Extreme Parallel Computing – The Man, Machine and the Maths behind it

Dr James A.D.W. Anderson

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Agenda

- The man
- An infinitely long pipeline with no exceptions can execute any Turing computable program
- Removing exceptions by using transarithmetics
- Physical applications of transarithmetics
- Hardware implementation of transarithmetics
- It ain't infinitely long, but it is a plan to build a 2 M core pipeline in a cabinet
- Where do we go from here?

The Man

- Started working life as an experimental psychologist doing research in visual psychophysics
- Switched to computer vision
- Discovered how to divide by zero using: perspective geometry; Pythagorean properties of triangles with integral sides; Newton's Arithmetica Universalis; polar-complex arithmetic. Worked with others to produce a machine proof that transreal division by zero is consistent if real arithmetic is; unified the Turing machine with Projective and Euclidean geometries
- Switched to digital system design

Parallel versus Pipelined

- Parallel computing is hard
- Pipelined computing is easy
- Let's get massive computation the easy way!
- Pipelines are co-linear parallel computers!

Pipeline

- Turing computable calculations have finitely many steps so we can unroll any Turing computable calculation and execute it inside an infinite pipeline
- Data can be circulated from end to beginning of a pipeline so that the outermost loop does not have to be unrolled
- Practical pipelines have a finite length
- Any finite machine has a finite waiting time for any digital calculation – regardless of whether it is Turing computable or not
- All practical calculations have a finite waiting time

Pipeline

- But if an exception occurs in a Turing program the computation stalls until an Oracle has been consulted
- In practical programs the pipeline passes NaNs or stalls until user code sorts out the problem
- If we could divide by zero there would be no arithmetical exceptions
- If we Gödelise a Turing computation with an arithmetic that has no exceptions then the Turing computation has no logical exceptions
- There is an easier way – build a dataflow machine that executes transarithmetic

Waiting time

Waiting time for various 64-bit floating-point calculations:

- 21 – reciprocal
- 23 – square root
- 83 – exponential
- 2 000 – interaction of two atoms in a particular molecular dynamics application

All have a throughput of one result per clock tick

So let's divide by zero …

A Word of Comfort

- Dividing by zero is no more mysterious than finding the square root of a negative number
- Transreal arithmetic divides by zero using only accepted algorithms of arithmetic – you already know how to divide by zero
- There is a machine proof that transreal arithmetic is consistent if real arithmetic is
- Every real result of mathematics stays the same, but there are some new non-finite results
- You can try out an implementation of transcomplex arithmetic

Can Calculators Divide by Zero?

- If you have an electronic calculator with you then turn it on and stand up
- Pick a number and divide it by zero on your calculator
- If your calculator shows an error or has crashed then sit down
- If your calculator is still working then multiply the current answer by zero
- If your calculator shows an error or has crashed then sit down
- Is there anyone left standing?

Can Computers Divide by Zero?

- My laptop can divide by zero. My FPGA model of a transreal computer can divide by zero. All of the PCs I have retrofitted with these arithmetics can divide by zero: trans-signed-integer, trans-two's-complement, transfloating-point, transreal, transcomplex

- Computers executing integer arithmetic cannot divide by zero

- Computers executing IEEE floating-point arithmetic cannot always divide by zero. They can produce infinities, but they also produce a class of objects that are all Not a Number (NaN)

Can Computers Divide by Zero?

- The bridge of the missile cruiser, USS Yorktown, had networked computer control of navigation, engine monitoring, fuel control, machinery control, and damage control

Can Computers Divide by Zero?

- On September 21st, 1997, a sailor on the USS Yorktown entered a zero into a database field, causing a division by zero error which cascaded through the ship's network, crashing every computer on the network, and leaving the ship dead in the water for 2 hours 45 minutes
- The world would be a safer place if computers, calculators and people could divide numbers by zero, getting a number as an answer
- Coincidentally, I worked out how to do this in 1997

Complex Numbers

People used to believe that it is impossible to find the square root of a negative number

- $\sqrt{-4} = ?$
- $2 \times 2 = 4$
- $(-2) \times (-2) = 4$

Complex Numbers

- Invent a new number $i = j = \sqrt{-1}$
- Use only accepted algorithms of arithmetic
- BUT change the way the algorithms are applied by making addition non-absorptive, i.e. keep real and imaginary sums separate

Complex Numbers

- For example, complex multiplication is defined by:

$$\begin{aligned}(a+ib)(c+id) &= a(c+id)+ib(c+id)\\ &= ac+iad+ibc+i^2bd\\ &= ac+iad+ibc+(-1)bd\\ &= (ac-bd)+i(ad+bc)\\ &= k_1+ik_2\end{aligned}$$

