Numbers in Non-Integer Bases

Connor Baker

Northern Virginia Community College

VMATYC, Spring 2017

Outline

1. Whole Numbers
   - Definitions
   - Examples
2. Language Generated by Whole Number Bases
3. Definitions (Part 2)
4. Examples and Properties of Non-Integer Bases
5. Language Generated by Non-Integer Bases

Overview

1. Whole Numbers
   - Definitions
   - Examples
2. Language Generated by Whole Number Bases
3. Definitions (Part 2)
4. Examples and Properties of Non-Integer Bases
5. Language Generated by Non-Integer Bases

Definitions

Base

A base (or radix) is a mathematical building block used to describe a number system whose digits are used to represent numbers

Definitions

Base

A base (or radix) is a mathematical building block used to describe a number system whose digits are used to represent numbers

Example (Different Whole Number Bases)

125_{10}

Definitions

Base

A base (or radix) is a mathematical building block used to describe a number system whose digits are used to represent numbers

Example (Different Whole Number Bases)

125_{10}
888_{9}

Definitions

Base

A base (or radix) is a mathematical building block used to describe a number system whose digits are used to represent numbers

Example (Different Whole Number Bases)

125_{10}
888_9
48.5_8

Definitions

Base

A base (or radix) is a mathematical building block used to describe a number system whose digits are used to represent numbers

Example (Different Whole Number Bases)

125_{10}
888_9
48.5_8?

Definitions

Maximum Allowed Numeral in Base

The radix is the number of numerals allowed in a base, and it includes zero.

Definitions

Maximum Allowed Numeral in Base

The radix is the number of numerals allowed in a base, and it includes zero.
The number of numerals in a base is one less than the base.

Definitions

Maximum Allowed Numeral in Base

The radix is the number of numerals allowed in a base, and it includes zero. The number of numerals in a base is one less than the base.

Example (Allowed Numbers in Different Bases)

125_{10}
888_{9}
48.5_{8}

Definitions

Maximum Allowed Numeral in Base

The radix is the number of numerals allowed in a base, and it includes zero. The number of numerals in a base is one less than the base.

Example (Allowed Numbers in Different Bases)

125_{10}
888_9
48.5_9

Definitions

Radix Point

A point used to separate the integer part of a number from the fractional part.

Definitions

Radix Point

A point used to separate the integer part of a number from the fractional part.

Example (Radix Point Expressions)

10.5_{10}
$A5.E_{16}$
1.1_{2}

Definitions

Beta Expansion

A means of rewriting a number as the digits multiplied by the base which is raised to the power of position of the digit.

Definitions

Beta Expansion

A means of rewriting a number as the digits multiplied by the base which is raised to the power of position of the digit.

Example (Beta Expansion of 125_{10})

$125_{10} = 1 \times 10^2 + 2 \times 10^1 + 5 \times 10^0$
$A5.E_{16} = 10 \times 16^1 + 5 \times 16^0 + 14 \times 16^-1$
$20_2 = 2 \times 10^1 + 0 \times 2^0$

Overview

1. Whole Numbers
   - Definitions
   - Examples

2. Language Generated by Whole Number Bases

3. Definitions (Part 2)

4. Examples and Properties of Non-Integer Bases

5. Language Generated by Non-Integer Bases

Let's Play a Game

- Suppose that you're given the interval $[0, 1]$, with a point somewhere on it

Let's Play a Game

- Suppose that you're given the interval $[0, 1]$, with a point somewhere on it

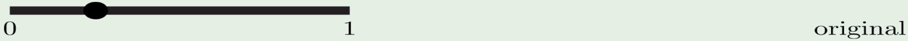
Let's Play a Game

- Suppose that you're given the interval $[0, 1]$, with a point somewhere on it

- You're allowed one operation
  - Multiplication by a whole number, followed by modulo one

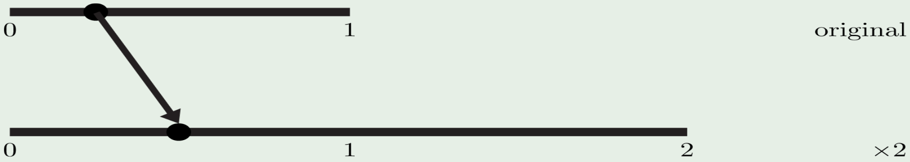
Dealing with Radix Point Numbers (Geometrically)

Example (Suppose you have a point...)



