Analysis I (Math 3205)
Fall 2020

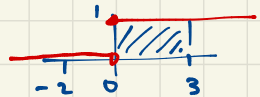
Book 2

$\left\{\begin{matrix}\text{Lebesgue}\\ \text{integrable}\\ \text{functions}\end{matrix}\right\} \supset \overset{\text{Riemann}}{\left\{\begin{matrix}\text{integrable}\\ \text{functions}\end{matrix}\right\}} \supset \left\{\begin{matrix}\text{continuous}\\ \text{functions}\end{matrix}\right\} \supset \left\{\begin{matrix}\text{differentiable}\\ \text{functions}\end{matrix}\right\} \supset \left\{\begin{matrix}\text{continuously}\\ \text{differentiable}\\ \text{functions}\end{matrix}\right\} \supset \cdots$

$\Downarrow$ $\quad$ $\Downarrow$

g Dirichlet function $\quad$ H Heaviside function

$$H(x) = \begin{cases} 1 & \text{if } x \geq 0; \\ 0 & \text{if } x < 0 \end{cases}$$



$$\int_{-2}^{3} H(x)\,dx = 3$$

$S = \{\frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}, \frac{5}{6}, \dots\}$ is bounded: 0 is a lower bound, 1 is an upper bound.

$\frac{1}{2}$ is the greatest lower bound.

Every $m \leq \frac{1}{2}$ is a lower bound for S, meaning $s \geq \frac{1}{2}$ for all $s \in S$.

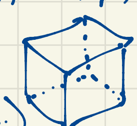
(so $\frac{1}{2}$ is a lower bound) and it is the greatest lower bound.

1 is the least upper bound of S.

Fact: $|[0,1]| = |\mathbb{R}^3|$

Basic idea of the ~~proof~~: $|(0,1)| = |(0,1)^3|$

$(0,1)^3 = (0,1)\times(0,1)\times(0,1) = \{(x,y,z) : 0 < x,y,z < 1\}$



Bijection: $a \longmapsto (0.a_1a_4a_7a_{10}a_{13}\cdots,\ 0.a_2a_5a_8a_{11}a_{14}\cdots,\ 0.a_3a_6a_9a_{12}a_{15}\cdots)$

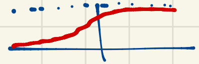
$0 < a < 1$

$\underset{\pi-3}{0.14159265358\dots} \longmapsto (0.1565\cdots,\ 0.4958\cdots,\ 0.1239\cdots)$

$a = 0.a_1a_2a_3a_4a_5a_6a_7a_8a_9a_{10}\cdots$

$= a_1\cdot 10^{-1} + a_2\cdot 10^{-2} + a_3\cdot 10^{-3} + a_4\cdot 10^{-4} + \cdots, \quad a_i \in \{0,1,2,\dots,9\}$

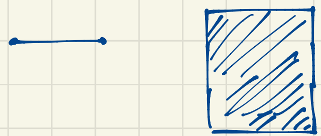
$|(0,1)| = |\mathbb{R}|$



see video on Cardinality

$|(0,1)| = |(0,1)^3| = |\mathbb{R}^3|$ and this bijection can be given constructively i.e. by an explicit formula (in particular this is a theorem in ZF, not requiring the Axiom of Choice)

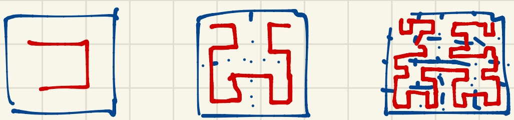
$|[0,1]| = |[0,1]^2|$



There is a bijection $[0,1] \to [0,1]^2$ but no continuous bijection.