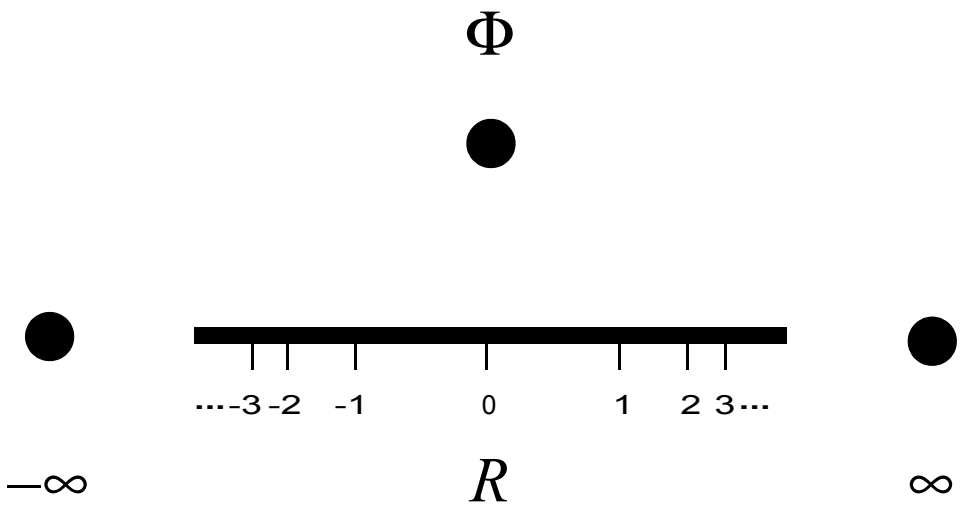
- Now $i2 \times i2 = i^2 4 = -1 \times 4 = -4$ so $\sqrt{-4} = i2$

Transreal Numbers

Invent some new numbers. For all $k > 0$ we define:

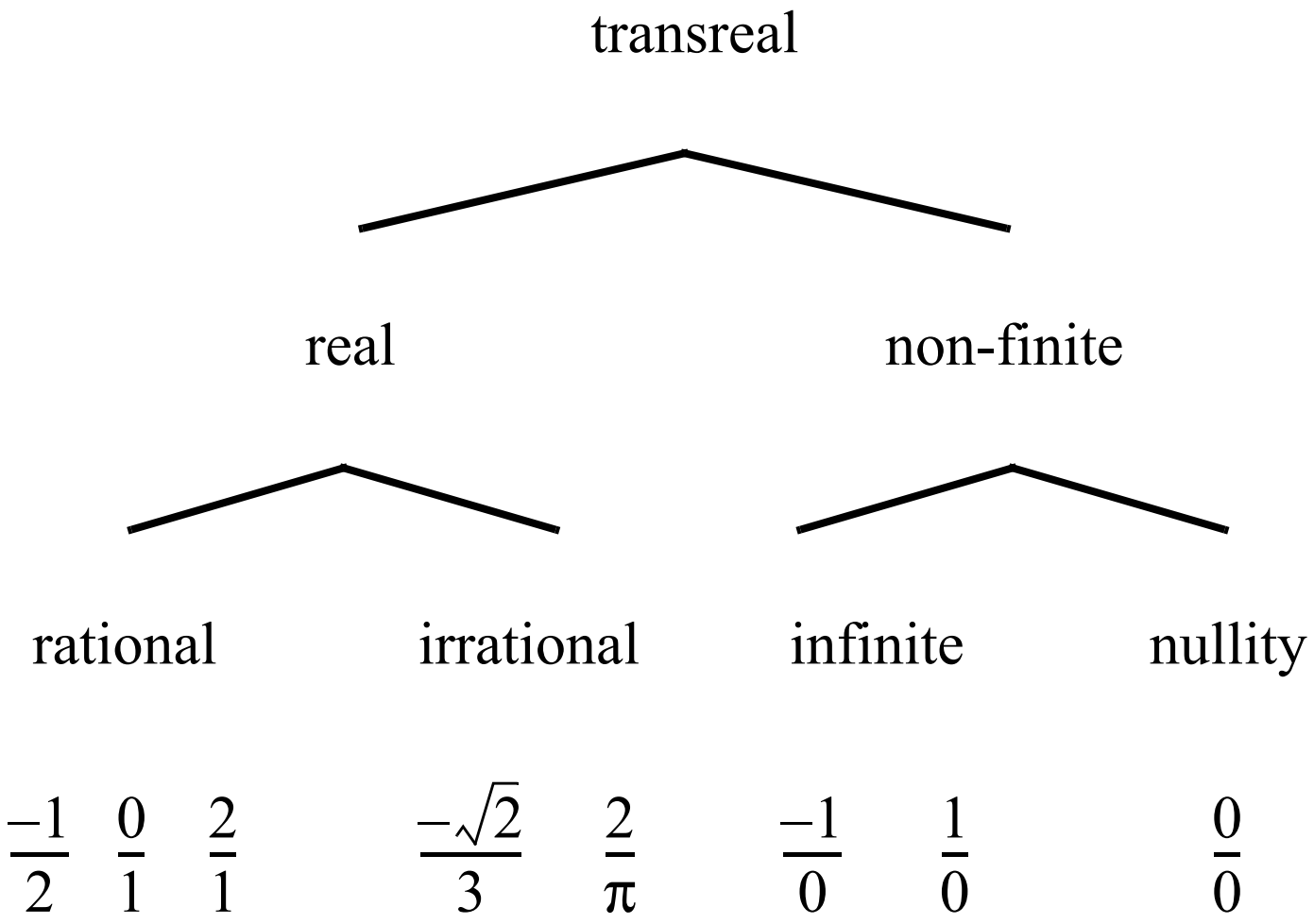
- $\infty = \frac{1}{0} \equiv \frac{k}{0}$
- $\Phi = \frac{0}{0}$
- $-\infty = \frac{-1}{0} \equiv \frac{-k}{0}$
- $0 = \frac{0}{1} \equiv \frac{0}{k} \equiv \frac{0}{-k}$

