DEFINITION: A **finite continued fraction** is an expression of the form

$$a_0 + \cfrac{1}{a_1 + \cfrac{1}{a_2 + \cfrac{1}{\ddots + \cfrac{1}{a_n}}}}$$

for some integers $a_0 \in \mathbb{Z}, a_1, \dots, a_n \in \mathbb{Z}_{>0}$. We write $[a_0; a_1, \dots, a_n]$ as shorthand for this.

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By a **continued fraction** we mean either an infinite or finite continued fraction. We call the numbers a_i the **partial quotients** in the continued fraction.

(1) Evaluating finite continued fractions:

- (a) Evaluate $2 + \cfrac{1}{13 + \frac{1}{2}}$.
- (b) Evaluate $[3; 2, 1, 4]$
- (c) Explain why every finite continued fraction evaluates to a rational number.

(2) Using the Euclidean algorithm to compute finite continued fractions:

- (a) What type of computation is the computation below?

$$\begin{aligned} 250 &= 2 \cdot 117 + 16 \\ 117 &= 7 \cdot 16 + 5 \\ 16 &= 3 \cdot 5 + 1 \\ 5 &= 5 \cdot 1 \end{aligned}$$

- (b) How does one obtain $\frac{250}{117} = 2 + \cfrac{1}{\frac{117}{16}}$ from the computation above?
- (c) Repeat (b) to obtain a finite continued fraction expansion for $\frac{250}{117}$.
- (d) Use the steps above to obtain a finite continued fraction expansion for $\frac{7}{5}$.
- (e) Use the steps above to obtain a finite continued fraction expansion for $\frac{39}{314}$.
- (f) What is the general formula for the continued fraction $[a_0; a_1, \dots, a_n]$ for m/n in terms of the Euclidean algorithm?

(3) Euclidean algorithm and continued fraction algorithm:

- (a) In the computation from (2a) above, check that

$$2 = \left\lfloor \frac{250}{117} \right\rfloor \text{ and that } \frac{117}{16} = \left(\frac{250}{117} - \left\lfloor \frac{250}{117} \right\rfloor \right)^{-1}.$$

- (b) More generally, in the Euclidean algorithm

$$\begin{array}{rcccl} \vdots & \vdots & \vdots & \vdots & \\ u_i = & q_i & \cdot\ v_i & +\, r_i & \qquad (u_{i+1} = v_i) \\ u_{i+1} = & q_{i+1} & \cdot\ v_{i+1} & +\, r_{i+1} & \qquad (v_{i+1} = r_i) \\ \vdots & \vdots & \vdots & \vdots & \end{array}$$

show that

$$q_i = \left\lfloor \frac{u_i}{v_i} \right\rfloor \text{ and } \frac{u_{i+1}}{v_{i+1}} = \left(\frac{u_i}{v_i} - \left\lfloor \frac{u_i}{v_i} \right\rfloor \right)^{-1}.$$

DEFINITION: Given an infinite continued fraction $[a_0; a_1, a_2, \ldots]$, the k-th **convergent** of the continued fraction is the value C_k of the finite continued fraction $[a_0; a_1, \ldots, a_k]$.

THEOREM (CONVERGENCE OF CONTINUED FRACTIONS): Every infinite continued fraction converges to a real number; i.e., for any $[a_0; a_1, a_2, a_3, \ldots]$ with $a_0 \in \mathbb{Z}$ and $a_1, a_2, \ldots \in \mathbb{Z}_{>0}$, the sequence of convergents $C_1, C_2, C_3, \ldots$ converges. We call this limit the value of the infinite continued fraction.

CONTINUED FRACTION ALGORITHM: Given a real number r,

(I) Start with $\beta_0 := r$ and $n := 0$.
(II) Set $a_n := \lfloor \beta_n \rfloor$.
(III) If $a_n = \beta_n$, STOP; the continued fraction is $[a_0; a_1, \ldots, a_n]$.
Else, set $\beta_{n+1} := (\beta_n - a_n)^{-1}$, and return to Step (II).

If the algorithm does not terminate, the continued fraction is $[a_0; a_1, a_2, \ldots]$.

THEOREM (CORRECTNESS OF CONTINUED FRACTION ALGORITHM): For any real number r, the continued fraction obtained from the Continued Fraction Algorithm with input r converges to r.

PROPOSITION: Let r be a real number. The Continued Fraction Algorithm with input r terminates in finitely many steps if and only if r is rational.

DIRICHLET APPROXIMATION THEOREM: Let $r = [a_0; a_1, a_2, a_3, \ldots]$ be a real number. Then for every convergent $C_k = \dfrac{p_k}{q_k}$ (in lowest terms), we have $\left| r - \dfrac{p_k}{q_k} \right| < \dfrac{1}{q_k^2}$.

In particular, if r is irrational, there are infinitely many rational numbers $\dfrac{p}{q}$ such that $\left| r - \dfrac{p}{q} \right| < \dfrac{1}{q^2}$.

(4) Use the continued fraction algorithm to find the first four ($n \leq 3$) partial quotients and convergents for $\sqrt{2}$, and π. Can you find the whole continued fraction for either of these?