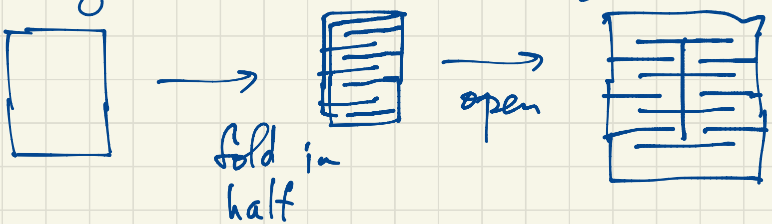
However there is a continuous surjection (map that is onto)

This gives a "space-filling curve": it goes through every point of the square.



etc.

How do you cut a hole in an $8\frac{1}{2}'' \times 11''$ sheet of paper that you can walk through?



Fact: There is a set of open intervals in $\mathbb{R}$ of total length less than 1 which covers all the rational numbers.

Since $\mathbb{Q}$ is countable, $\mathbb{Q} = \{a_1, a_2, a_3, a_4, a_5, \dots\}$. Then

$$\mathbb{Q} \subseteq \bigcup_{n=1}^{\infty} \left(a_n - \tfrac{1}{2^{n+1}}, a_n + \tfrac{1}{2^{n+1}}\right) = \left(a_1 - \tfrac{1}{4}, a_1 + \tfrac{1}{4}\right) \cup \left(a_2 - \tfrac{1}{8}, a_2 + \tfrac{1}{8}\right) \cup \left(a_3 - \tfrac{1}{16}, a_3 + \tfrac{1}{16}\right) \cup \left(a_4 - \tfrac{1}{32}, a_4 + \tfrac{1}{32}\right) \cup \cdots$$

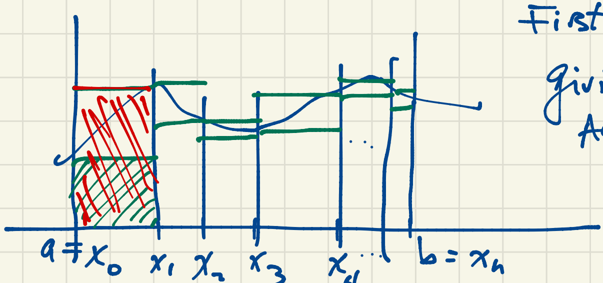
Total length $< \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \cdots = 1$

Once again the set of intervals can be given constructively i.e. explicitly with no need for the Axiom of Choice.

What is a (Riemann) integral? i.e. the integral as defined in Calculus I-II?

Suppose $f : [a,b] \to \mathbb{R}$. We want to define $\int_a^b f(x)\,dx$. We start with lower and upper bounds for the integral (these being upper and lower Riemann sums).

We then take $\sup\{\text{lower Riemann sums}\}$ and $\inf\{\text{upper Riemann sums}\}$.



First subdivide $[a,b]$ at points $a = x_0 \le x_1 \le x_2 \le \cdots \le x_n = b$ giving n subintervals $[x_{i-1}, x_i]$, $i = 1, 2, \dots, n$.

Assuming f is bounded, $m_i \le f(x) \le M_i$ on $[x_{i-1}, x_i]$

where $M_i = \sup\{f(x) : x_{i-1} \le x \le x_i\} = \sup\limits_{[x_{i-1}, x_i]} f$, $\quad m_i = \inf\{f(x) : x_{i-1} \le x \le x_i\} = \inf\limits_{[x_{i-1}, x_i]} f$

The Riemann Sums corresponding to the partition $a = x_0 \le x_1 \le x_2 \le \cdots \le x_{n-1} \le x_n = b$ of $[a,b]$ are:

Upper sum $\displaystyle\sum_{i=1}^{n} \underbrace{(x_i - x_{i-1})}_{\text{base}} \underbrace{M_i}_{\text{height}} = (x_1 - x_0)M_1 + (x_2 - x_1)M_2 + \cdots + (x_n - x_{n-1})M_n$.

