The Muffin Problem

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How it Began

A Recreational Math Conference
(Gathering for Gardner)
May 2016

I found a pamphlet:
The Julia Robinson Mathematics Festival:
A Sample of Mathematical Puzzles
Compiled by Nancy Blachman
which had this problem, proposed by Alan Frank:

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?
### 5 Muffins, 3 Students, Proc by Picture

<table>
<thead>
<tr>
<th>Person</th>
<th>Color</th>
<th>What they Get</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alice</td>
<td>RED</td>
<td>$1 + \frac{2}{3} = \frac{5}{3}$</td>
</tr>
<tr>
<td>Bob</td>
<td>BLUE</td>
<td>$1 + \frac{2}{3} = \frac{5}{3}$</td>
</tr>
<tr>
<td>Carol</td>
<td>GREEN</td>
<td>$1 + \frac{1}{3} + \frac{1}{3} = \frac{5}{3}$</td>
</tr>
</tbody>
</table>

**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 neighbor*
5 Muffins, 3 People—Proc by Picture

YES WE CAN!

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<td>$\frac{6}{12} + \frac{7}{12} + \frac{7}{12}$</td>
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<td>GREEN</td>
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Smallest Piece: $\frac{5}{12}$
Can We Do Better?

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

**Is there a procedure with a larger smallest piece?**

**Work on it with your neighbor**
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 cut into $\geq 2$ pieces.)
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**Case 1:** Some muffin is cut into $\geq 3$ pieces. Then $N \leq \frac{1}{3} < \frac{5}{12}$. (**Henceforth:** All muffins cut into 2 pieces.)
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 $N \leq \frac{5}{12}$.

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Case 1: Some muffin is cut into $\geq 3$ pieces. Then $N \leq \frac{1}{3} < \frac{5}{12}$. (Henceforth: All muffins cut into 2 pieces.)

Case 2: All muffins are cut into 2 pieces. 10 pieces, 3 students: Someone gets $\geq 4$ pieces. He has some piece

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

Great to see $\frac{5}{12}$
The pamphlet also had asked about

1. 4 muffins, 7 students.
2. 12 muffins, 11 students.
3. a few others
What Else Was in the Pamphlet?

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This seemed like a nice exercise and it was.

There can’t be much more to this.
If there is not much more to this then how come

https://www.amazon.com/
Mathematical-Muffin-Morsels-Problem-Mathematics/dp/
9811215170
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The following happened:

► Find a technique that solves many problems (e.g., Floor-Ceiling).
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The following happened:

- Find a technique that solves many problems (e.g., Floor-Ceiling).
- Come across a problem where the techniques do not work.
- Find a new technique which was interesting.
- Lather, Rinse, Repeat.
**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 \( f(5, 3) = \frac{5}{12} \) here.

We have shown \( f(m, s) \) exists, is rational, and is computable using a **Mixed Int Program**.
General Problem

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We have shown \( f(5, 3) = \frac{5}{12} \) here.

We have shown \( f(m, s) \) exists, is rational, and is computable using a Mixed Int Program.
This was a case of a Theorem in Applied Math being used to prove a Theorem in Pure Math.
Amazing Results!/Amazing Theorems!

1. \( f(43, 33) = \frac{91}{264} \).
2. \( f(52, 11) = \frac{83}{176} \).
3. \( f(35, 13) = \frac{64}{143} \).

All done by hand, no use of a computer by Co-author Erik Metz is a muffin savant!

Have General Theorems from which upper bounds follow.

Have General Procedures from which lower bounds follow.
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Conventions

**Duality Theorem:** \( f(m, s) = \frac{m}{s} f(s, m) \).
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4. If assuming \( f(m, s) > \alpha > \frac{1}{3} \), assume all muffin in \( \leq 2 \) pcs.
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We know and use the following:

1. By Duality Theorem can assume $m > s$
2. By REASONS we can assume $m, s$ are relatively prime.
3. All muffins are cut in $\geq 2$ pcs. Replace uncut muff with $2 \frac{1}{2}$’s
4. If assuming $f(m, s) > \alpha > \frac{1}{3}$, assume all muffin in $\leq 2$ pcs.
5. $f(m, s) > \alpha > \frac{1}{3}$, so exactly 2 pcs, is common case.
FC Thm Generalizes \( f(5, 3) \leq \frac{5}{12} \)

\[
f(m, s) \leq \text{FC}(m, s) = \max\left\{ \frac{1}{3}, \min\left\{ \frac{m}{s \left\lceil 2m/s \right\rceil}, 1 - \frac{m}{s \left\lfloor 2m/s \right\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.
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Someone gets $\geq \left\lceil \frac{2m}{s} \right\rceil$ pieces. $\exists$ piece $\leq \frac{m}{s} \times \left\lfloor \frac{1}{2m/s} \right\rfloor = \frac{m}{s \lfloor 2m/s \rfloor}$. 
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Someone gets $\geq \left\lfloor \frac{2m}{s} \right\rfloor$ pieces. $\exists$ piece $\leq \frac{m}{s} \times \frac{1}{\lfloor 2m/s \rfloor} = \frac{m}{s \lfloor 2m/s \rfloor}$.

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

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

CLEVERNESS, COMP PROGS for the procedure.

FC Theorem for optimality.
THREE Students

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\[ f(1, 3) = \frac{1}{3} \]
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\[ f(3k, 3) = 1. \]
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FC Theorem for optimality.

\[ f(1, 3) = \frac{1}{3} \]

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\[ f(3k + 1, 3) = \frac{3k - 1}{6k}, \quad k \geq 1. \]
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\[ f(3k + 2, 3) = \frac{3k+2}{6k+6}. \]
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Note: A Mod 3 Pattern.

Theorem: For all \( m \geq 3 \), \( f(m, 3) = FC(m, 3) \).
FOUR Students

CLEVERNESS, COMP PROGS for procedures.

FC Theorem for optimality.
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\[ f(4k, 4) = 1 \text{ (easy)} \]
FOUR Students

**CLEVERNESS, COMP PROGS** for procedures.

**FC Theorem** for optimality.

\[ f(4k, 4) = 1 \text{ (easy)} \]

\[ f(1, 4) = \frac{1}{4} \text{ (easy)} \]
FOUR Students

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FC Theorem for optimality.

\[ f(4k, 4) = 1 \text{ (easy)} \]

\[ f(1, 4) = \frac{1}{4} \text{ (easy)} \]

\[ f(4k + 1, 4) = \frac{4k-1}{8k}, \, k \geq 1. \]
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\[ f(4k + 2, 4) = \frac{1}{2}. \]
FOUR Students

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\[ f(4k + 2, 4) = \frac{1}{2}. \]
\[ f(4k + 3, 4) = \frac{4k+1}{8k+4}. \]

Note: A Mod 4 Pattern.

Theorem: For all \( m \geq 4 \), \( f(m, 4) = FC(m, 4) \).
FOUR Students

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FC Theorem for optimality.

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Note: A Mod 4 Pattern.

Theorem: For all \( m \geq 4 \), \( f(m, 4) = FC(m, 4) \).

FC-Conjecture: For all \( m, s \) with \( m \geq s \), \( f(m, s) = FC(m, s) \).
FIVE Students

CLEVERNESS, COMP PROGS for procedures.

