

Goodstein Sequences

Exposition by William Gasarch-U of MD

Goodstein Sequences

Writing a number as a sum of powers of 2.

$$1000 = 2^9 + 2^8 + 2^7 + 2^6 + 2^5 + 2^3$$

Goodstein Sequences

Writing a number as a sum of powers of 2.

$$1000 = 2^9 + 2^8 + 2^7 + 2^6 + 2^5 + 2^3$$

But we can also write the exponents as sums of power of 2

$$1000 = 2^{2^3+2^0} + 2^{2^3} + 2^{2^2+2^1+2^0} + 2^{2^1+2^0}$$

Goodstein Sequences

Writing a number as a sum of powers of 2.

$$1000 = 2^9 + 2^8 + 2^7 + 2^6 + 2^5 + 2^3$$

But we can also write the exponents as sums of power of 2

$$1000 = 2^{2^3+2^0} + 2^{2^3} + 2^{2^2+2^1+2^0} + 2^{2^1+2^0}$$

We can even write the exponents that are not already powers of 2 as sums of powers of 2.

$$1000 = 2^{2^{2^1+2^0}+2^0} + 2^{2^{2^1+2^0}} + 2^{2^2+2^1+2^0} + 2^{2^1+2^0}$$

Goodstein Sequences

Writing a number as a sum of powers of 2.

$$1000 = 2^9 + 2^8 + 2^7 + 2^6 + 2^5 + 2^3$$

But we can also write the exponents as sums of power of 2

$$1000 = 2^{2^3+2^0} + 2^{2^3} + 2^{2^2+2^1+2^0} + 2^{2^1+2^0}$$

We can even write the exponents that are not already powers of 2 as sums of powers of 2.

$$1000 = 2^{2^{2^1+2^0}+2^0} + 2^{2^{2^1+2^0}} + 2^{2^2+2^1+2^0} + 2^{2^1+2^0}$$

This is called **Hereditary Base n Notation**

Ackerman's Function and Goodstein Seq

$$1000 = 2^{2^{2^1+2^0}+2^0} + 2^{2^{2^1+2^0}} + 2^{2^2+2^1+2^0} + 2^{2^1+2^0}$$

Replace all of the 2's with 3's:

$$3^{3^{3^1+3^0}+3^0} + 3^{3^{3^1+3^0}} + 3^{3^3+3^1+3^0} + 3^{3^1+3^0}$$

Ackerman's Function and Goodstein Seq

$$1000 = 2^{2^{2^1+2^0}+2^0} + 2^{2^{2^1+2^0}} + 2^{2^2+2^1+2^0} + 2^{2^1+2^0}$$

Replace all of the 2's with 3's:

$$3^{3^{3^1+3^0}+3^0} + 3^{3^{3^1+3^0}} + 3^{3^3+3^1+3^0} + 3^{3^1+3^0}$$

This number just went WAY up. Now subtract 1.

$$3^{3^{3^1+3^0}+3^0} + 3^{3^{3^1+3^0}} + 3^{3^3+3^1+3^0} + 3^{3^1+3^0} - 1$$

Ackerman's Function and Goodstein Seq

$$1000 = 2^{2^{2^1+2^0}+2^0} + 2^{2^{2^1+2^0}} + 2^{2^2+2^1+2^0} + 2^{2^1+2^0}$$

Replace all of the 2's with 3's:

$$3^{3^{3^1+3^0}+3^0} + 3^{3^{3^1+3^0}} + 3^{3^3+3^1+3^0} + 3^{3^1+3^0}$$

This number just went WAY up. Now subtract 1.

$$3^{3^{3^1+3^0}+3^0} + 3^{3^{3^1+3^0}} + 3^{3^3+3^1+3^0} + 3^{3^1+3^0} - 1$$

Repeat the process:

Replace 3 by 4, and subtract 1, Replace 4 by 5, and subtract 1, \dots .