Lower sum $\displaystyle\sum_{i=1}^{n} (x_i - x_{i-1}) m_i$

We should have
$$\underset{\sum (x_i - x_{i-1}) m_i}{\text{Lower sum}} \le \int_a^b f(x)\,dx \le \underset{\sum (x_i - x_{i-1}) M_i}{\text{Upper sum}}$$

We can't just let $n \to \infty$. By the Least Upper Bound Property, sup{lower bounds} exists and inf{upper bounds} exists. And

$$\sup\{\text{lower bounds}\} \le \inf\{\text{upper bounds}\}.$$

If these two values agree, this gives a definite value for $\int_a^b f(x)\,dx$.

For lots of functions (eg. the Heaviside function and for all continuous functions), this works. For Dirichlet's function, the Riemann integral $\int_0^1 g(x)\,dx$ is undefined.

why? For Dirichlet's function $g(x)=\begin{cases}1, & \text{if } x\in\mathbb{Q};\\ 0, & \text{if } x\notin\mathbb{Q}\end{cases}$

$$m_i = 0, \quad M_i = 1 \quad \text{for each } i=1,2,\dots,n$$

Upper sums: $\sum_{i=1}^{n}(x_i-x_{i-1})\underbrace{M_i}_{1} = (\cancel{x_1}-x_0)+(\cancel{x_2}-\cancel{x_1})+(\cancel{x_3}-\cancel{x_2})+\cdots+(\cancel{x_{n-1}}-\cancel{x_{n-2}})+(x_n-\cancel{x_{n-1}})$

$$= x_n - x_0 = b-a = 1-0 = 1$$

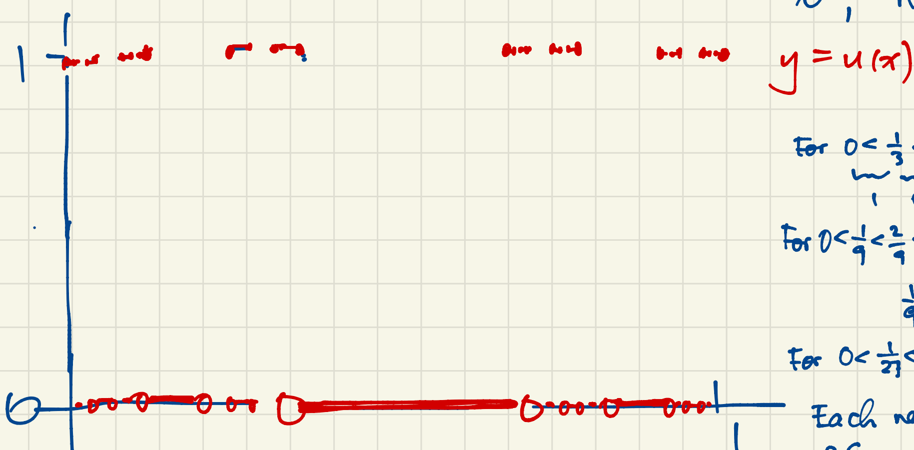
Lower sums: $\sum_{i=1}^{m}(x_i-x_{i-1})\underbrace{m_i}_{0} = 0+0+\cdots+0 = 0.$

For C the Cantor set define $u(x)=\begin{cases}1, & \text{if } x\in C\\ 0, & \text{if } x\notin C.\end{cases}$

What is $\int_0^1 u(x)\,dx$?

Lower sums are 0.

Upper sums can be made as small as we want.



For $\underbrace{0<\tfrac{1}{3}}_{1}\underbrace{<\tfrac{2}{3}}_{0}\underbrace{<1}_{1}$ the Riemann Sum is $\frac{1}{3}\cdot 1+\frac{1}{3}\cdot 0+\frac{1}{3}\cdot 1=\frac{2}{3}$.