FC Theorem for optimality.
FIVE Students

**CLEVERNESS, COMP PROGS** for procedures.

**FC Theorem** for optimality.

For $k \geq 1$, $f(5k, 5) = 1$. 

Note: A Mod 5 Pattern.

Theorem: For all $m \geq 5$ except $m=11$, $f(m, 5) = FC(m, 5)$. 

FIVE Students

CLEVERNESS, COMP PROGS for procedures.

FC Theorem for optimality.

For $k \geq 1$, $f(5k, 5) = 1$.

For $k = 1$ and $k \geq 3$, $f(5k + 1, 5) = \frac{5k+1}{10k+5}$. $f(11, 5)$?
Cleverness, Comp Progs for procedures.

FC Theorem for optimality.

For $k \geq 1$, $f(5k, 5) = 1$.

For $k = 1$ and $k \geq 3$, $f(5k + 1, 5) = \frac{5k+1}{10k+5}$. $f(11, 5)$?

For $k \geq 2$, $f(5k + 2, 5) = \frac{5k-2}{10k}$. $f(7, 5) = FC(7, 5) = \frac{1}{3}$
CLEVERNESS, COMP PROGS for procedures.

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For $k \geq 2$, $f(5k + 2, 5) = \frac{5k-2}{10k}$. $f(7, 5) = FC(7, 5) = \frac{1}{3}$

For $k \geq 1$, $f(5k + 3, 5) = \frac{5k+3}{10k+10}$
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For $k \geq 1$, $f(5k, 5) = 1$.

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For $k \geq 2$, $f(5k + 2, 5) = \frac{5k-2}{10k}$. $f(7, 5) = FC(7, 5) = \frac{1}{3}$

For $k \geq 1$, $f(5k + 3, 5) = \frac{5k+3}{10k+10}$

For $k \geq 1$, $f(5k + 4, 5) = \frac{5k+1}{10k+5}$

Note: A Mod 5 Pattern.
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FC Theorem for optimality.

For \( k \geq 1 \), \( f(5k, 5) = 1 \).

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For \( k \geq 2 \), \( f(5k + 2, 5) = \frac{5k-2}{10k} \). \( f(7, 5) = FC(7, 5) = \frac{1}{3} \)

For \( k \geq 1 \), \( f(5k + 3, 5) = \frac{5k+3}{10k+10} \)

For \( k \geq 1 \), \( f(5k + 4, 5) = \frac{5k+1}{10k+5} \)

Note: A Mod 5 Pattern.

Theorem: For all \( m \geq 5 \) except \( m=11 \), \( f(m, 5) = FC(m, 5) \).
What About FIVE students, ELEVEN muffins?

\[ f(11, 5) \leq \max \left\{ \frac{1}{3}, \min \left\{ \frac{11}{5 \lceil 22/5 \rceil}, 1 - \frac{11}{5 \lceil 22/5 \rceil} \right\} \right\} = \frac{11}{25}. \]
What About FIVE students, ELEVEN muffins?

\[
f(11, 5) \leq \max \left\{ \frac{1}{3}, \min \left\{ \frac{11}{5 \lceil 22/5 \rceil}, 1 - \frac{11}{5 \lceil 22/5 \rceil} \right\} \right\} = \frac{11}{25}.
\]

We tried to find a protocol to divide 11 muffins for 5 people, each gets \( \frac{11}{5} \), and smallest piece is size \( \frac{11}{25} = 0.44 \).
What About FIVE students, ELEVEN muffins?

\[
f(11, 5) \leq \max \left\{ \frac{1}{3}, \min \left\{ \frac{11}{5 \lceil \frac{22}{5} \rceil}, 1 - \frac{11}{5 \lfloor \frac{22}{5} \rfloor} \right\} \right\} = \frac{11}{25}.
\]

We tried to find a protocol to divide 11 muffins for 5 people, each gets \( \frac{11}{5} \), and smallest piece is size \( \frac{11}{25} = 0.44 \).
We found a protocol with smallest piece \( \frac{13}{30} = 0.4333 \ldots \).

1. Divide 1 muffin \( \left( \frac{15}{30}, \frac{15}{30} \right) \).
2. Divide 2 muffins \( \left( \frac{14}{30}, \frac{16}{30} \right) \).
3. Divide 8 muffins \( \left( \frac{13}{30}, \frac{17}{30} \right) \).
4. Give 2 students \( \left[ \frac{13}{30}, \frac{13}{30}, \frac{13}{30}, \frac{13}{30}, \frac{14}{30} \right] \).
5. Give 1 students \( \left[ \frac{16}{30}, \frac{16}{30}, \frac{17}{30}, \frac{17}{30} \right] \).
6. Give 2 students \( \left[ \frac{15}{30}, \frac{17}{30}, \frac{17}{30}, \frac{17}{30} \right] \).
So Now What?

We have:

\[
\frac{13}{30} \leq f(11, 5) \leq \frac{11}{25} \quad \text{Diff} = 0.006666 \ldots
\]
So Now What?

We have:

\[
\frac{13}{30} \leq f(11, 5) \leq \frac{11}{25} \quad \text{Diff} = 0.006666\ldots
\]

Options:

1. \( f(11, 5) = \frac{11}{25} \). Need to find procedure.
2. \( f(11, 5) = \frac{13}{30} \). Need to find new technique for upper bounds.
3. \( f(11, 5) \) in between. Need to find both.
4. \( f(11, 5) \) unknown to science!

Vote
So Now What?

We have:

$$\frac{13}{30} \leq f(11, 5) \leq \frac{11}{25} \quad \text{Diff} = 0.006666\ldots$$

Options:

1. \( f(11, 5) = \frac{11}{25} \). Need to find procedure.
2. \( f(11, 5) = \frac{13}{30} \). Need to find new technique for upper bounds.
3. \( f(11, 5) \) in between. Need to find both.
4. \( f(11, 5) \) unknown to science!

Vote WE SHOW: \( f(11, 5) = \frac{13}{30} \). Exciting new technique!
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 \( \left( \frac{1}{2}, \frac{1}{2} \right) \) and give both halves to whoever got the uncut muffin. Reduces to other cases.

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

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

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

\[
N \leq \frac{11}{5} \times \frac{1}{6} = \frac{11}{30} < \frac{13}{30}.
\]
\( f(11, 5) = \frac{13}{30}, \) 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

\[
\geq \frac{11}{5} \times \frac{1}{3} = \frac{11}{15}.
\]
\[ f(11, 5) = \frac{13}{30}, \text{ Easy Case Based on Students} \]

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

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

**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

\[ \leq 1 - \frac{11}{15} = \frac{4}{15} < \frac{13}{30}. \]
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 $> \frac{1}{2}$. 

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.
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 $> \frac{1}{2}$.

- $s_4$ is number of students who get 4 pieces
- $s_5$ is number of students who get 5 pieces

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.
$f(11, 5) = \frac{13}{30}$, Fun Cases

**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 $> \frac{1}{2}$.

- $s_4$ is number of students who get 4 pieces
- $s_5$ is number of students who get 5 pieces

\[
4s_4 + 5s_5 = 22
\]
\[
s_4 + s_5 = 5
\]
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 \( > \frac{1}{2} \).