(5) Find[1] the value of the continued fraction $1 + \cfrac{1}{1 + \cfrac{1}{1 + \cfrac{1}{\ddots}}}$.

(6) Continued fraction algorithm and rational numbers.
   (a) Explain why the continued fraction algorithm just creates a continued fraction in the same way the Euclidean algorithm does as we did in problem (2).
   (b) Explain why the Proposition above is true.

(7) Dirichlet Approximation Theorem.
   (a) Let r be any real number. Explain why for *any* positive integer q, there is some integer p such that $|r - \frac{p}{q}| < \frac{1}{q}$. Conclude that $|r - \frac{p}{q}| < \frac{1}{q}$ is "not very impressive".
   (b) For $r = \sqrt{2}$, find all rational numbers p/q with $|r - \frac{p}{q}| < \frac{1}{q^2}$ with $q \leq 6$ and compare to the list of convergents C_0, C_1, C_2. What about $|r - \frac{p}{q}| < \frac{1}{2q^2}$? Conclude that $|r - \frac{p}{q}| < \frac{1}{q^2}$ is "pretty impressive".
   (c) Discuss $\pi \approx \frac{22}{7}$ in the context of the results above. Give a better approximation.

[1]Hint: This limit has a value L. Find an equation that L satisfies by recognizing L as a smaller piece of this continued fraction.

PROPOSITION: Let $[a_0; a_1, a_2, \dots]$ be a continued fraction. Set

$$\begin{aligned} p_0 &:= a_0, & p_1 &:= a_0 a_1 + 1, & p_k &:= a_k p_{k-1} + p_{k-2} \\ q_0 &:= 1, & q_1 &:= a_1, & q_k &:= a_k q_{k-1} + q_{k-2}. \end{aligned}$$

Then,

(1) $C_k = \dfrac{p_k}{q_k}$ for all $k \geq 0$, and

(2) $p_k q_{k-1} - p_{k-1} q_k = (-1)^{k-1}$ for all $k \geq 1$.

(8) Proof of convergence Theorem and Dirichlet Approximation Theorem.

(a) Use the Proposition above to show that $C_k - C_{k-1} = \dfrac{(-1)^{k-1}}{q_k q_{k-1}}$ for all $k \geq 1$.

(b) Use the Proposition above to show that $C_k - C_{k-2} = \dfrac{(-1)^k a_k}{q_k q_{k-2}}$ for all $k \geq 2$.

(c) Use (8b) to show that the sequence $C_0, C_2, C_4, \dots$ is increasing, that the sequence $C_1, C_3, C_5, \dots$ is decreasing; use (8a) to show that $C_{2k} < C_{2\ell+1}$ for all k, ℓ. Deduce that $\lim_{k\to\infty} C_{2k} = \sup\{C_{2k} \mid k \in \mathbb{N}\}$ and $\lim_{\ell\to\infty} C_{2\ell+1} = \inf\{C_{2\ell+1} \mid \ell \in \mathbb{N}\}$ both exist.

(d) Use (8a) to show that $\sup\{C_{2k} \mid k \in \mathbb{N}\} = \inf\{C_{2\ell+1} \mid \ell \in \mathbb{N}\}$, and hence that $\lim_{n\to\infty} C_n$ exists and is equal to both of these values. Thus, every continued fraction converges.

(e) Suppose that β is the value of our continued fraction. Use (8d) to show that $|\beta - C_n| \leq |C_{n+1} - C_n|$, and use (8a) to deduce Dirichlet's Approximation.

(9) Prove the Proposition above.

(10) Proof of Correctness of Continued Fraction Algorithm:

If r is rational, the algorithm terminates and returns r, so we can assume that r is irrational and that the algorithm does not terminate. Given r, let $a_0, a_1, a_2, a_3, \dots$ and $\beta_0, \beta_1, \beta_2, \dots$ be the sequences arising from the continued fraction algorithm.

(a) Explain why $r = [a_0; a_1, \dots, a_k, \beta_{k+1}]$. (Note, β_{k+1} is not an integer, but we can plug it into a finite continued fraction anyway.)

(b) Explain why $r = \dfrac{\beta_{k+1} p_k + p_{k-1}}{\beta_{k+1} q_k + q_{k-1}}$ where p_k, q_k, where p_k, q_k are the numbers coming from the continued fraction (with an irrational number snuck in) $[a_0; a_1, \dots, a_k, \beta_{k+1}]$ as in the Proposition above.

(c) Show that $|r - C_k| < \dfrac{1}{q_k q_{k+1}}$ for all $k \geq 1$ and deduce the result.

(11) Prove the following theorem, which basically says that the convergents are the *best* approximations of a rational number.

THEOREM: Let r be a real number, $C_k = \frac{p_k}{q_k}$ be the k-th convergent of r, and $\frac{p}{q} \neq r$ be a rational number. If $q \leq q_k$, then $\left| r - \dfrac{p}{q} \right| \geq \left| r - \dfrac{p_k}{q_k} \right|$.