For $0<\frac{1}{9}<\frac{2}{9}<\frac{1}{3}<\frac{2}{3}<\frac{7}{9}<\frac{8}{9}<1$ the Riemann Sum is

$$\frac{1}{9}\cdot 1+\frac{1}{9}\cdot 0+\frac{1}{9}\cdot 1+\frac{1}{3}\cdot 0+\frac{1}{9}\cdot 1+\frac{1}{9}\cdot 0+\frac{1}{9}\cdot 1=\frac{4}{9}$$

For $0<\frac{1}{27}<\frac{2}{27}<\cdots<\frac{26}{27}<1$ the corresponding Riemann Sum is $\frac{8}{27}$.

Each new upper Riemann Sum is $\frac{2}{3}$ of the previous one ie $\left(\frac{2}{3}\right)^n$.

$\inf\{\text{upper Sums}\} = 0.$

For the function $u(x)$, $\underbrace{\sup\{\underbrace{\text{lower sums}}_{0}\}}_{0} \leq \int_0^1 u(x)\,dx \leq \underbrace{\inf\{\text{upper sums}\}}_{0}$

So $\int_0^1 u(x)\,dx = 0$.

Note: $u(x)$ has infinitely many discontinuities but it is not discontinuous everywhere. $u(x)$ is continuous on a set of open intervals inside $[0,1]$ of total length 1.

The total length of the Cantor set C (where $u=1$) is 0.

However C is uncountable; $|C| = |\mathbb{R}|$. Why?

Every $a \in [0,1]$ has a ternary expansion

$$a = 0.a_1 a_2 a_3 a_4 a_5 \cdots \qquad (a_i \in \{0,1,2\})$$

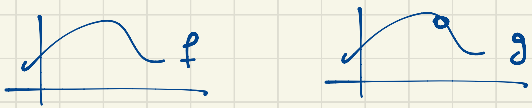
$$= \frac{a_1}{3} + \frac{a_2}{3^2} + \frac{a_3}{3^3} + \frac{a_4}{3^4} + \frac{a_5}{3^5} + \cdots$$

The points in C are those with $a_i \in \{0,2\}$ only.

$|C| = |\mathbb{R}| = |[0,1]|$. A bijection $C \longrightarrow [0,1]$

$$\underset{\substack{\text{(base 3)}\\\text{ternary}}}{0.20022202002\cdots} \longmapsto \underset{\substack{\text{(base 2)}\\\text{binary}}}{0.10011101001\cdots}$$

If two functions f and g agree except at a single point, the $\int_a^b f(x)\,dx = \int_a^b g(x)\,dx$

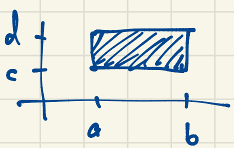


The same holds for changing a function at any finite number of points.

We want to be able to <u>measure</u> sets to distinguish their size, not as cardinality, but length (in one dimension), area (in two dimensions), volume (in 3 dimensions), etc.
Defining measure of a set is equivalent to being able to integrate.
In one dimension, $\lambda([a,b]) = b-a$ for $a \le b$. (the length)

Greek letter lambda)

In two dimensions, $\lambda([a,b]\times[c,d]) = (b-a)(d-c)$



Cartesian product $\{(x,y) : x \in [a,b],\ y \in [c,d]\}$.

Borel measure extends this notion to larger sets and more complicated constructions.
Borel measure extends to Lebesgue measure which is the gold standard for measuring sets.

Lebesgue measure of $A \subseteq \mathbb{R}^n$ is denoted $\lambda(A)$.

$\lambda([a,b]) = b-a$ for $a \le b$

$\lambda(A) \geq 0$ for all measurable A.

$\lambda(\{a\}) = 0$

$\lambda(A \sqcup B) = \lambda(A) + \lambda(B)$

$\sqcup$ disjoint union.

This extends to countable disjoint unions:

$$\lambda\left(\bigsqcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} \lambda(A_i)$$

If $A \subseteq B$ then $\lambda(A) \leq \lambda(B)$.