- \( s_4 \) 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.
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 \( > \frac{1}{2} \).

- \( s_4 \) 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.
Case 4.1: Some 4-share is $\leq \frac{1}{2}$.

Alice gets $w \leq x \leq y \leq z$ and $w \leq \frac{1}{2}$.

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

$$x + y + z \geq \frac{11}{5} - \frac{1}{2} = \frac{17}{10}$$
Case 4.1: Some 4-share is \( \leq \frac{1}{2} \).

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

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

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

\[
z \geq \frac{17}{10} \times \frac{1}{3} = \frac{17}{30}
\]
Case 4.1: Some 4-share is ≤ \( \frac{1}{2} \).

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

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

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

Look at \textbf{buddy} of \( z \).

\[
B(z) \leq 1 - z = 1 - \frac{17}{30} = \frac{13}{30}
\]
Case 4.1: Some 4-share is $\leq \frac{1}{2}$.

Alice gets $w \leq x \leq y \leq z$ and $w \leq \frac{1}{2}$.

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

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

$$z \geq \frac{17}{10} \times \frac{1}{3} = \frac{17}{30}$$

Look at buddy of $z$.

$$B(z) \leq 1 - z = 1 - \frac{17}{30} = \frac{13}{30}$$

GREAT! This is where $\frac{13}{30}$ comes from!
Case 4.2: All 4-shares are $> \frac{1}{2}$. There are $4s_4 = 12$ 4-shares. There are $\geq 12$ pieces $> \frac{1}{2}$. Can’t occur.
INT Method

Proof that $f(11, 5) \leq \frac{13}{30}$ was an example of the HALF method.
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FC or HALF worked on everything with $m = 3, 4, 5, \ldots, 23$. 
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FC or HALF worked on everything with $m = 3, 4, 5, \ldots, 23$.

Then we found a case where neither FC nor HALF worked.
INT Method

Proof that \( f(11, 5) \leq \frac{13}{30} \) was an example of the HALF method.

FC or HALF worked on everything with \( m = 3, 4, 5, \ldots, 23 \).

Then we found a case where neither FC nor HALF worked.

We found a new method: INT.
Assume (24, 11)-procedure with smallest piece $> \frac{19}{44}$. Can assume all muffin cut in two and all student gets $\geq 2$ shares. We show that there is a piece $\leq \frac{19}{44}$. 

Case 1: A student gets $\geq 6$ shares. Some piece $\leq \frac{24}{11} \times 6 < \frac{19}{44}$.

Case 2: A student gets $\leq 3$ shares. Some piece $\geq \frac{24}{11} \times 3 = \frac{8}{11}$. Buddy of that piece $\leq 1 - \frac{8}{11} \leq 3 \frac{1}{11} < \frac{19}{44}$.

Case 3: Every muffin is cut in 2 pieces and every student gets either 4 or 5 shares. Total number of shares is 48.
More Sophisticated INT: $f(24, 11) \leq \frac{19}{44}$

Assume $(24, 11)$-procedure with smallest piece $> \frac{19}{44}$. Can assume all muffin cut in two and all student gets $\geq 2$ shares. We show that there is a piece $\leq \frac{19}{44}$.

**Case 1:** A student gets $\geq 6$ shares. Some piece $\leq \frac{24}{11 \times 6} < \frac{19}{44}$. 
Assume $(24, 11)$-procedure with smallest piece $> \frac{19}{44}$. Can assume all muffin cut in two and all student gets $\geq 2$ shares. We show that there is a piece $\leq \frac{19}{44}$.

**Case 1:** A student gets $\geq 6$ shares. Some piece $\leq \frac{24}{11 \times 6} < \frac{19}{44}$.

**Case 2:** A student gets $\leq 3$ shares. Some piece $\geq \frac{24}{11 \times 3} = \frac{8}{11}$. Buddy of that piece $\leq 1 - \frac{8}{11} \leq \frac{3}{11} < \frac{19}{44}$. 

More Sophisticated INT: $f(24, 11) \leq \frac{19}{44}$

Assume $(24, 11)$-procedure with smallest piece $> \frac{19}{44}$. Can assume all muffin cut in two and all student gets $\geq 2$ shares. We show that there is a piece $\leq \frac{19}{44}$.

**Case 1:** A student gets $\geq 6$ shares. Some piece $\leq \frac{24}{11 \times 6} < \frac{19}{44}$.

**Case 2:** A student gets $\leq 3$ shares. Some piece $\geq \frac{24}{11 \times 3} = \frac{8}{11}$. Buddy of that piece $\leq 1 - \frac{8}{11} \leq \frac{3}{11} < \frac{19}{44}$.

**Case 3:** Every muffin is cut in 2 pieces and every student gets either 4 or 5 shares. Total number of shares is 48.
How many students get 4? 5? Where are Shares?

4-students: a student who gets 4 shares. $s_4$ is the number of them.

5-students: a student who gets 5 shares. $s_5$ is the number of them.

$4s_4 + 5s_5 = 48$

$s_4 + s_5 = 11$

$s_4 = 7$. Hence there are 4 $s_4 = 4 \times 7 = 28$ 4-shares.

$s_5 = 4$. Hence there are 5 $s_5 = 5 \times 4 = 20$ 5-shares.
How many students get 4? 5? Where are Shares?

4-students: a student who gets 4 shares. $s_4$ is the number of them.
5-students: a student who gets 5 shares. $s_5$ is the number of them.

4-share: a share that a 4-student who gets.
5-share: a share that a 5-student who gets.
How many students get 4? 5? Where are Shares?

4-students: a student who gets 4 shares. \( s_4 \) is the number of them.

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4s_4 + 5s_5 = 48 \\
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How many students get 4? 5? Where are Shares?

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5-students: a student who gets 5 shares. \( s_5 \) is the number of them.

4-share: a share that a 4-student who gets.
5-share: a share that a 5-student who gets.

\[
4s_4 + 5s_5 = 48 \\
s_4 + s_5 = 11
\]

\( s_4 = 7 \). Hence there are \( 4s_4 = 4 \times 7 = 28 \) 4-shares.
\( s_5 = 4 \). Hence there are \( 5s_5 = 5 \times 4 = 20 \) 5-shares.
Case 3.1 and 3.2: Too Big or Too Small

Case 3.1: There is a share $\geq \frac{25}{44}$. Then its buddy is $\leq 1 - \frac{25}{44} = \frac{19}{44}$.

Case 3.2: There is a share $\leq \frac{19}{44}$. Duh.

Henceforth assume that all shares are in $\left( \frac{19}{44}, \frac{25}{44} \right)$. 
Case 3.1 and 3.2: Too Big or Too Small

**Case 3.1:** There is a share \( \geq \frac{25}{44} \). Then its buddy is

\[
\leq 1 - \frac{25}{44} = \frac{19}{44}
\]
Case 3.1 and 3.2: Too Big or Too Small

**Case 3.1:** There is a share $\geq \frac{25}{44}$. Then its buddy is

\[
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\]

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Case 3.1 and 3.2: Too Big or Too Small

**Case 3.1:** There is a share $\geq \frac{25}{44}$. Then its buddy is

$$\leq 1 - \frac{25}{44} = \frac{19}{44}$$

**Case 3.2:** There is a share $\leq \frac{19}{44}$. Duh.

Henceforth assume that all shares are in

$$\left( \frac{19}{44}, \frac{25}{44} \right)$$

$$\left( \frac{19}{44}, \frac{25}{44} \right)$$
Case 3.3: Some 5-shares $\geq \frac{20}{44}$

5-share: a share that a 5-student who gets.