Ackerman's Function and Goodstein Seq

$$1000 = 2^{2^{2^1+2^0}+2^0} + 2^{2^{2^1+2^0}} + 2^{2^2+2^1+2^0} + 2^{2^1+2^0}$$

Replace all of the 2's with 3's:

$$3^{3^{3^1+3^0}+3^0} + 3^{3^{3^1+3^0}} + 3^{3^3+3^1+3^0} + 3^{3^1+3^0}$$

This number just went WAY up. Now subtract 1.

$$3^{3^{3^1+3^0}+3^0} + 3^{3^{3^1+3^0}} + 3^{3^3+3^1+3^0} + 3^{3^1+3^0} - 1$$

Repeat the process:

Replace 3 by 4, and subtract 1, Replace 4 by 5, and subtract 1, \dots .

Vote Does the seq:

- ▶ Goto infinity (and if so how fast- perhaps Ack-like?)
- ▶ Eventually stabilizes (e.g., goes to 18 and then stops there)
- ▶ Cycles- goes UP then DOWN then UP then DOWN \dots

Ackerman's Function and Goodstein Seq

$$1000 = 2^{2^{2^1+2^0}+2^0} + 2^{2^{2^1+2^0}} + 2^{2^2+2^1+2^0} + 2^{2^1+2^0}$$

Replace all of the 2's with 3's:

$$3^{3^{3^1+3^0}+3^0} + 3^{3^{3^1+3^0}} + 3^{3^3+3^1+3^0} + 3^{3^1+3^0}$$

This number just went WAY up. Now subtract 1.

$$3^{3^{3^1+3^0}+3^0} + 3^{3^{3^1+3^0}} + 3^{3^3+3^1+3^0} + 3^{3^1+3^0} - 1$$

Repeat the process:

Replace 3 by 4, and subtract 1, Replace 4 by 5, and subtract 1, \dots

Vote Does the seq:

- ▶ Goto infinity (and if so how fast- perhaps Ack-like?)
- ▶ Eventually stabilizes (e.g., goes to 18 and then stops there)
- ▶ Cycles- goes UP then DOWN then UP then DOWN \dots

Answer on Next Slide

The Sequence ...

The seq goes to 0.

The Sequence ...

The seq goes to 0.

The number of steps for n to goto 0 is roughly $ACK(n, n)$.

The Sequence ...

The seq goes to 0.

The number of steps for n to goto 0 is roughly $ACK(n, n)$.

Really? Really!

An Example of a Similar Sequence

We will not deal with the actual Goodstein Sequence defined above.

An Example of a Similar Sequence

We will not deal with the actual Goodstein Sequence defined above. **Boo!**

An Example of a Similar Sequence

We will not deal with the actual Goodstein Sequence defined above. **Boo!**

We will instead deal with a weaker version that

An Example of a Similar Sequence

We will not deal with the actual Goodstein Sequence defined above. **Boo!**

We will instead deal with a weaker version that

1. Contains most of the ideas.

An Example of a Similar Sequence

We will not deal with the actual Goodstein Sequence defined above. **Boo!**

We will instead deal with a weaker version that

1. Contains most of the ideas. **Yeah!**

An Example of a Similar Sequence

We will not deal with the actual Goodstein Sequence defined above. **Boo!**

We will instead deal with a weaker version that

1. Contains most of the ideas. **Yeah!**
2. Will go to 0 before the heat death of the Universe.

An Example of a Similar Sequence

We will not deal with the actual Goodstein Sequence defined above. **Boo!**

We will instead deal with a weaker version that

1. Contains most of the ideas. **Yeah!**
2. Will go to 0 before the heat death of the Universe. **Yeah!**

Weak Goodstein: Unit Position

Take a number in base 10.

Weak Goodstein: Unit Position

Take a number in base 10.

$$(986)_{10} = 9 \times 10^2 + 8 \times 10^1 + 6 \times 10^0.$$

Weak Goodstein: Unit Position

Take a number in base 10.

$$(986)_{10} = 9 \times 10^2 + 8 \times 10^1 + 6 \times 10^0.$$

Increase the base and subtract 1. Assume BWOC that the seq goes on forever.

$$9^2 + 8 \times 11^1 + 6 \times 11^0 - 1 = 9 \times 11^2 + 8 \times 11^1 + 5 \times 11^0 = (985)_{11}.$$

Weak Goodstein: Unit Position

Take a number in base 10.

$$(986)_{10} = 9 \times 10^2 + 8 \times 10^1 + 6 \times 10^0.$$

Increase the base and subtract 1. Assume BWOC that the seq goes on forever.

$$9^2 + 8 \times 11^1 + 6 \times 11^0 - 1 = 9 \times 11^2 + 8 \times 11^1 + 5 \times 11^0 = (985)_{11}.$$

Repeat this to get: $(984)_{12}$, $(983)_{13}$, $(982)_{14}$, $(981)_{15}$, $(980)_{16}$.