Transreal Numbers



- Positive infinity, ∞, is the biggest transreal number
- Negative infinity, −∞, is the smallest transreal number
- Nullity, Φ, is the only transreal number that is not negative, not zero, and not positive

Transreal Numbers



Transreal Fractions

A *transreal number* is a *transreal fraction* of the form $\frac{n}{d}$, where:

- n is the *numerator* of the fraction
- d is the *denominator* of the fraction
- n, d are *real numbers*
- $d \geq 0$
- Fractions with non-finite components simplify to the above form

Transreal Fractions

- An *improper transreal fraction,* $\frac{n}{-d}$, may have a negative denominator, $-d < 0$

- An improper transreal fraction is converted to a *proper transreal fraction* by multiplying both the numerator and denominator by minus one; or by negating both the numerator and the denominator, using subtraction; or it can be done, lexically, by moving the minus sign from the denominator to the numerator

$$\frac{n}{-d} = \frac{-1 \times n}{-1 \times (-d)} = \frac{-n}{-(-d)} = \frac{-n}{d}$$

Transreal Fractions

- Example: $\frac{2}{-3} = \frac{-1 \times 2}{-1 \times (-3)} = \frac{-2}{3}$
- Example: $\frac{0}{-1} = \frac{-0}{-(-1)} = \frac{0}{1}$
- Example: $\frac{x}{-y} = \begin{cases} \frac{x}{y} & : y = 0 \\ \frac{-x}{y} & : \text{otherwise} \end{cases}$

Transreal Multiplication

Two *proper transreal fractions* are multiplied like this:

- $\frac{a}{b} \times \frac{c}{d} = \frac{a \times c}{b \times d}$

- Example: $3 \times \infty = \frac{3}{1} \times \frac{1}{0} = \frac{3 \times 1}{1 \times 0} = \frac{3}{0} = \infty$

- Example: $0 \times \infty = \frac{0}{1} \times \frac{1}{0} = \frac{0 \times 1}{1 \times 0} = \frac{0}{0} = \Phi$

- Example: $\frac{1}{2} \times \frac{3}{5} = \frac{1 \times 3}{2 \times 5} = \frac{3}{10}$

Transreal Division

Two *proper transreal fractions* are divided like this:

- $$\frac{a}{b} \div \frac{c}{d} = \frac{a}{b} \times \frac{d}{c}$$

- Example: $$\infty \div 3 = \frac{1}{0} \div \frac{3}{1} = \frac{1}{0} \times \frac{1}{3} = \frac{1 \times 1}{0 \times 3} = \frac{1}{0} = \infty$$

- Example:

$$\infty \div (-3) = \frac{1}{0} \div \frac{-3}{1} = \frac{1}{0} \times \frac{1}{-3} = \frac{1}{0} \times \frac{-1 \times 1}{-1 \times (-3)}$$

$$= \frac{1}{0} \times \frac{-1}{3} = \frac{1 \times (-1)}{0 \times 3} = \frac{-1}{0} = -\infty$$

Transreal Division

- Example: $\frac{1}{2} \div \frac{5}{3} = \frac{1}{2} \times \frac{3}{5} = \frac{1 \times 3}{2 \times 5} = \frac{3}{10}$

Transreal Addition

Two *proper transreal fractions* are added like this:

- $\frac{a}{b} + \frac{c}{d} = \frac{ad + bc}{bd}$, except that:

- $(\pm\infty) + (\pm\infty) = \frac{\pm 1}{0} + \frac{\pm 1}{0} = \frac{(\pm 1) + (\pm 1)}{0}$ with the signs of $\pm$ chosen independently