Claim: If some 5-shares is $\geq \frac{20}{44}$ then some share $\leq \frac{19}{44}$.
Case 3.3: Some 5-shares ≥ $\frac{20}{44}$

5-share: a share that a 5-student who gets.

Claim: If some 5-shares is $\geq \frac{20}{44}$ then some share $\leq \frac{19}{44}$.

Proof: Assume Alice has $v \leq w \leq x \leq y \leq z$ and $z \geq \frac{20}{44}$. Since $v + w + x + y + z = \frac{24}{11}$ and $z \geq \frac{20}{44}$, $v + w + x + y \leq \frac{24}{11} - \frac{20}{44} = \frac{76}{44}$, hence $v \leq \frac{76}{44} \times \frac{1}{5} = \frac{19}{44}.$

Henceforth we assume all 5-shares are in $\left(\frac{19}{44}, \frac{20}{44}\right].$
Case 3.3: Some 5-shares $\geq \frac{20}{44}$

5-share: a share that a 5-student who gets.

Claim: If some 5-shares is $\geq \frac{20}{44}$ then some share $\leq \frac{19}{44}$.

Proof: Assume Alice has $v \leq w \leq x \leq y \leq z$ and $z \geq \frac{20}{44}$. Since $v + w + x + y + z = \frac{24}{11}$ and $z \geq \frac{20}{44}$
Case 3.3: Some 5-shares $\geq \frac{20}{44}$

5-share: a share that a 5-student who gets.

Claim: If some 5-shares is $\geq \frac{20}{44}$ then some share $\leq \frac{19}{44}$.

Proof: Assume Alice has $v \leq w \leq x \leq y \leq z$ and $z \geq \frac{20}{44}$.

Since $v + w + x + y + z = \frac{24}{11}$ and $z \geq \frac{20}{44}$

$$v + w + x + y \leq \frac{24}{11} - \frac{20}{44} = \frac{76}{44}$$
Case 3.3: Some 5-shares $\geq \frac{20}{44}$

5-share: a share that a 5-student who gets.

Claim: If some 5-shares is $\geq \frac{20}{44}$ then some share $\leq \frac{19}{44}$.

Proof: Assume Alice has $v \leq w \leq x \leq y \leq z$ and $z \geq \frac{20}{44}$.
Since $v + w + x + y + z = \frac{24}{11}$ and $z \geq \frac{20}{44}$

$$v + w + x + y \leq \frac{24}{11} - \frac{20}{44} = \frac{76}{44}$$

$$v \leq \frac{76}{44} \times \frac{1}{4} = \frac{19}{44}$$
Case 3.3: Some 5-shares $\geq \frac{20}{44}$

5-share: a share that a 5-student who gets.

Claim: If some 5-shares is $\geq \frac{20}{44}$ then some share $\leq \frac{19}{44}$.

Proof: Assume Alice has $v \leq w \leq x \leq y \leq z$ and $z \geq \frac{20}{44}$.
Since $v + w + x + y + z = \frac{24}{11}$ and $z \geq \frac{20}{44}$

$$v + w + x + y \leq \frac{24}{11} - \frac{20}{44} = \frac{76}{44}$$

$$v \leq \frac{76}{44} \times \frac{1}{4} = \frac{19}{44}$$

Henceforth we assume all 5-shares are in $\left(\frac{19}{44}, \frac{20}{44}\right)$. 
Case 3.3: Some 5-shares \( \geq \frac{20}{44} \)

5-share: a share that a 5-student who gets.

Claim: If some 5-shares is \( \geq \frac{20}{44} \) then some share \( \leq \frac{19}{44} \).

Proof: Assume Alice has \( v \leq w \leq x \leq y \leq z \) and \( z \geq \frac{20}{44} \).

Since \( v + w + x + y + z = \frac{24}{11} \) and \( z \geq \frac{20}{44} \)

\[
 v + w + x + y \leq \frac{24}{11} - \frac{20}{44} = \frac{76}{44}
\]

\[
 v \leq \frac{76}{44} \times \frac{1}{4} = \frac{19}{44}
\]

Henceforth we assume all 5-shares are in \( \left( \frac{19}{44}, \frac{20}{44} \right) \).

\[
 \left( \begin{array}{c} \frac{19}{44} \\ \frac{20}{44} \end{array} \right) \]
Case 3.3: Some 5-shares $\geq \frac{20}{44}$

5-share: a share that a 5-student who gets.

Claim: If some 5-shares is $\geq \frac{20}{44}$ then some share $\leq \frac{19}{44}$.

Proof: Assume Alice has $v \leq w \leq x \leq y \leq z$ and $z \geq \frac{20}{44}$.

Since $v + w + x + y + z = \frac{24}{11}$ and $z \geq \frac{20}{44}$

$$v + w + x + y \leq \frac{24}{11} - \frac{20}{44} = \frac{76}{44}$$

$$v \leq \frac{76}{44} \times \frac{1}{4} = \frac{19}{44}$$

Henceforth we assume all 5-shares are in $\left(\frac{19}{44}, \frac{20}{44}\right)$.

$$\left(\begin{array}{c}
\frac{19}{44} \\
\frac{20}{44} \\
\frac{25}{44}
\end{array}\right)$$
Case 3.4: Some 4-shares $\leq \frac{21}{44}$

4-share: a share that a 4-student who gets.

Claim: If some 4-shares is $\leq \frac{21}{44}$ then some share $\leq \frac{19}{44}$.
Case 3.4: Some 4-shares $\leq \frac{21}{44}$

4-share: a share that a 4-student who gets.

Claim: If some 4-shares is $\leq \frac{21}{44}$ then some share $\leq \frac{19}{44}$.

Proof: Assume Alice has $w \leq x \leq y \leq z \leq$ and $w \leq \frac{21}{44}$.

$w + x + y + z = \frac{24}{44}$ and $w \leq \frac{21}{44}$

$x + y + z \geq 24\frac{1}{44} - 21\frac{1}{44} = 3\frac{1}{44}$

$z \geq 3\frac{1}{44} \times 1 = 3\frac{1}{44}$

Henceforth we assume all 4-shares are in $\frac{21}{44}, \frac{25}{44}$.
Case 3.4: Some 4-shares $\leq \frac{21}{44}$

4-share: a share that a 4-student who gets.

Claim: If some 4-shares is $\leq \frac{21}{44}$ then some share $\leq \frac{19}{44}$.

Proof: Assume Alice has $w \leq x \leq y \leq z \leq \text{ and } w \leq \frac{21}{44}$.
Since $w + x + y + z = \frac{24}{11}$ and $w \leq \frac{21}{44}$
Case 3.4: Some 4-shares $\leq \frac{21}{44}$

4-share: a share that a 4-student who gets.