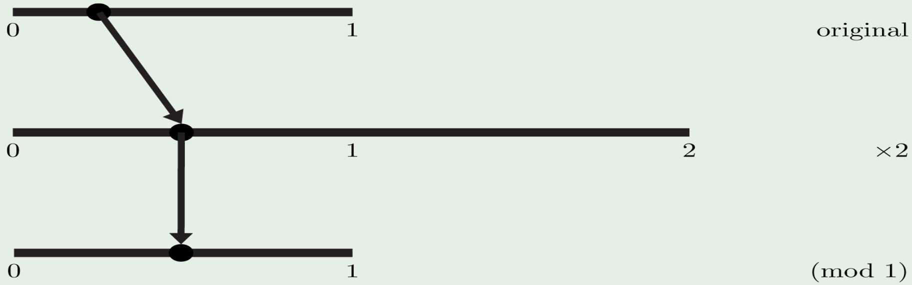
Dealing with Radix Point Numbers (Geometrically)

Example (Suppose you have a point...)



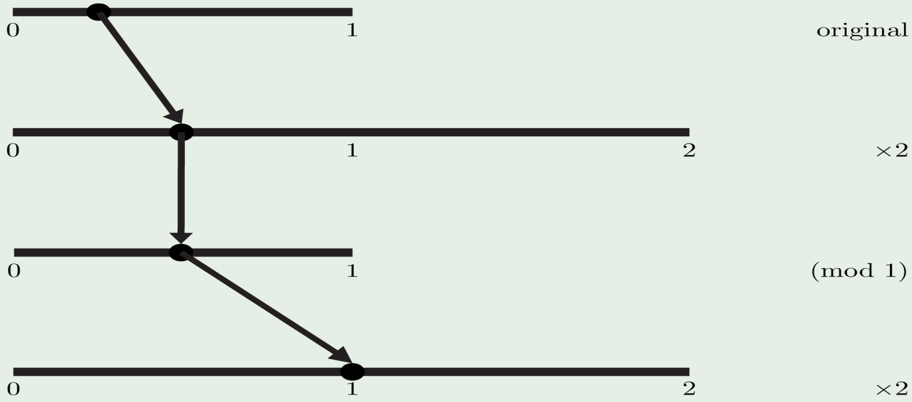
Dealing with Radix Point Numbers (Geometrically)

Example (Suppose you have a point...)



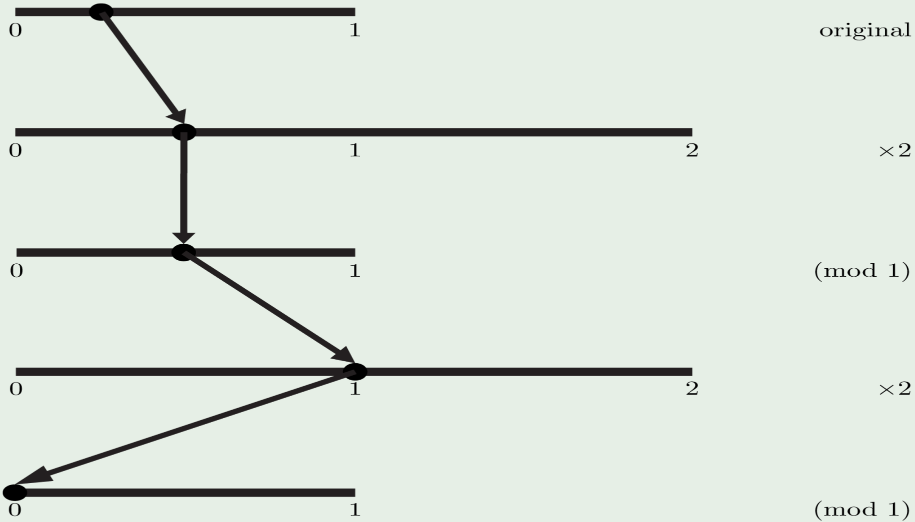
Dealing with Radix Point Numbers (Geometrically)

Example (Suppose you have a point...)



Dealing with Radix Point Numbers (Geometrically)

Example (Suppose you have a point...)



What this Tells Us

- This tells us two things:
    - Where the point was originally
    - Whether there is a finite radix point expression in a given base

Wait, What?