Transreal Addition

- $(\pm\infty) + (\pm\infty) = \frac{\pm 1}{0} + \frac{\pm 1}{0} = \frac{(\pm 1) + (\pm 1)}{0}$

Examples:

- $\infty + \infty = \frac{1}{0} + \frac{1}{0} = \frac{1 + 1}{0} = \frac{2}{0} = \infty$
- $(-\infty) + (-\infty) = \frac{-1}{0} + \frac{-1}{0} = \frac{(-1) + (-1)}{0} = \frac{-2}{0} = -\infty$
- $\infty + (-\infty) = \frac{1}{0} + \frac{-1}{0} = \frac{1 + (-1)}{0} = \frac{0}{0} = \Phi$

Transreal Addition

- $\frac{a}{b} + \frac{c}{d} = \frac{ad + bc}{bd}$

Examples:

- $\frac{2}{3} + \infty = \frac{2}{3} + \frac{1}{0} = \frac{2 \times 0 + 3 \times 1}{3 \times 0} = \frac{3}{0} = \infty$
- $\frac{2}{3} + \Phi = \frac{2}{3} + \frac{0}{0} = \frac{2 \times 0 + 3 \times 0}{3 \times 0} = \frac{0}{0} = \Phi$
- $\frac{2}{3} + \frac{4}{5} = \frac{2 \times 5 + 3 \times 4}{3 \times 5} = \frac{22}{15}$

Transreal Subtraction

Two *proper transreal fractions* are subtracted like this:

- $$\frac{a}{b} - \frac{c}{d} = \frac{a}{b} + \frac{-c}{d}$$

Examples:

- $$\infty - \infty = \frac{1}{0} - \frac{1}{0} = \frac{1}{0} + \frac{-1}{0} = \frac{1 + (-1)}{0} = \frac{1 - 1}{0} = \frac{0}{0} = \Phi$$

- $$\frac{1}{2} - \frac{3}{5} = \frac{1}{2} + \frac{-3}{5} = \frac{(1 \times 5) + (2 \times (-3))}{2 \times 5} = \frac{5 + (-6)}{10} = \frac{-1}{10}$$

Transreal Arithmetic

- Transreal arithmetic is a superset of real arithmetic
- Transreal arithmetic is *total* – every operation of transreal arithmetic can be applied to any transreal numbers with the result being a transreal number
- Real arithmetic is *partial* – it fails on division by zero and on each of the infinitely many mathematical consequences of division by zero

Transreal Associativity

Transreal arithmetic is totally associative over addition and multiplication:

- $a + (b + c) = (a + b) + c$
- $a \times (b \times c) = (a \times b) \times c$

Transreal Commutativity

Transreal arithmetic is totally commutative over addition and multiplication:

- $a + b = b + a$
- $a \times b = b \times a$

Transreal Distributivity

Transreal arithmetic is only partially distributive:

$$a \times (b + c) = (a \times b) + (a \times c)$$

- If a is finite or nullity then a distributes over any $b + c$
- If a is infinity or minus infinity then a distributes if $b + c = \Phi$ or $b + c = 0$ or b and c have the same sign
- Two numbers have the same sign if they are both positive, both negative, both zero, or both nullity

Transreal Distributivity

Despite the fact that transreal arithmetic is only partially distributive, it is still a total arithmetic because we can always evaluate any arithmetical expression, including both of:

- $a \times (b + c)$
- $(a \times b) + (a \times c)$

It's just that these two expressions might, or might not, be equal!

- Computational paths generally bifurcate into a distributive and a non-distributive branch

Moral

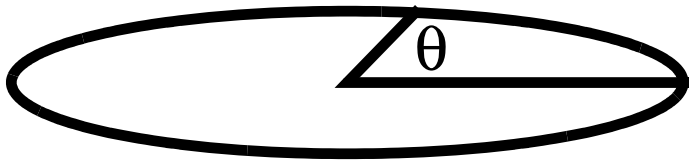
- The arithmetic you have just seen has been taught to 12 year old children in England
- These children understand infinity and nullity
- These children use an arithmetic that never fails
- What do you want for your children?
- What do you want for your computers?
- What do you want for your self?

Advantages for Computing!