$\lambda(\mathbb{Q}) = 0$. This follows from the properties above:

$$\mathbb{Q} = \{a_1, a_2, a_3, \dots\} = \bigsqcup_{i=1}^{\infty} \{a_i\}$$

singleton sets (sets with single elements)

$$\Rightarrow \lambda(\mathbb{Q}) = \sum_{i=1}^{\infty} \lambda(\{a_i\})$$

$$= \sum_{i=1}^{\infty} 0 = 0.$$

$\mathbb{R} = \bigsqcup_{a \in \mathbb{R}} \{a\}$ but this is not a countable union so $\lambda(\mathbb{R}) \neq 0$.

Recall, as observed about 5 slides back,

$$\mathbb{Q} \subset \underbrace{\bigcup_{i} \left(a_i - \frac{1}{2^{i+1}},\ a_i + \frac{1}{2^{i+1}}\right)}_{\text{set of Lebesgue measure } < 1.}$$

<u>Sets of measure zero</u> are sets which can be covered by countable unions of intervals of total length as small as we want (i.e. for every $\varepsilon > 0$, the set is covered by intervals of total length $< \varepsilon$). Such sets are considered 'negligible' in the sense of length i.e. measure.

Sets of Lebesgue measure zero have $\lambda(A) = 0$.

eg. $\lambda(\mathbb{Q}) = 0$ so $\mathbb{Q}$ has Lebesgue measure zero.

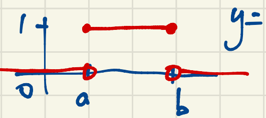
Also the Cantor set $C \subset [0,1]$ has measure zero.

$\mathbb{Q}$ is countable and C is uncountable so from the perspective of cardinality, there is a big difference in size between these two sets. But in terms of length (Lebesgue measure), both have measure zero: $\lambda(\mathbb{Q}) = \lambda(C) = 0$.

Connection between measure and integration:

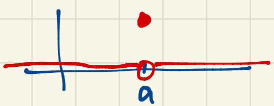
Given a set $A \subseteq \mathbb{R}$, its <u>characteristic function</u> $\chi_A(x) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A \end{cases}$

Greek "chi"



$y = \chi_{[a,b]}(x)$

$$\int_{-\infty}^{\infty} \chi_{[a,b]}(x)\,dx = b-a = \lambda([a,b])$$



$$\int_{-\infty}^{\infty} \chi_{\{a\}}(x)\,dx = 0 = \lambda(\{a\})$$

Similarly,

$$\int_{-\infty}^{\infty} \chi_C(x)\,dx = \lambda(C) = 0$$

where $C \subset [0,1]$ is the Cantor set

(and this integral is defined as both a Riemann integral and as a Lebesgue integral).

In general, $\displaystyle\int_{-\infty}^{\infty} \chi_A(x)\,dx = \lambda(A)$.

$\chi_{\mathbb{Q}} = g$ is Dirichlet's function

$\displaystyle\int_{-\infty}^{\infty} \chi_{\mathbb{Q}}(x)\,dx = \lambda(\mathbb{Q}) = 0$. (This however is the <u>Lebesgue integral</u>, not the Riemann integral of Calculus I and II).

The Riemann integral is undefined.

If f and g agree except at a finite number of points, $\underbrace{\int_a^b f(x)\,dx}_{\int_{[a,b]} f} = \int_a^b g(x)\,dx$

More generally, if f and g agree almost everywhere (i.e. except on a set of measure zero) then $\int_a^b f(x)\,dx = \int_a^b g(x)\,dx$ for every interval $[a,b]$.

f and g agree almost everywhere (f and g agree a.e.)

$\iff \lambda(\{x \in \mathbb{R} : f(x) \neq g(x)\}) = 0$

This is an important example of an equivalence relation.

If $f = g$ a.e. and $g = h$ a.e. then $f = h$ a.e.

$f = f$ a.e.

If $f = g$ a.e. then $g = f$ a.e.

$\lambda(A \sqcup B) = \lambda(A) + \lambda(B)$ for all measurable sets A, B.