Claim: If some 4-shares is $\leq \frac{21}{44}$ then some share $\leq \frac{19}{44}$.

Proof: Assume Alice has $w \leq x \leq y \leq z \leq$ and $w \leq \frac{21}{44}$. Since $w + x + y + z = \frac{24}{11}$ and $w \leq \frac{21}{44}$

\[ x + y + z \geq \frac{24}{11} - \frac{21}{44} = \frac{75}{44} \]
Case 3.4: Some 4-shares \( \leq \frac{21}{44} \)

4-share: a share that a 4-student who gets.

Claim: If some 4-shares is \( \leq \frac{21}{44} \) then some share \( \leq \frac{19}{44} \).

Proof: Assume Alice has \( w \leq x \leq y \leq z \leq \) and \( w \leq \frac{21}{44} \).

Since \( w + x + y + z = \frac{24}{11} \) and \( w \leq \frac{21}{44} \)

\[
\begin{align*}
x + y + z & \geq \frac{24}{11} - \frac{21}{44} = \frac{75}{44} \\
z & \geq \frac{75}{44} \times \frac{1}{3} = \frac{25}{44}
\end{align*}
\]
Case 3.4: Some 4-shares $\leq \frac{21}{44}$

4-share: a share that a 4-student who gets.

Claim: If some 4-shares is $\leq \frac{21}{44}$ then some share $\leq \frac{19}{44}$.

Proof: Assume Alice has $w \leq x \leq y \leq z \leq$ and $w \leq \frac{21}{44}$.

Since $w + x + y + z = \frac{24}{11}$ and $w \leq \frac{21}{44}$

$$x + y + z \geq \frac{24}{11} - \frac{21}{44} = \frac{75}{44}$$

$$z \geq \frac{75}{44} \times \frac{1}{3} = \frac{25}{44}$$

The buddy of $z$ is of size

$$\leq 1 - \frac{25}{44} = \frac{19}{44}$$

Henceforth we assume all 4-shares are in

$$\left( \frac{21}{44}, \frac{25}{44} \right)$$
Case 3.5: All Shares in Their Proper Intervals

**Case 3.5:** 4-shares in \( \left( \frac{21}{44}, \frac{25}{44} \right) \), 5-shares in \( \left( \frac{19}{44}, \frac{20}{44} \right) \).
Case 3.5: All Shares in Their Proper Intervals

Case 3.5: 4-shares in \( \left( \frac{21}{44}, \frac{25}{44} \right) \), 5-shares in \( \left( \frac{19}{44}, \frac{20}{44} \right) \).

\[
\left( \frac{19}{44} \right) \left[ \frac{20}{44} \right] \frac{0}{44} \left( \frac{21}{44} \right) \left[ \frac{25}{44} \right] \]
Case 3.5: All Shares in Their Proper Intervals

**Case 3.5:** 4-shares in \((\frac{21}{44}, \frac{25}{44})\), 5-shares in \((\frac{19}{44}, \frac{20}{44})\).

\[
\begin{pmatrix}
?? & 5\text{-shs} & 0 \text{ shs} & ?? & 4\text{-shs} \\
\frac{19}{44} & \frac{20}{44} & \frac{21}{44} & \frac{25}{44}
\end{pmatrix}
\]

**Recall:** there are \(4s_4 = 4 \times 7 = 28\) 4-shares.

**Recall:** there are \(5s_5 = 5 \times 4 = 20\) 5-shares.
Case 3.5: All Shares in Their Proper Intervals

**Case 3.5:** 4-shares in \( (\frac{21}{44}, \frac{25}{44}) \), 5-shares in \( (\frac{19}{44}, \frac{20}{44}) \).

\[
\begin{pmatrix}
?? & 5\text{-shs} & [ & 0 \text{ shs} & ] & ( & ?? & 4\text{-shs} & ) \\
\frac{19}{44} & & \frac{20}{44} & & \frac{21}{44} & & \frac{25}{44}
\end{pmatrix}
\]

**Recall:** there are \( 4s_4 = 4 \times 7 = 28 \) 4-shares.

**Recall:** there are \( 5s_5 = 5 \times 4 = 20 \) 5-shares.

\[
\begin{pmatrix}
20 & 5\text{-shs} & [ & 0 \text{ shs} & ] & ( & 28 & 4\text{-shs} & ) \\
\frac{19}{44} & & \frac{20}{44} & & \frac{21}{44} & & \frac{25}{44}
\end{pmatrix}
\]
More Refined Picture of What is Going On

\[
\begin{pmatrix}
19/44 & 20/44 & 0/44 & 21/44 & 25/44
\end{pmatrix}
\]

Claim 1: There are no shares \( x \in [23/44, 24/44] \). If there was such a share then buddy is in \([20/44, 21/44]\). QED.

The following picture captures what we know so far.

( 20 5-shs ) [ 0 shs ] ( 28 4-shs )
More Refined Picture of What is Going On

Claim 1: There are no shares $x \in \left[\frac{23}{44}, \frac{24}{44}\right]$. 
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The following picture captures what we know so far.

\[
\begin{pmatrix}
\begin{array}{ccc}
20 & 5\text{-shs} & | & 0 & \text{shs} & | & 28 & 4\text{-shs}
\end{array}
\end{pmatrix}
\]

\[
\begin{pmatrix}
\begin{array}{ccc}
\frac{19}{44} & | & 20 & | & 20 & \frac{21}{44} & | & 25
\end{array}
\end{pmatrix}
\]
More Refined Picture of What is Going On

Claim 1: There are no shares \( x \in \left[ \frac{23}{44}, \frac{24}{44} \right] \).

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The following picture captures what we know so far.

\[
\begin{pmatrix}
20 \text{ 5-shs} \\
19 \text{ 44}
\end{pmatrix}
\begin{pmatrix}
0 \text{ shs} \\
20 \text{ 44}
\end{pmatrix}

\begin{pmatrix}
28 \text{ 4-shs} \\
21 \text{ 44}
\end{pmatrix}
\begin{pmatrix}
25 \text{ 44}
\end{pmatrix}
\]

S4= Small 4-shares
L4= Large 4-shares. L4 shares, 5-share: **buddies**, so \( |L4| = 20 \).
Claim 2: Every 4-student has at least 3 L4 shares. If a 4-student had $\leq 2$ L4 shares then he has $< 2 \times \frac{23}{44} + 2 \times \frac{25}{44} = \frac{24}{44}$. Contradiction: Each 4-student gets $\geq 3$ L4 shares. There are $s_{4} = 7$ 4-students. Hence there are $\geq 21$ L4-shares. But there are only 20.
Claim 2: Every 4-student has at least 3 L4 shares.
Claim 2: Every 4-student has at least 3 L4 shares.

If a 4-student had \( \leq 2 \) L4 shares then he has

\[
< 2 \times \left( \frac{23}{44} \right) + 2 \times \left( \frac{25}{44} \right) = \frac{24}{11}.
\]
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GAPS Method

Proof that $f(24, 11) \leq \frac{19}{44}$ was an example of the INT method.
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FC or HALF or INT worked on everything with $m = 3, 4, 5, \ldots, 30$. 