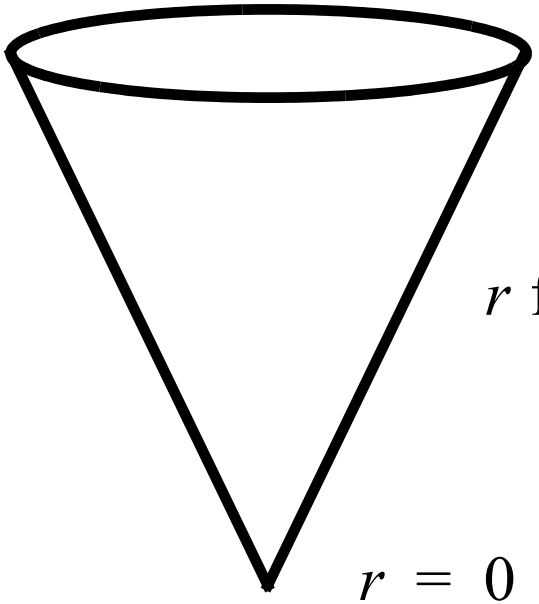
- All mathematical software can be extended to use transreal or transcomplex numbers
- Transcomplex numbers are polar-complex numbers where the radius and angle are transreal, but all of the arithmetical operations are continuous in the complex plane, without using Riemann surfaces or cuts
- Transcomplex numbers are bijective with the points in the union of an extended-real cone and a non-negative transreal axle at angle nullity – the top and whip!

Top and Whip

θ finite



$r = \infty$



r finite

$r = 0$

$\theta = \Phi$

- $r = \Phi$
- $r = \infty$

r finite

$r = 0$

Advantages for Computing!

Every syntactically correct transarithmetical expression is semantically correct when overflow rounds to an inexact infinity and underflow rounds to an inexact zero

- Compilers can perform full type checking
- There are no arithmetical run-time errors
- Any Turing program, whether Turing computable or not, can be executed without any logical run-time errors
- Sufficiently wide pipelines accommodate branching and never break

Advantages for Computing!

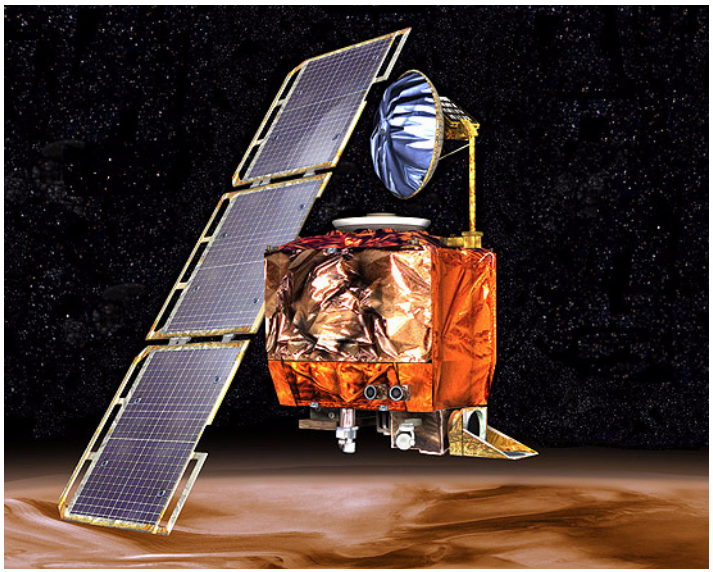
- If the waiting time of the body of the outermost loop is known then the entire program can be pipelined
- Transreal arithmetic removes an intrinsic bug from two's complement arithmetic, making both hardware and software safer, and removing a source of bias from signal processing and inertial navigation
- Floating-point hardware can have all wasted states re-allocated to transreal numbers, thereby improving arithmetical range or precision
- Floating-point hardware and software can have simplified ordering operations and exceptions making them simpler, safer, and faster

Advantages for Computing!

- It is possible to remove all exceptions from floating-point hardware by reserving an inexact flag in the number representation and by knowing the rounding mode

Mars

- NASA's Climate Orbiter, which cost $125 M, crashed into the surface of Mars on 23 September, 1999, because a computer program mixed up foot-pound-second units with metre-kilogram-second units



- "People sometimes make errors," Edward Weiler, NASA's Associate Administrator for Space Science

Mars

- This bug could have been caught if the compiler had used dimensional analysis
- All ordinary type checking and ordinary dimensional analysis fail on division by zero – collapsing to a bottom state
- But all syntactically correct sentences of transarithmetic are semantically correct – which means that a compiler can always check, or generate code to check, every possible evaluation of the transarithmetic in any program
- How much would NASA pay for a compiler that can always apply dimensional analysis?

Mars

- Would NASA pay more for a compiler that implements physical units so that arithmetic is more accurate?