If B is a closed unit ball in $\mathbb{R}^3$ then $\lambda(B) = \frac{4\pi}{3}$ (volume)

radius 1

$B = A_1 \sqcup \cdots \sqcup A_5$ where $A_1, \cdots, A_5$ can be repositioned to form two unit balls of total Lebesgue measure (volume) $\frac{8\pi}{3}$.

$$\lambda(B) \stackrel{?}{=} \underbrace{\cancel{\lambda(A_1) + \cdots + \lambda(A_5)}}_{\text{undefined}} = 2\lambda(B).$$

$A_1, \cdots, A_5$ are non-measurable.

Sequences $a_1, a_2, a_3, a_4, \dots$

The <u>limit</u> of a sequence $(a_n)_{n\in\mathbb{N}}$ is L if :

For all $\varepsilon > 0$, there exists N such that $|a_n - L| < \varepsilon$ whenever $n > N$.

Eg. the sequence $\left(\frac{n}{2n+1}\right)_{n\in\mathbb{N}} = \left(\frac{1}{3}, \frac{2}{5}, \frac{3}{7}, \frac{4}{9}, \frac{5}{11}, \dots\right)$ converges to $\frac{1}{2}$.

$\lim\limits_{n\to\infty} \frac{n}{2n+1} = \frac{1}{2}$ i.e. $(a_n) \to \frac{1}{2}$ i.e. $a_n \to \frac{1}{2}$ as $n \to \infty$.

In this case $\lim\limits_{n\to\infty} \frac{n}{2n+1} = \frac{1}{2}$ follows from $\lim\limits_{x\to\infty} \frac{x}{2x+1} = \lim\limits_{x\to\infty} \frac{1}{2+\frac{1}{x}} = \frac{1}{2+0} = \frac{1}{2}$.

Eg. $(\sin n\pi)_{n\in\mathbb{N}} = (0, 0, 0, \dots)$ converges to 0.

$(\sin n\pi)_{n\in\mathbb{N}} \to 0$

<u>But</u> $\lim\limits_{x\to\infty} \sin(\pi x)$ does not exist.

Some sequences are defined recursively eg. the Fibonacci sequence $1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, \dots$

Eg. consider the sequence $a_n = \begin{cases} 0, & \text{for } n=1; \\ \frac{1}{5}(2a_{n-1}+7), & \text{for } n=2,3,4,\dots \end{cases}$

This is a <u>recursive</u> definition.

n	1	2	3	4	5	6
a_n	0	$\frac{7}{5}$	$\frac{49}{25}$	$\frac{273}{125}$	$\frac{1421}{625}$	$\frac{7217}{3125}$

etc.

$$a_1 \xrightarrow{f} a_2 \xrightarrow{f} a_3 \xrightarrow{f} a_4 \xrightarrow{f} a_5 \longrightarrow \cdots$$

$$a_{n+1} = f(a_n)$$

where $f(x) = \frac{1}{5}(2x+7)$.

Iteration: repetition.

The n^{th} term of the sequence is $a_n = f^{n-1}(a_1)$ where $f^{n-1} = \underbrace{f \circ f \circ f \circ \cdots \circ f}_{n-1}$

$$a_2 = f(a_1)$$
$$a_3 = f(f(a_1))$$
$$a_4 = f(ff(a_1)) = f^3(a_1)$$
etc.

Let's look at the sequence in decimal approximations to get a better ideal of its behavior.

From our computer session it appears that $(a_n)_n$ is increasing and converges to $2\frac{1}{3} = \frac{7}{3}$.
Let's prove $(a_n)_n \to \frac{7}{3}$. We'll do this in two ways. One way is to find an explicit formula for a_n. It is obvious that a_n has denominator 5^{n-1} but what is its numerator? We don't see an obvious pattern yet.

But first, why is it no surprise that the limit is $\frac{7}{3}$?