Weak Goodstein: Unit Position

Take a number in base 10.

$$(986)_{10} = 9 \times 10^2 + 8 \times 10^1 + 6 \times 10^0.$$

Increase the base and subtract 1. Assume BWOC that the seq goes on forever.

$$9^2 + 8 \times 11^1 + 6 \times 11^0 - 1 = 9 \times 11^2 + 8 \times 11^1 + 5 \times 11^0 = (985)_{11}.$$

Repeat this to get: $(984)_{12}$, $(983)_{13}$, $(982)_{14}$, $(981)_{15}$, $(980)_{16}$.

$$(980)_{16} = 9 \times 16^2 + 8 \times 16^1$$

Weak Goodstein: Unit Position

Take a number in base 10.

$$(986)_{10} = 9 \times 10^2 + 8 \times 10^1 + 6 \times 10^0.$$

Increase the base and subtract 1. Assume BWOC that the seq goes on forever.

$$9^2 + 8 \times 11^1 + 6 \times 11^0 - 1 = 9 \times 11^2 + 8 \times 11^1 + 5 \times 11^0 = (985)_{11}.$$

Repeat this to get: $(984)_{12}$, $(983)_{13}$, $(982)_{14}$, $(981)_{15}$, $(980)_{16}$.

$$(980)_{16} = 9 \times 16^2 + 8 \times 16^1$$

Note that the right most digit is 0. That will happen ∞ often.

Weak Goodstein: Second Position

$$(980)_{16} = 9 \times 16^2 + 8 \times 16^1$$

Increase the base and subtract 1 to get

Weak Goodstein: Second Position

$$(980)_{16} = 9 \times 16^2 + 8 \times 16^1$$

Increase the base and subtract 1 to get

$$9 \times 17^2 + 8 \times 17^1 - 1 = 9 \times 17^2 + 7 \times 17^1 + 16 \times 17^0 = (97(16))_{17}$$

Weak Goodstein: Second Position

$$(980)_{16} = 9 \times 16^2 + 8 \times 16^1$$

Increase the base and subtract 1 to get

$$9 \times 17^2 + 8 \times 17^1 - 1 = 9 \times 17^2 + 7 \times 17^1 + 16 \times 17^0 = (97(16))_{17}$$

The second digit decreased!

Weak Goodstein: Second Position

$$(980)_{16} = 9 \times 16^2 + 8 \times 16^1$$

Increase the base and subtract 1 to get

$$9 \times 17^2 + 8 \times 17^1 - 1 = 9 \times 17^2 + 7 \times 17^1 + 16 \times 17^0 = (97(16))_{17}$$

The second digit decreased!

Recap and go forward:

Weak Goodstein: Second Position

$$(980)_{16} = 9 \times 16^2 + 8 \times 16^1$$

Increase the base and subtract 1 to get

$$9 \times 17^2 + 8 \times 17^1 - 1 = 9 \times 17^2 + 7 \times 17^1 + 16 \times 17^0 = (97(16))_{17}$$

The second digit decreased!

Recap and go forward:

$$(986)_{10} \rightarrow (980)_{16} \rightarrow (97(16))_{17} \rightarrow (970)_{23}$$

Weak Goodstein: Second Position

$$(980)_{16} = 9 \times 16^2 + 8 \times 16^1$$

Increase the base and subtract 1 to get

$$9 \times 17^2 + 8 \times 17^1 - 1 = 9 \times 17^2 + 7 \times 17^1 + 16 \times 17^0 = (97(16))_{17}$$

The second digit decreased!