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Then we found a case where neither FC nor HALF nor INT worked.
Proof that $f(24, 11) \leq \frac{19}{44}$ was an example of the INT method.

FC or HALF or INT worked on everything with $m = 3, 4, 5, \ldots, 30$.

Then we found a case where neither FC nor HALF nor INT worked.

We found a new method: GAP.
Example of GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

We show $f(31, 19) \leq \frac{54}{133}$.
Assume $(31, 19)$-procedure with smallest piece $> \frac{54}{133}$.
Example of GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

We show $f(31, 19) \leq \frac{54}{133}$.
Assume $(31, 19)$-procedure with smallest piece $> \frac{54}{133}$.
By INT-technique methods obtain:
$s_3 = 14$, $s_4 = 5$.

$$
\begin{pmatrix}
\frac{54}{133} & 20 \text{ 4-shs} & 0 & 22 \text{ S3 shs} & 0 & 20 \text{ L3-shs} \\
\frac{55}{133} & \frac{59}{133} & \frac{74}{133} & \frac{78}{133} & \frac{79}{133}
\end{pmatrix}
$$

We just look at the 3-shares:
Example of GAPS Technique: \( f(31, 19) \leq \frac{54}{133} \)

We show \( f(31, 19) \leq \frac{54}{133} \).
Assume \((31, 19)\)-procedure with smallest piece \( > \frac{54}{133} \).
By INT-technique methods obtain:
\( s_3 = 14, s_4 = 5 \).

\[
\begin{pmatrix}
54 & 0 & 22 & 0 & 20 \\
133 & 133 & 133 & 133 & 133
\end{pmatrix}
\]

We just look at the 3-shares:

\[
\begin{pmatrix}
59 & 0 & 20 \\
133 & 133 & 133
\end{pmatrix}
\]

\[
\begin{pmatrix}
74 & 0 & 20 \\
133 & 133 & 133
\end{pmatrix}
\]

\[
\begin{pmatrix}
78 & 0 & 20 \\
133 & 133 & 133
\end{pmatrix}
\]

\[
\begin{pmatrix}
79 & 0 & 20 \\
133 & 133 & 133
\end{pmatrix}
\]
GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

\[
\begin{pmatrix}
\frac{59}{133} & 22 \text{ S3 shs} & \frac{74}{133} & 0 & \frac{78}{133} & 20 \text{ L3-shs} & \frac{79}{133}
\end{pmatrix}
\]
GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

$$
\begin{pmatrix}
\frac{59}{133} & 22 \text{ S3 shs} & \frac{74}{133} & 0 \\
\frac{74}{133} & 74 & \frac{78}{133} & 20 \text{ L3-shs} \\
\frac{78}{133} & 78 & \frac{79}{133} & 79 \\
\end{pmatrix}
$$

1. $J_1 = \left( \frac{59}{133}, \frac{66.5}{133} \right)$
2. $J_2 = \left( \frac{66.5}{133}, \frac{74}{133} \right)$ ($|J_1| = |J_2|$)
3. $J_3 = \left( \frac{78}{133}, \frac{79}{133} \right)$ ($|J_3| = 20$)
GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

\[
\begin{pmatrix}
\frac{59}{133} & 22 \text{ S3 shs} & 0 \\
\frac{74}{133} & 74 & \frac{78}{133} \\
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**Notation:** An $e(1, 1, 3)$ students is a student who has a $J_1$-share, a $J_1$-share, and a $J_3$-share.

Generalize to $e(i, j, k)$ easily.
GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

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1. $J_1 = (\frac{59}{133}, \frac{66.5}{133})$
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**Notation:** An $e(1, 1, 3)$ students is a student who has a $J_1$-share, a $J_1$-share, and a $J_3$-share. Generalize to $e(i, j, k)$ easily.

**FOR THE TALK I SKIPPED THE NEXT FEW SLIDE, BUT HERE I INCLUDE THEM**
GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

1. $J_1 = \left( \frac{59}{133}, \frac{66.5}{133} \right)$
2. $J_2 = \left( \frac{66.5}{133}, \frac{74}{133} \right) \quad (|J_1| = |J_2|)$
3. $J_3 = \left( \frac{78}{133}, \frac{79}{133} \right) \quad (|J_3| = 20)$
GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

1. $J_1 = \left( \frac{59}{133}, \frac{66.5}{133} \right)$
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3. $J_3 = \left( \frac{78}{133}, \frac{79}{133} \right) \ (|J_3| = 20)$

1) Only students allowed: $e(1, 2, 3), e(1, 3, 3), e(2, 2, 2), e(2, 2, 3)$. All others have either $< \frac{31}{19}$ or $> \frac{31}{19}$. 
GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

1. $J_1 = (\frac{59}{133}, \frac{66.5}{133})$
2. $J_2 = (\frac{66.5}{133}, \frac{74}{133}) \ (|J_1| = |J_2|)$
3. $J_3 = (\frac{78}{133}, \frac{79}{133}) \ (|J_3| = 20)$

1) Only students allowed: $e(1, 2, 3), e(1, 3, 3), e(2, 2, 2), e(2, 2, 3)$. All others have either $< \frac{31}{19}$ or $> \frac{31}{19}$.

2) No shares in $[\frac{61}{133}, \frac{64}{133}]$. Look at $J_1$-shares:
An $e(1, 2, 3)$-student has $J_1$-share $> \frac{31}{19} - \frac{74}{133} - \frac{79}{133} = \frac{64}{133}$.
An $e(1, 3, 3)$-student has $J_1$-share $< \frac{31}{19} - 2 \times \frac{78}{133} = \frac{61}{133}$.
GAPS Technique: \( f(31, 19) \leq \frac{54}{133} \)

1. \( J_1 = \left( \frac{59}{133}, \frac{66.5}{133} \right) \)
2. \( J_2 = \left( \frac{66.5}{133}, \frac{74}{133} \right) \) (\(|J_1| = |J_2|\))
3. \( J_3 = \left( \frac{78}{133}, \frac{79}{133} \right) \) (\(|J_3| = 20\))

1) Only students allowed: \( e(1, 2, 3), e(1, 3, 3), e(2, 2, 2), e(2, 2, 3) \). All others have either \(< \frac{31}{19}\) or \(> \frac{31}{19}\).

2) No shares in \( [\frac{61}{133}, \frac{64}{133}] \). Look at \( J_1 \)-shares:
An \( e(1, 2, 3) \)-student has \( J_1 \)-share \(> \frac{31}{19} - \frac{74}{133} - \frac{79}{133} = \frac{64}{133} \).
An \( e(1, 3, 3) \)-student has \( J_1 \)-share \(< \frac{31}{19} - 2 \times \frac{78}{133} = \frac{61}{133} \).