If the sequence converges to L then

$$a_{n+1} = \frac{1}{5}(2a_n + 7) \qquad \text{for } n = 1, 2, 3, \ldots$$

where we can take the limit on both sides as $n \to \infty$ and get

$$L = \frac{1}{5}(2L + 7)$$

$$5L = 2L + 7$$

$$3L = 7$$

$$L = \frac{7}{3}.$$

But this doesn't prove $(a_n)_n \to \frac{7}{3}$ since we assumed the sequence converges.

How do we know this?

Look at $a_n - \frac{7}{3}$ (which should converge to zero) and see if this exhibits a pattern.

From the table of values it appears that $\frac{7}{3} - a_n = \frac{7}{3} \cdot \left(\frac{2}{5}\right)^{n-1}$ for $n = 1, 2, 3, \ldots$

i.e. $a_n = \frac{7}{3}\left[1 - \left(\frac{2}{5}\right)^{n-1}\right]$ for $n = 1, 2, 3, \ldots$ which is an explicit formula for a_n.

Let's prove this formula by induction. When $n = 1$, $a_1 = 0$ and this agrees with the formula which gives $\frac{7}{3}\left[1 - \left(\frac{2}{5}\right)^0\right] = 0$.

Assuming $a_n = \frac{7}{3}\left[1-\left(\frac{2}{5}\right)^{n-1}\right]$ for some positive integer n,

$$a_{n+1} = \frac{1}{5}(2a_n+7) = \frac{1}{5}\left(2\times\frac{7}{3}\left[1-\left(\frac{2}{5}\right)^{n-1}\right]+7\right) = \frac{14}{15}\left[1-\left(\frac{2}{5}\right)^{n-1}\right]+\frac{7}{5}$$

$$= \frac{14}{15} - \frac{14}{15}\left(\frac{2}{5}\right)^{n-1} + \frac{21}{15} = \frac{35}{15} - \frac{14}{15}\left(\frac{2}{5}\right)^{n-1} = \frac{7}{3} - \frac{7}{3}\cdot\frac{2}{5}\left(\frac{2}{5}\right)^{n-1} = \frac{7}{3}-\frac{7}{3}\left(\frac{2}{5}\right)^{n}$$

$$= \frac{7}{3}\left[1-\left(\frac{2}{5}\right)^{n}\right],$$ which is correctly predicted by our explicit formula.

By induction, the conjectured explicit formula for a_n holds for all $n = 1, 2, 3, 4, \ldots$. $\square$

At this point, $\lim_{n\to\infty} a_n = \lim_{n\to\infty} \frac{7}{3}\left[1-\left(\frac{2}{5}\right)^{n-1}\right] = \frac{7}{3}[1-0] = \frac{7}{3}$.

Alternative proof: Substitute $b_n = \frac{7}{3} - a_n$. This gives a new sequence which also satisfies a recursive formula

$$b_{n+1} = \frac{7}{3} - a_{n+1} = \frac{7}{3} - f(a_n) = \frac{7}{3} - \frac{1}{5}(2a_n+7) = \frac{14}{15} - \frac{2}{5}a_n = \frac{14}{15} - \frac{2}{5}\left(\frac{7}{3}-b_n\right) = \frac{2}{5}b_n.$$

i.e. $b_n = \begin{cases} \frac{7}{3}, & \text{if } n=1; \\ \frac{2}{5}b_{n-1}, & \text{for } n=2,3,4,\ldots \end{cases}$

n	1	2	3	4	5
b_n	$\frac{7}{3}$	$\frac{7}{3}\cdot\frac{2}{5}$	$\frac{7}{3}\cdot\left(\frac{2}{5}\right)^2$	$\frac{7}{3}\left(\frac{2}{5}\right)^3$	$\frac{7}{3}\left(\frac{2}{5}\right)^4$

etc.

$$b_n = \frac{7}{3}\cdot\left(\frac{2}{5}\right)^{n-1}$$