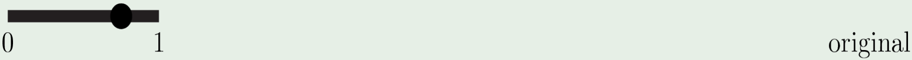
- Our choice of partitioning and multiplication matter
  - We just converted 0.25_{10} to a number in binary: 0.01_2
  - We can check with a beta expansion:
    $0.01_2 = 0 \times 2^0 + 0 \times 2^{-1} + 1 \times 2^{-2} = 1/4 = 0.25_{10}$
- The fact we didn't get stuck in a loop means that there was a finite representation
- This is what is happening geometrically when we change bases

Wait, What?

- Our choice of partitioning and multiplication matter
  - We just converted 0.25_{10} to a number in binary: 0.01_2
  - We can check with a beta expansion:
    $0.01_2 = 0 \times 2^0 + 0 \times 2^{-1} + 1 \times 2^{-2} = 1/4 = 0.25_{10}$
- The fact we didn't get stuck in a loop means that there was a finite representation
- This is what is happening geometrically when we change bases
- What happens when multiply by a different number?

Dealing with Radix Point Numbers (Geometrically)

Example (Suppose you have a point...)

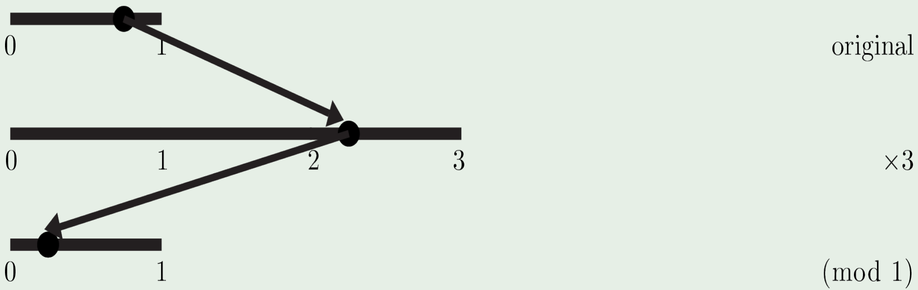


Dealing with Radix Point Numbers (Geometrically)

Example (Suppose you have a point...)

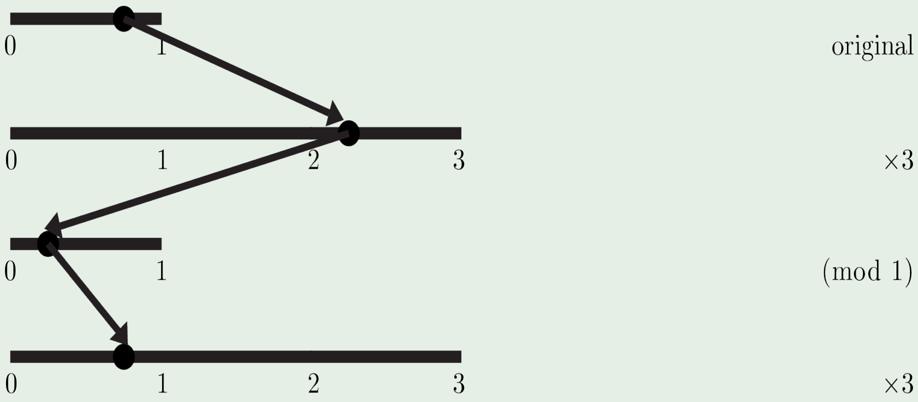
Dealing with Radix Point Numbers (Geometrically)

Example (Suppose you have a point...)



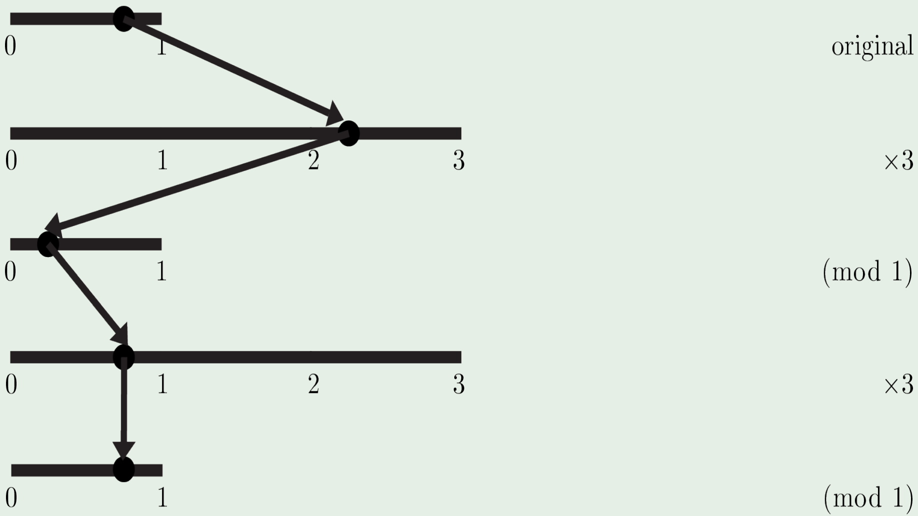
Dealing with Radix Point Numbers (Geometrically)

Example (Suppose you have a point...)