3) No shares in \( [\frac{69}{133}, \frac{72}{133}] \): \( x \in [\frac{69}{133}, \frac{72}{133}] \implies 1 - x \in [\frac{61}{133}, \frac{64}{133}] \).
GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

1. $J_1 = \left(\frac{59}{133}, \frac{61}{133}\right)$
2. $J_2 = \left(\frac{64}{133}, \frac{66.5}{133}\right)$
3. $J_3 = \left(\frac{66.5}{133}, \frac{69}{133}\right)$ ($|J_2| = |J_3|$)
4. $J_4 = \left(\frac{72}{133}, \frac{74}{133}\right)$ ($|J_1| = |J_4|$)
5. $J_5 = \left(\frac{78}{133}, \frac{79}{133}\right)$ ($|J_5| = 20$)
GAPS Technique: \( f(31, 19) \leq \frac{54}{133} \)

1. \( J_1 = (\frac{59}{133}, \frac{61}{133}) \)
2. \( J_2 = (\frac{64}{133}, \frac{66.5}{133}) \)
3. \( J_3 = (\frac{66.5}{133}, \frac{69}{133})\) \(|J_2| = |J_3|\)
4. \( J_4 = (\frac{72}{133}, \frac{74}{133})\) \(|J_1| = |J_4|\)
5. \( J_5 = (\frac{78}{133}, \frac{79}{133})\) \(|J_5| = 20\)

The following are the only students who are allowed.

\( e(1, 5, 5). \)
\( e(2, 4, 5). \)
\( e(3, 4, 5). \)
\( e(4, 4, 4). \)
GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

$e(1, 5, 5)$. Let the number of such students be $x$.
$e(2, 4, 5)$. Let the number of such students be $y_1$.
$e(3, 4, 5)$. Let the number of such students be $y_2$.
$e(4, 4, 4)$. Let the number of such students be $z$.  

Hence $y_1 = y_2$. We call them both $y$.

2) Since $|J_1| = |J_4|$, $x = 2y + 3z$.
3) Since $s_3 = 14$, $x + 2y + z = 14$.

$(2y + 3z) + 2y + z = 14 \Rightarrow 4(y + z) = 14 \Rightarrow y + z = 7$.
Contradiction.
GAPS Technique: \( f(31, 19) \leq \frac{54}{133} \)

\( e(1, 5, 5) \). Let the number of such students be \( x \)
\( e(2, 4, 5) \). Let the number of such students be \( y_1 \)
\( e(3, 4, 5) \). Let the number of such students be \( y_2 \).
\( e(4, 4, 4) \). Let the number of such students be \( z \).

1) \( |J_2| = |J_3| \),
only students using \( J_2 \) are \( e(2, 4, 5) \) – they use one share each,
only students using \( J_3 \) are \( e(3, 4, 5) \) – they use one share each.
Hence \( y_1 = y_2 \). We call them both \( y \).
GAPS Technique: $f(31, 19) \leq \frac{54}{133}$

$e(1, 5, 5)$. Let the number of such students be $x$
$e(2, 4, 5)$. Let the number of such students be $y_1$
$e(3, 4, 5)$. Let the number of such students be $y_2$.
$e(4, 4, 4)$. Let the number of such students be $z$.

1) $|J_2| = |J_3|$,
only students using $J_2$ are $e(2, 4, 5)$ – they use one share each,
only students using $J_3$ are $e(3, 4, 5)$ – they use one share each.
Hence $y_1 = y_2$. We call them both $y$.

2) Since $|J_1| = |J_4|$, $x = 2y + 3z$. 
GAPS Technique: \( f(31, 19) \leq \frac{54}{133} \)

\( e(1, 5, 5) \). Let the number of such students be \( x \)
\( e(2, 4, 5) \). Let the number of such students be \( y_1 \)
\( e(3, 4, 5) \). Let the number of such students be \( y_2 \).
\( e(4, 4, 4) \). Let the number of such students be \( z \).

1) \( |J_2| = |J_3| \),
only students using \( J_2 \) are \( e(2, 4, 5) \) – they use one share each,
only students using \( J_3 \) are \( e(3, 4, 5) \) – they use one share each.
Hence \( y_1 = y_2 \). We call them both \( y \).

2) Since \( |J_1| = |J_4| \), \( x = 2y + 3z \).

3) Since \( s_3 = 14 \), \( x + 2y + z = 14 \).

\[(2y + 3z) + 2y + z = 14 \iff 4(y + z) = 14 \iff y + z = \frac{7}{2}.
Contradiction.\]
MATRIX Technique: \( f(5, 3) \geq \frac{5}{12} \)

Want proc for \( f(5, 3) \geq \frac{5}{12} \).
MATRIX Technique: $f(5, 3) \geq \frac{5}{12}$

Want proc for $f(5, 3) \geq \frac{5}{12}$.

1) **Guess** that the only piece sizes are $\frac{5}{12}, \frac{6}{12}, \frac{7}{12}$
MATRIX Technique: \( f(5, 3) \geq \frac{5}{12} \)

Want proc for \( f(5, 3) \geq \frac{5}{12} \).

1) **Guess** that the only piece sizes are \( \frac{5}{12}, \frac{6}{12}, \frac{7}{12} \)

2) **Muffin**=

   pieces add to 1: \( \{ \frac{6}{12}, \frac{6}{12} \}, \{ \frac{5}{12}, \frac{7}{12} \} \). Vectors

   \( \{ \frac{6}{12}, \frac{6}{12} \} \) is \( (0, 2, 0) \), \( m_1 \) muffins of this type.

   \( \{ \frac{5}{12}, \frac{7}{12} \} \) is \( (1, 0, 1) \), \( m_2 \) muffins of this type.

---

\[ m_1 (0, 2, 0) + m_2 (1, 0, 1) = s_1 (0, 1, 2) + s_2 (4, 0, 0) \]

**Natural Number Solution**:

\( m_1 = 1 \), \( m_2 = 4 \), \( s_1 = 2 \), \( s_2 = 1 \)
Want proc for $f(5, 3) \geq \frac{5}{12}$.

1) **Guess** that the only piece sizes are $\frac{5}{12}, \frac{6}{12}, \frac{7}{12}$

2) **Muffin**=pieces add to 1: $\{\frac{6}{12}, \frac{6}{12}\}, \{\frac{5}{12}, \frac{7}{12}\}$. Vectors
   $\{\frac{6}{12}, \frac{6}{12}\}$ is (0, 2, 0), $m_1$ muffins of this type.
   $\{\frac{5}{12}, \frac{7}{12}\}$ is (1, 0, 1), $m_2$ muffins of this type.

3) **Student**=pieces add to $\frac{5}{3}$
   $\{\frac{6}{12}, \frac{7}{12}, \frac{7}{12}\}$ is (0, 1, 2), $s_1$ students of this type.
   $\{\frac{5}{12}, \frac{5}{12}, \frac{5}{12}\}$ is (4, 0, 0), $s_2$ students of this type.
MATRIX Technique: \( f(5, 3) \geq \frac{5}{12} \)

Want proc for \( f(5, 3) \geq \frac{5}{12} \).

1) **Guess** that the only piece sizes are \( \frac{5}{12}, \frac{6}{12}, \frac{7}{12} \).

2) **Muffin**=pieces add to 1: \( \{ \frac{6}{12}, \frac{6}{12} \}, \{ \frac{5}{12}, \frac{7}{12} \} \). Vectors

\( \{ \frac{6}{12}, \frac{6}{12} \} \) is \( (0, 2, 0) \), \( m_1 \) muffins of this type.