Recap and go forward:

$$(986)_{10} \rightarrow (980)_{16} \rightarrow (97(16))_{17} \rightarrow (970)_{23}$$

$$\rightarrow (96(23))_{24} \rightarrow (960)_{47} \rightarrow (95(47))_{48}$$

Weak Goodstein: Second Position

$$(980)_{16} = 9 \times 16^2 + 8 \times 16^1$$

Increase the base and subtract 1 to get

$$9 \times 17^2 + 8 \times 17^1 - 1 = 9 \times 17^2 + 7 \times 17^1 + 16 \times 17^0 = (97(16))_{17}$$

The second digit decreased!

Recap and go forward:

$$(986)_{10} \rightarrow (980)_{16} \rightarrow (97(16))_{17} \rightarrow (970)_{23}$$

$$\rightarrow (96(23))_{24} \rightarrow (960)_{47} \rightarrow (95(47))_{48}$$

$$(95(47))_{48} \rightarrow \dots \rightarrow (900)_x$$

Weak Goodstein: Second Position

$$(900)_x = 9 \times x^2$$

Weak Goodstein: Second Position

$$(900)_x = 9 \times x^2$$

Increase base and subtract 1 to get

Weak Goodstein: Second Position

$$(900)_x = 9 \times x^2$$

Increase base and subtract 1 to get

$$9 \times (x+1)^2 - 1 = 8 \times (x+1)^2 + x(x+1)^1 + x(x+1)^0 = (8xx)x + 1$$

Weak Goodstein: Second Position

$$(900)_x = 9 \times x^2$$

Increase base and subtract 1 to get

$$9 \times (x+1)^2 - 1 = 8 \times (x+1)^2 + x(x+1)^1 + x(x+1)^0 = (8xx)_x + 1$$

$$(8xx)_{x+1} \rightarrow \cdots \rightarrow (0yy)_{y+1}$$

Weak Goodstein: Second Position

$$(900)_x = 9 \times x^2$$

Increase base and subtract 1 to get

$$9 \times (x+1)^2 - 1 = 8 \times (x+1)^2 + x(x+1)^1 + x(x+1)^0 = (8xx)_x + 1$$

$$(8xx)_{x+1} \rightarrow \cdots \rightarrow (0yy)_{y+1}$$

Now its a 2-digit number and use induction.

Why Does the Sequence Always Go To 0?

Why Does the Sequence Always Go To 0?

1. If original number is 1-digit long then it will clearly go to 0.

Why Does the Sequence Always Go To 0?

1. If original number is 1-digit long then it will clearly go to 0.
2. If the original number is L digits long then

Why Does the Sequence Always Go To 0?

1. If original number is 1-digit long then it will clearly go to 0.
2. If the original number is L digits long then
 - 2.1 The left most digit is 0 ∞ often.

Why Does the Sequence Always Go To 0?

1. If original number is 1-digit long then it will clearly go to 0.
2. If the original number is L digits long then
 - 2.1 The left most digit is 0 ∞ often.
 - 2.2 Within that the second digit is 0 ∞ often.

Why Does the Sequence Always Go To 0?

1. If original number is 1-digit long then it will clearly go to 0.
2. If the original number is L digits long then
 - 2.1 The left most digit is 0 ∞ often.
 - 2.2 Within that the second digit is 0 ∞ often.
 - 2.3 \dots within that the lead digit is eventually 0.

Why Does the Sequence Always Go To 0?

1. If original number is 1-digit long then it will clearly go to 0.
2. If the original number is L digits long then
 - 2.1 The left most digit is 0 ∞ often.
 - 2.2 Within that the second digit is 0 ∞ often.
 - 2.3 \dots within that the lead digit is eventually 0. Then the problem is an $L - 1$ digit long seq.

Why Does the Sequence Always Go To 0?

1. If original number is 1-digit long then it will clearly go to 0.
2. If the original number is L digits long then
 - 2.1 The left most digit is 0 ∞ often.
 - 2.2 Within that the second digit is 0 ∞ often.
 - 2.3 \dots within that the lead digit is eventually 0. Then the problem is an $L - 1$ digit long seq. Use Induction.