Dealing with Radix Point Numbers (Geometrically)

Example (Suppose you have a point...)



What this Tells Us

- What does this cycle mean?
  - This number is not representable as a finite radix point expression in base 3
- This can happen in any base
  - Arithmetically this happens when the number can't be written as something divided by multiples of the prime factors of the base

Dealing with Radix Point Numbers (Arithmetically)

Example (Convert 0.1_{10} to binary.)

Dealing with Radix Point Numbers (Arithmetically)

Example (Convert 0.1_{10} to binary.)

$0.1 * 2 = 0.2$ $\qquad$ $0.2 \bmod (1) = 0.2$ $\qquad$ 0.0

Dealing with Radix Point Numbers (Arithmetically)

Example (Convert 0.1_{10} to binary.)

$0.1 * 2 = 0.2$	$0.2 \bmod (1) = 0.2$	0.0
$0.2 * 2 = 0.4$	$0.4 \bmod (1) = 0.4$	0.00

Dealing with Radix Point Numbers (Arithmetically)

Example (Convert 0.1_{10} to binary.)

$0.1 * 2 = 0.2$	$0.2 \bmod (1) = 0.2$	0.0
$0.2 * 2 = 0.4$	$0.4 \bmod (1) = 0.4$	0.00
$0.4 * 2 = 0.8$	$0.8 \bmod (1) = 0.8$	0.000

Dealing with Radix Point Numbers (Arithmetically)

Example (Convert 0.1_{10} to binary.)

$0.1 * 2 = 0.2$	$0.2 \bmod (1) = 0.2$	0.0
$0.2 * 2 = 0.4$	$0.4 \bmod (1) = 0.4$	0.00
$0.4 * 2 = 0.8$	$0.8 \bmod (1) = 0.8$	0.000
$0.8 * 2 = 1.6$	$1.6 \bmod (1) = 0.6$	0.0001

Dealing with Radix Point Numbers (Arithmetically)

Example (Convert 0.1_{10} to binary.)

$0.1 * 2 = 0.2$	$0.2 \bmod (1) = 0.2$	0.0
$0.2 * 2 = 0.4$	$0.4 \bmod (1) = 0.4$	0.00
$0.4 * 2 = 0.8$	$0.8 \bmod (1) = 0.8$	0.000
$0.8 * 2 = 1.6$	$1.6 \bmod (1) = 0.6$	0.0001
$0.6 * 2 = 1.2$	$1.2 \bmod (1) = 0.2$	0.00011

Dealing with Radix Point Numbers (Arithmetically)

Example (Convert 0.1_{10} to binary.)

$0.1 * 2 = 0.2$	$0.2 \bmod (1) = 0.2$	0.0
$0.2 * 2 = 0.4$	$0.4 \bmod (1) = 0.4$	0.00
$0.4 * 2 = 0.8$	$0.8 \bmod (1) = 0.8$	0.000
$0.8 * 2 = 1.6$	$1.6 \bmod (1) = 0.6$	0.0001
$0.6 * 2 = 1.2$	$1.2 \bmod (1) = 0.2$	0.00011
$0.2 * 2 = 0.4$	$0.4 \bmod (1) = 0.4$	...

Dealing with Radix Point Numbers (Arithmetically)

Example (Convert 0.1_{10} to binary.)

$0.1 * 2 = 0.2$	$0.2 \bmod (1) = 0.2$	0.0
$0.2 * 2 = 0.4$	$0.4 \bmod (1) = 0.4$	0.00
$0.4 * 2 = 0.8$	$0.8 \bmod (1) = 0.8$	0.000
$0.8 * 2 = 1.6$	$1.6 \bmod (1) = 0.6$	0.0001
$0.6 * 2 = 1.2$	$1.2 \bmod (1) = 0.2$	0.00011
$0.2 * 2 = 0.4$	$0.4 \bmod (1) = 0.4$	$\ldots$
		$0.0\overline{0011}_2$

What Makes a Number have a Finite Radix Point Expression

- This is another example of a number that is not expressable as a finite representation
- We know why this happens geometrically, but not arithmetically
- Why does this happen?