\( \{ \frac{5}{12}, \frac{7}{12} \} \) is \( (1, 0, 1) \), \( m_2 \) muffins of this type.

3) **Student**=pieces add to \( \frac{5}{3} \)

\( \{ \frac{6}{12}, \frac{7}{12}, \frac{7}{12} \} \) is \( (0, 1, 2) \), \( s_1 \) students of this type.

\( \{ \frac{5}{12}, \frac{5}{12}, \frac{5}{12}, \frac{5}{12} \} \) is \( (4, 0, 0) \), \( s_2 \) students of this type.

4) **Set up equations:**

\( m_1(0, 2, 0) + m_2(1, 0, 1) = s_1(0, 1, 2) + s_2(4, 0, 0) \)

\( m_1 + m_2 = 5 \)

\( s_1 + s_2 = 3 \)
**MATRIX Technique: \( f(5, 3) \geq \frac{5}{12} \)**

Want proc for \( f(5, 3) \geq \frac{5}{12} \).

1) **Guess** that the only piece sizes are \( \frac{5}{12}, \frac{6}{12}, \frac{7}{12} \).

2) **Muffin**—pieces add to 1: \( \{\frac{6}{12}, \frac{6}{12}\}, \{\frac{5}{12}, \frac{7}{12}\} \). Vectors \( \{\frac{6}{12}, \frac{6}{12}\} \) is \((0, 2, 0)\), \( m_1 \) muffins of this type.  
\( \{\frac{5}{12}, \frac{7}{12}\} \) is \((1, 0, 1)\), \( m_2 \) muffins of this type.

3) **Student**—pieces add to \( \frac{5}{3} \).  
\( \{\frac{6}{12}, \frac{7}{12}, \frac{7}{12}\} \) is \((0, 1, 2)\), \( s_1 \) students of this type.  
\( \{\frac{5}{12}, \frac{5}{12}, \frac{5}{12}, \frac{5}{12}\} \) is \((4, 0, 0)\), \( s_2 \) students of this type.

4) **Set up equations:**  
\( m_1(0, 2, 0) + m_2(1, 0, 1) = s_1(0, 1, 2) + s_2(4, 0, 0) \)  
\( m_1 + m_2 = 5 \)  
\( s_1 + s_2 = 3 \)

**Natural Number Solution:** \( m_1 = 1, \ m_2 = 4, \ s_1 = 2, \ s_2 = 1 \)
MATRIX Technique

Want proc for \( f(m, s) \geq \frac{a}{b} \).
Want proc for $f(m, s) \geq \frac{a}{b}$.

1) **Guess** that the only piece sizes are $\frac{a}{b}, \ldots, \frac{b-a}{b}$
MATRIX Technique

Want proc for \( f(m, s) \geq \frac{a}{b} \).

1) **Guess** that the only piece sizes are \( \frac{a}{b}, \ldots, \frac{b-a}{b} \)

2) **Muffin**=pieces add to 1: Vectors \( \vec{v}_i \). \( x \) types. 
   \( m_i \) muffins of type \( \vec{v}_i \)
Want proc for $f(m, s) \geq \frac{a}{b}$.

1) **Guess** that the only piece sizes are $\frac{a}{b}, \ldots, \frac{b-a}{b}$.

2) **Muffin** = pieces add to 1: Vectors $\vec{v}_i$. $x$ types. $m_i$ muffins of type $\vec{v}_i$.

3) **Student** = pieces add to $\frac{m}{s}$: Vectors $\vec{u}_j$. $y$ types. $s_j$ students of type $\vec{u}_j$.
Want proc for \( f(m, s) \geq \frac{a}{b} \).

1) **Guess** that the only piece sizes are \( \frac{a}{b}, \ldots, \frac{b-a}{b} \)

2) **Muffin** = pieces add to 1: Vectors \( \vec{v}_i \). \( x \) types.
   \( m_i \) muffins of type \( \vec{v}_i \)

3) **Student** = pieces add to \( \frac{m}{s} \): Vectors \( \vec{u}_j \). \( y \) types.
   \( s_j \) students of type \( \vec{u}_j \)

4) **Set up equations:**
   \[
   m_1 \vec{v}_1 + \cdots + m_x \vec{v}_x = s_1 \vec{u}_1 + \cdots + s_y \vec{u}_y \\
   m_1 + \cdots + m_x = m \\
   s_1 + \cdots + s_y = s
   \]
MATRX Technique

Want proc for \( f(m, s) \geq \frac{a}{b} \).

1) **Guess** that the only piece sizes are \( \frac{a}{b}, \ldots, \frac{b-a}{b} \)

2) **Muffin** = pieces add to 1: Vectors \( \vec{v}_i \). \( x \) types. 
   \( m_i \) muffins of type \( \vec{v}_i \)

3) **Student** = pieces add to \( \frac{m}{s} \): Vectors \( \vec{u}_j \). \( y \) types. 
   \( s_j \) students of type \( \vec{u}_j \)

4) **Set up equations:**
   \[ m_1 \vec{v}_1 + \cdots + m_x \vec{v}_x = s_1 \vec{u}_1 + \cdots + s_y \vec{u}_y \]
   \[ m_1 + \cdots + m_x = m \]
   \[ s_1 + \cdots + s_y = s \]

5) **Look for Nat Numb sol.** If find can translate into procedure.
Later Results by Other People

1. In Fall 2018 Scott Huddleston had code for an algorithm that, on input $m, s$, found $f(m, s)$ and the procedure REALLY FAST.

2. Jacob and Erik Understand WHAT his algorithm does and Jacob coded it up to make sure he understood it. Jacob’s code is also REALLY FAST.

3. Neither Scott, Bill, Jacob, or Erik had a proof that Scott’s algorithm was fast (poly in $m, s$).

4. Richard Chatwin independently came up with the same algorithm; however, he also has a proof that it works. Its on arXiv.

5. One corollary of the work: $f(m, s)$ only depends on $m/s$. 

TV Show Leverage and Our Book

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1. Sophie Devereux: A Grifter. (Not her real name.)
2. Parker: A Thief (First or last name? Nobody knows!)
3. Alec Hardison: A Hacker (breaks into computer systems)
4. Eliot Spencer: A Hitter (beats people up)
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1. Erik: A Math Genius (solves muffin problems)
2. Jacob and Daniel: Programmers (codes up techniques)
3. Bill: The Mastermind (writers it all up and consolidates)
How it worked

We kept increasing $s$. 

1. Bill tells Erik the least case we can't do.
2. Erik solves and sends Bill a 1-page sketch.
3. Bill fills in the details and obtains general technique.
4. Jacob & Daniel code up technique and find least case that can't be done. Send to Bill to check.
5. Goto Step 1.

This happened 7 times leading to techniques now called: Floor Ceiling, Half, Int, Midpoint, Gaps, Easy Buddy-Match, Hard buddy-Match,

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  1 cut \( \left( \frac{15}{30}, \frac{15}{30} \right) \), 2 cut \( \left( \frac{14}{30}, \frac{16}{30} \right) \), 8 cut \( \left( \frac{13}{30}, \frac{17}{30} \right) \).
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  Second Year Royalties: $50.00. I’m up by $10.00. Wow!
  Third Year Royalties: $20.00. He is up by $20.00.