Weak Goodstein and Strong Goldstein

Weak Goodstein and Strong Goldstein

1. From what I've presented you can prove rigorously that the weak Goodstein seq always goes to 0.

Weak Goodstein and Strong Goldstein

1. From what I've presented you can prove rigorously that the weak Goodstein seq always goes to 0.
2. The proof for strong Goldstein is similar but requires some other ideas.

Weak Goodstein and Strong Goldstein

1. From what I've presented you can prove rigorously that the weak Goodstein seq always goes to 0.
2. The proof for strong Goldstein is similar but requires some other ideas.

Goodstein's Thm The strong Goodstein seq always goes to 0.

Weak Goodstein and Strong Goldstein

1. From what I've presented you can prove rigorously that the weak Goodstein seq always goes to 0.
2. The proof for strong Goldstein is similar but requires some other ideas.

Goodstein's Thm The strong Goodstein seq always goes to 0.

Do you find his theorem to be natural? This is not a VOTE since its a matter of opinion and opinion and is not well defined.

Weak Goodstein and Strong Goldstein

1. From what I've presented you can prove rigorously that the weak Goodstein seq always goes to 0.
2. The proof for strong Goldstein is similar but requires some other ideas.

Goodstein's Thm The strong Goodstein seq always goes to 0.

Do you find his theorem to be natural? This is not a VOTE since its a matter of opinion and opinion and is not well defined.

Next Slide will indicate why am asking this.

Peano Arithmetic and Godel's Inc. Thm

Peano Arithmetic (PA) is a standard system of axioms. Almost all theorems from Number Theory and combinatorics can be proven in PA.

Peano Arithmetic and Godel's Inc. Thm

Peano Arithmetic (PA) is a standard system of axioms. Almost all theorems from Number Theory and combinatorics can be proven in PA.

Godel's Inc Thm \exists statements that are TRUE but cannot be proven in PA.

Peano Arithmetic and Godel's Inc. Thm

Peano Arithmetic (PA) is a standard system of axioms. Almost all theorems from Number Theory and combinatorics can be proven in PA.

Godel's Inc Thm \exists statements that are TRUE but cannot be proven in PA.

The statements Godel obtained were **not natural**. They were designed for the whole purpose of being unprovable in PA.

Peano Arithmetic and Godel's Inc. Thm

Peano Arithmetic (PA) is a standard system of axioms. Almost all theorems from Number Theory and combinatorics can be proven in PA.

Godel's Inc Thm \exists statements that are TRUE but cannot be proven in PA.

The statements Godel obtained were **not natural**. They were designed for the whole purpose of being unprovable in PA.

The question arose: Are there Natural statements that are not provable in PA?

Peano Arithmetic and Godel's Inc. Thm

Peano Arithmetic (PA) is a standard system of axioms. Almost all theorems from Number Theory and combinatorics can be proven in PA.

Godel's Inc Thm \exists statements that are TRUE but cannot be proven in PA.

The statements Godel obtained were **not natural**. They were designed for the whole purpose of being unprovable in PA.

The question arose: Are there Natural statements that are not provable in PA?

There are a few such statements.

Peano Arithmetic and Godel's Inc. Thm

Peano Arithmetic (PA) is a standard system of axioms. Almost all theorems from Number Theory and combinatorics can be proven in PA.

Godel's Inc Thm \exists statements that are TRUE but cannot be proven in PA.

The statements Godel obtained were **not natural**. They were designed for the whole purpose of being unprovable in PA.

The question arose: Are there Natural statements that are not provable in PA?

There are a few such statements.

1. Every strong Goodstein Sequence goes to 0.

Peano Arithmetic and Godel's Inc. Thm

Peano Arithmetic (PA) is a standard system of axioms. Almost all theorems from Number Theory and combinatorics can be proven in PA.

Godel's Inc Thm \exists statements that are TRUE but cannot be proven in PA.

The statements Godel obtained were **not natural**. They were designed for the whole purpose of being unprovable in PA.

The question arose: Are there Natural statements that are not provable in PA?

There are a few such statements.

1. Every strong Goodstein Sequence goes to 0.
2. The Paris-Harrington Ramsey Thm