Cosmology

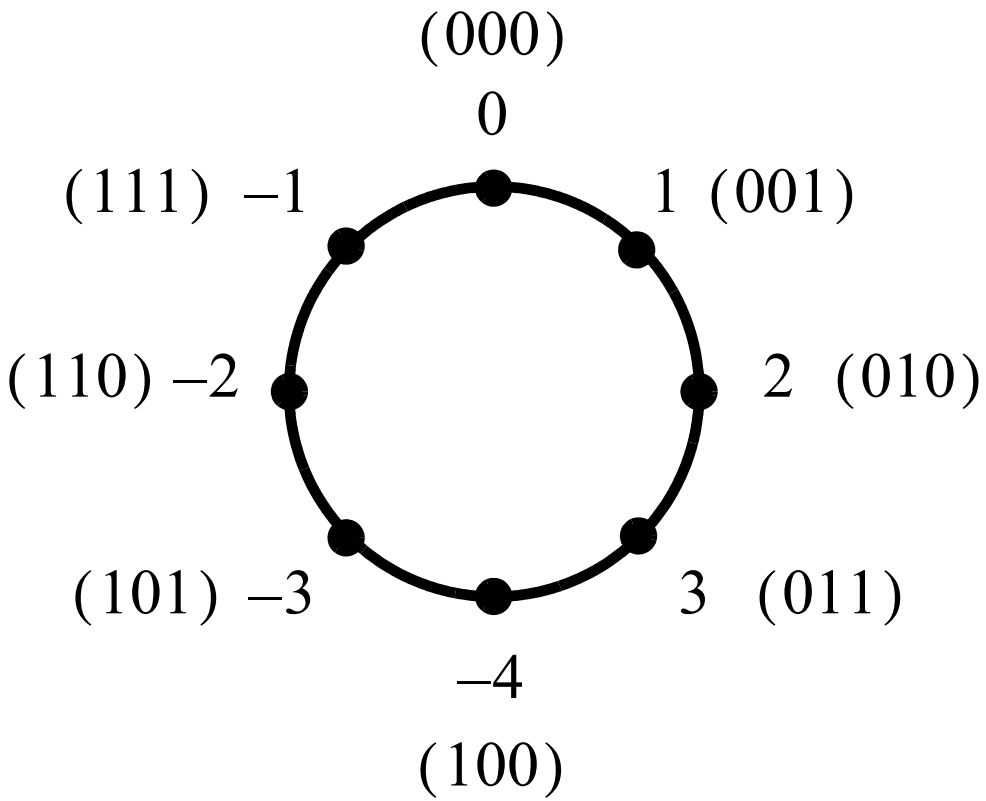
- If every action has an equal and opposite reaction then the nett momentum of the universe is zero or nullity, i.e. non-infinite, but nullity lies outside the real universe so the real part of the universe has a nett momentum of zero

- Hence moving real particles can be created from an initial zero

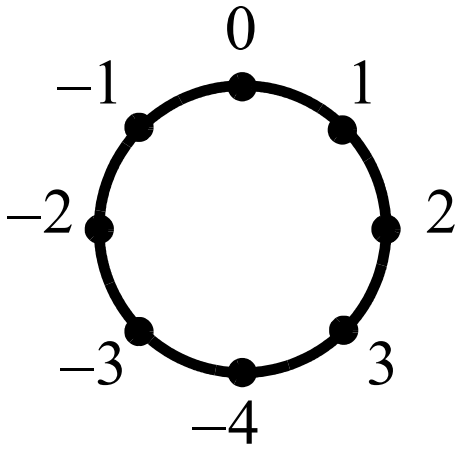
Cosmology

- Real particles at a nullity singularity are bound by a zero force, but a perturbation from zero can allow a particle to escape the singularity, e.g. by inflation
- Hence all universes that are created with opposite charges and expand from a nullity singularity have a stochastic motion of particles, e.g. a wave function
- All physical functions can be evaluated exactly at a singularity, but it is an open question whether they can be evaluated asymptotically close to a singularity
- If space and/or time is discrete (quantal) then all physical functions can be evaluated everywhere

Two's Complement

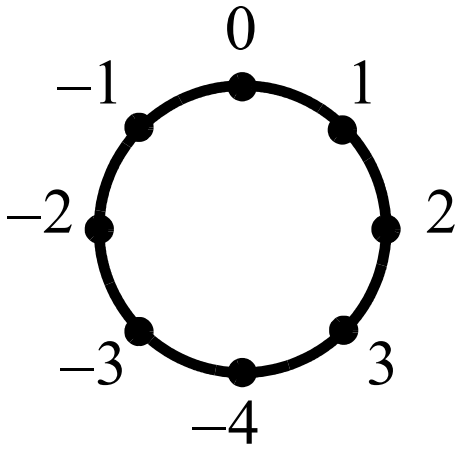


Two's Complement



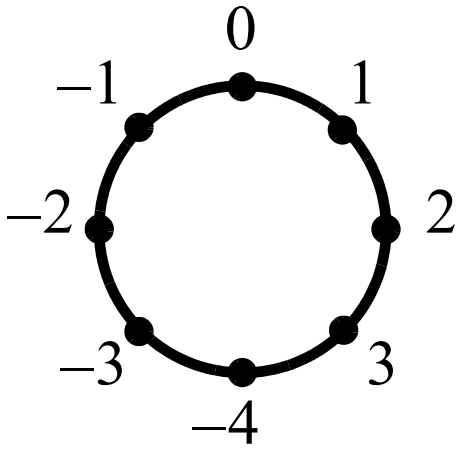
- Having one more negative number than positive numbers biases arithmetic in the negative direction
- This can be a serious problem in signal processing and inertial navigation