Finite Radix Point Expression

Finite Radix Point Expression

A number p is said to have a finite radix point expression if

$$p = \frac{n}{m_1 m_2 \ldots m_k}$$

where $n \in \mathbb{N}$, and $m_1 m_2 \ldots m_k$ are all the prime factors of the base raised to some power

http://mathworld.wolfram.com/DecimalExpansion.html

Finite Radix Point Expression

Finite Radix Point Expression

A number p is said to have a finite radix point expression if

$$p = \frac{n}{m_1 m_2 \ldots m_k}$$

where $n \in \mathbb{N}$, and $m_1 m_2 \ldots m_k$ are all the prime factors of the base raised to some power

---

http://mathworld.wolfram.com/DecimalExpansion.html

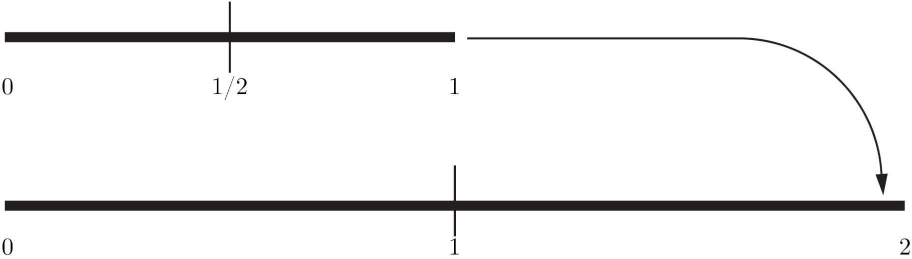
Example (1/3 in Base 10)

$$\frac{1}{3} \neq \frac{n}{2^\alpha 5^\beta}$$

where $n, \alpha, \beta \in \mathbb{N}$.

How Partitioning Works

- We partition before we multiply
- We multiply so that the first partition becomes the unit interval
  - The number we multiply by is the base that we are converting to
- So for binary:



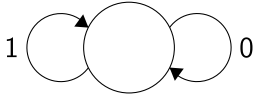
Language Generated by Whole Number Bases

- Language generated by a whole number base is a fancy way of saying any number you could write in a base
- A word is not allowed in a language if it contains a forbidden subword
  - Acceptable words in base 10 include 9, or 5.5 – but not CAT or 5A: they contain forbidden subwords
  - Acceptable words in base 2 include 1, or 0.110000 – but not 3, or 4: they contain forbidden subwords
- With whole number bases, our allowed subwords are any sequence of numerals less than the base minus one

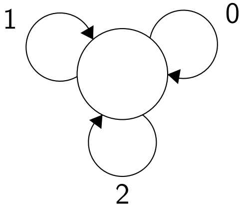
Using FSMs to Represent a Language

- A finite state machine (FSM) is a mathematical structure that allows us to imagine a machine with no memory.

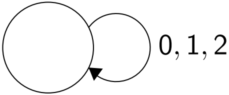
FSM for Binary



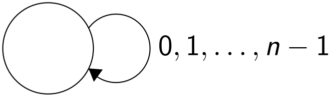
FSM for Ternary



Simplified FSM for Ternary



FSM for Whole Number Bases



- $n \in \mathbb{N}, \;\; n > 1$

Definitions (Part 2)

Orbit

The unique, non-terminating radix point representation of a number in any base.

Algebraic Integer

A number x is an algebraic integer if it is the root of a monic polynomial $f(x) = x^n + a_{n-1}x^{n-1} + \cdots + a_1 x + a_0$, where $a_{n-1}, \ldots, a_0 \in \mathbb{Z}$.

Beta Map

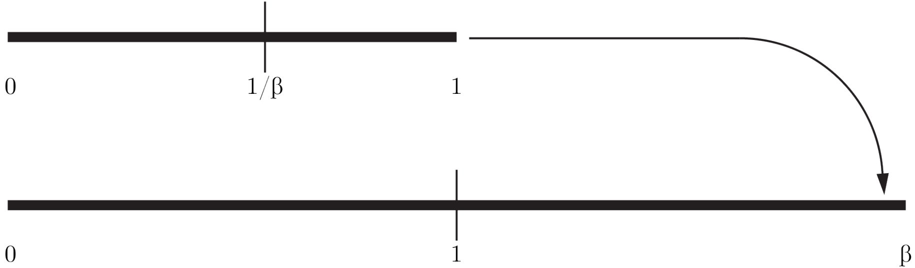
The transformation $T : [0,1) \to [0,1)$ defined by $T = (x \cdot \beta) \pmod 1$.

