case 3:** Some student gets $\leq 3$ pieces.

One of the pieces is

$$\geq \frac{11}{5} \times \frac{1}{3} = \frac{11}{15}.$$ 

Look at the muffin it came from to find a piece that is

$$\leq 1 - \frac{11}{15} = \frac{4}{15} < \frac{13}{30}.$$ 

(Negation of Cases 2 and 3: Every student gets 4 or 5 pieces.)
**Case 4:** Every muffin is cut in 2 pieces, every student gets 4 or 5 pieces. Number of pieces: 22. Note \( \leq 11 \) pieces are \( \geq \frac{1}{2} \).

- \( s_4 \) is number of students who get 4 pieces
- \( s_5 \) is number of students who get 5 pieces

\[
4s_4 + 5s_5 = 22 \\
 s_4 + s_5 = 5
\]

\( s_4 = 3 \): There are 3 students who have 4 shares.
\( s_5 = 2 \): There are 2 students who have 5 shares.

We call a share that goes to a person who gets 4 shares a **4-share**.
We call a share that goes to a person who gets 5 shares a **5-share**.
\[ f(11, 5) = \frac{13}{30}, \text{ Fun Cases} \]

**Case 4.1:** Some 4-share is \( \leq \frac{1}{2} \).

Alice gets \( w, x, y, z \) and \( w \leq \frac{1}{2} \).

Since \( w + x + y + z = \frac{11}{5} \) and \( w \leq \frac{1}{2} \)

\[
x + y + z \geq \frac{11}{5} - \frac{1}{2} = \frac{17}{10}
\]

Let \( x \) be the largest of \( x, y, z \)

\[
x \geq \frac{17}{10} \times \frac{1}{3} = \frac{17}{30}
\]

Look at **buddy** of \( x \).

\[
B(x) \leq 1 - x = 1 - \frac{17}{30} = \frac{13}{30}
\]

GREAT! This is where \( \frac{13}{30} \) comes from!
\[ f(11, 5) = \frac{13}{30}, \text{ Fun Cases} \]

**Case 4.2:** All 4-shares are \( > \frac{1}{2} \). There are 4\( s_4 = 12 \) 4-shares. There are \( \geq 12 \) pieces \( > \frac{1}{2} \). Can’t occur. So we are done!
History and What Else is Known

1. I found the problem in a pamphlet at the Gathering for Gardner Meeting in 2015.
2. I worked on 3 students, 4 students, but got stuck on 5 students until I got the HALF method.
3. I worked on 6 students, 7, etc. Whenever I got stuck I would ask someone to help me.
4. I now have many methods for finding $f(m,s)$: FC, HALF, MID, INT, GAP, TRAIN, Easy-Buddy-Match, Hard-Buddy-Match, Scott's Method. Matrix.
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History and What Else is Known

1. I found the problem in a pamphlet at the Gathering for Gardner Meeting in 2015.

2. I worked on 3 students, 4 students, but got stuck on 5 students until I got the HALF method.

3. I worked on 6 students, 7, etc. Whenever I got stuck I would ask someone to help me.

4. I now have many methods for finding $f(m, s)$: FC, HALF, MID, INT, GAP, TRAIN, Easy-Buddy-Match, Hard-Buddy-Match, Scott’s Method. Matrix.


But wait! There is more! Next Slide!
Fame and Fortune!

Where can I read about all this great stuff!
Fame and Fortune!

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In my book:
https://www.amazon.com/
Mathematical-Muffin-Morsels-Problem-Mathematics/dp/9811215170

Is there a song about this mathematics?
https://www.youtube.com/watch?v=4xQFlsK7jKg&t=1s

Does Alan Frank know about the work?
I gave a talk on this at the MIT combinatorics seminar and I knew Alan Frank was in Boston so we agreed to meet. He gave me \( \frac{5}{12} - \frac{7}{12} \) and one \( \frac{6}{12} - \frac{6}{12} \). I gave him a free signed copy of my book.
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