Two's Complement



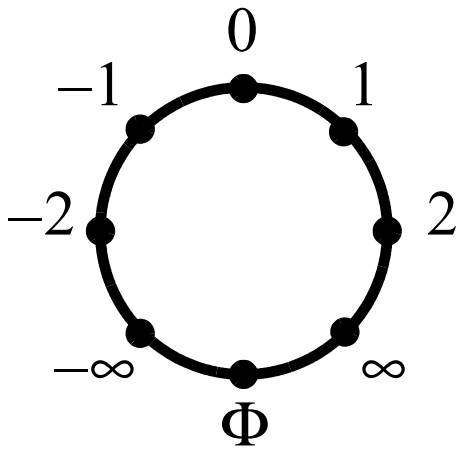
- Incrementing the most positive number produces the most negative number: 3 + 1 = –4
- Similarly – 4 – 1 = 3
- Computers with saturated arithmetic do not suffer wrap-around errors – but very few computers use saturated arithmetic

Two's Complement



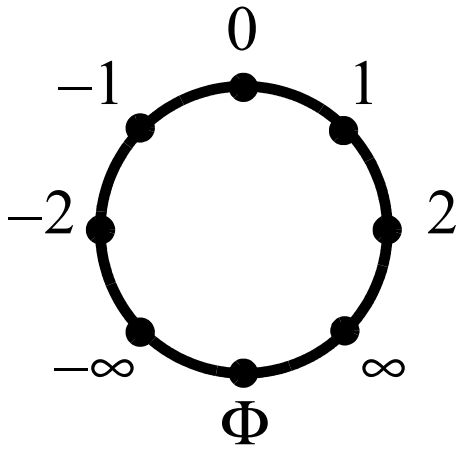
- The complement of the most negative number is not its negation: –(–4) = –4
- Almost every computer suffers this weird-number fault

Trans Two's Complement



- By having equal numbers of positive and negative numbers the bias is removed
- This either has no effect on, or else improves, all signal processing and inertial navigation systems

Trans Two's Complement

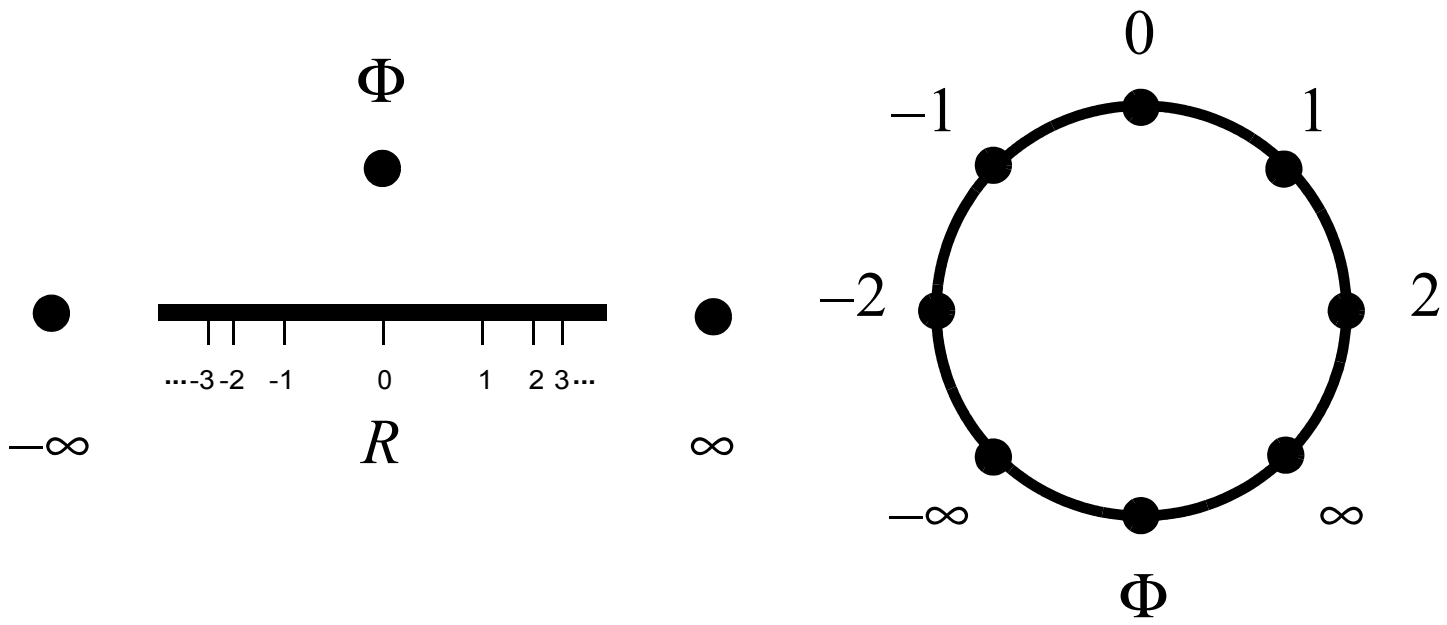


- By saturating at signed infinities, the complement of the most negative number is now its negation
  $-(-\infty) = \infty$ and there are no wrap-around errors