Simplest Form

A number is in simplest form if we are unable to rewrite the beta expansion such that it includes a higher power.

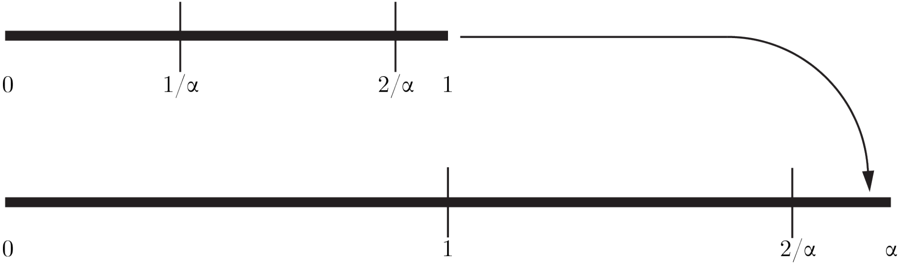
Partitioning Differently

- We don't have to use a whole number
- The partitions won't be even, but that's not a problem



Partitioning Differently

- We don't have to use a whole number
- The partitions won't be even, but that's not a problem



Examples of Non-Integer Bases

- Base Golden Ratio
- Base Silver Ratio

Properties of Non-Integer Bases

- There will be forbidden words
  - We can find these by using the orbit of any whole number in these bases (one is the easiest choice)
- It is easy/interesting to represent certain numbers in these bases
- Arithmetic is more of a pain than usual

Golden Ratio

Golden Ratio

The positive solution to the equation $\varphi^2 = \varphi + 1$.
$\varphi = \frac{1+\sqrt{5}}{2} \approx 1.618$.

Golden Ratio Addition

Example ($1_\varphi + 1_\varphi$)

$1_\varphi = 0.11\varphi$

$1_\varphi + 0.11\varphi = 1.11\varphi = 10.01_\varphi$

We can double check this operation by doing a beta expansion and using the definition of the base.

Golden Ratio Addition

Example ($1_\varphi + 1_\varphi$)

$10.01_\varphi = 1 \times \varphi^1 + 0 \times \varphi^0 + 0 \times \varphi^{-1} + 1 \times \varphi^{-2} = \varphi + 1/\varphi^2 = (\varphi^2 + 1)/\varphi^2 = 2_{10}$

Silver Ratio

Silver Ratio

The positive solution to the equation $\alpha^2 = 2\alpha + 1$.
$\alpha = 1 + \sqrt{2} \approx 2.414$.

Finding Forbidden Words

- Take the orbit of one
- Find the period
- Any sequence of numerals greater than the numerals of the period is not allowed

What Makes a Word Forbidden in Non-Integer Bases?

- In general, a word is forbidden if it is not in simplest form
- In actuality, it is because it escapes the range of the beta map

Escaping the Beta Map

Example ($T(0.011_\varphi)$)

$T(0.011_\varphi) = 0.11_\varphi = 1.00_\varphi$ But that can't happen! By definition, $T : [0,1) \to [0,1)$. As such, we say that this is a forbidden word.
How do we find forbidden words?

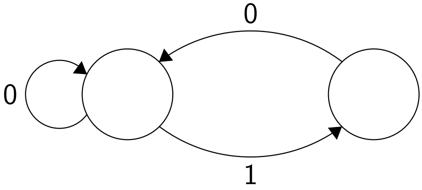
Finding Forbidden Words

- The orbit of one is composed of the maximum allowed word in a language
- All the forbidden words then will subwords of the orbit, with one added until the word is the maximum allowed in the language

Language Generated by base Golden Ratio

- $0.\overline{10}_{\varphi}$ is the orbit of one in base golden ratio
- Since the maximum allowed word in the language is 10, we add one and find that the forbidden word is 11.
- There can be more than one forbidden word, but since the maximum allowed numeral in base golden ratio is 1, we can't add one again without changing the length.
- With this in mind, we can now create a finite state machine

FSM For Language Generated by Base Golden Ratio



Language Generated by base Silver Ratio

- $0.\overline{20}_\alpha$ is the orbit of one in base silver ratio
- Therefore, 21 and 22 are forbidden words in the language

FSM For Language Generated by Base Silver Ratio