- And the complement of nullity is its negation $-\Phi = \Phi$

Trans Two's Complement

- Trans two's complement removes bias, wrap-around errors and the weird-number fault, and it preserves the topology of the transreal numbers



Trans Two's Complement

- Trans two's complement gives transinteger and transfixed-point programming superior exception handling to ordinary floating-point arithmetic – transinteger leapfrogs float

- The topology of transreal numbers extends to floating-point arithmetic so that it can match, and exceed, the exception handling of transinteger and transfixed arithmetic by using its rounding modes – transfloat leapfrogs transinteger

Trans Two's Complement

- But we can upgrade all computer arithmetics by encoding an inexact flag in all number formats and by having common rounding modes so that all arithmetics have the same high quality exception handling – the frog turns into a prince!

Trans Sign-Bit Arithmetic

- Sign-bit set describes negative, clear non-negative
- The arithmetic saturates so that all bits set in the magnitude describes infinity. The sign-bit gives the sign of the infinity
- Sign-bit clear on all magnitude bits clear describes zero
- Sign-bit set on all magnitude bits clear describes nullity
- Exact-bit set describes exact solution, clear inexact

Floating-Point

- IEEE 754 defines floating point numbers in terms of three of bit fields that encode the Sign (S), Exponent (E) and Mantissa (M)

- In general, a floating point number $n = -1^{S} 2^{E} M$, but bit patterns are reserved for –0, –∞, ∞, NaN_i where $i = 2^{m+1} - 2$ with m being the number of bits explicitly represented in the mantissa. The "+1" arises from the sign bit and the "–2" from –∞ and +∞

- IEEE arithmetic encodes –0, but –0 does not occur in transreal arithmetic so transfloating-point arithmetic reallocates the binary code for –0 to Φ

Floating-Point

- Nullity now lies in the middle of the lexical collation range of floating-point numbers so sorting routines must handle the unique nullity as a special case (IEEE sorting routines must handle all NaNs as special cases)
- Notice that IEEE arithmetic collates numbers with the negative numbers reversed because S is the most significant bit and $S = 1$ encodes negative numbers
- IEEE arithmetic uses this collation so that the binary codes for integer zero and floating-point positive-zero are identical. As many computers have a fast integer test zero instruction this makes positive-zero floating-point comparisons quick

Floating-Point

- Transfloating-point arithmetic uses the most positive binary code for ∞ and the most negative binary code for –∞

- IEEE arithmetic has $2^{m+1} - 2$ NaNs, but transreal arithmetic has no NaNs so all of these states can be reallocated to real numbers

- Taking the reallocated codes as signed numbers means that there are $2^m - 1$ new mantissas. This is almost one binade: $2^m - 1$ bit patterns in a near binade as against 2^m bit patterns in an entire binade

Floating-Point

- Leaving the exponent bias unchanged takes this near binade with a positive exponent so as to almost double the arithmetical range of the real floating-point numbers
- Incrementing the bias takes this near binade with a positive exponent, but frees up an entire binade with a negative exponent, thereby increasing precision by delaying underflow to denormal numbers
- Only one of these options can be taken in one thread: either increase the range or else increase the precision

Floating-Point

Name	Common Name	m	Wasted NaN States
binary16	half precision	10	2 046
binary32	single precision	23	16 777 214
binary64	double precision	52	9 007 199 254 740 990
binary128	quadruple precision	112	10 384 593 717 069 655 257 060 992 658 440 190

Floating-Point

- The IEEE standard defines four relational operations: *less-than* (<), *equal* (=), *greater-than* (>), *unordered* (?)
- Transreal arithmetic defines three relational operations: *less-than* (<), *equal* (=), *greater-than* (>)

Floating-Point

- The IEEE standard defines 14 composite relations:
  =, ?<>, >, >=, <, <=, ?, <>, <=>, ?>, ?>=, ?<, ?<=, ?=
- The IEEE standard defines negations of 12 out of 14 of the composite relations:
  NOT(>), NOT(>=), NOT(<), NOT(<=), NOT(?),
  NOT(<>), NOT(<=>), NOT(?>), NOT(?>=),
  NOT(?<), NOT(?<=), NOT(?=)
- I have never seen a computer language that supports all of these 26 composite relations with 26 relational operators

Floating-Point

- Transreal arithmetic supports 7 composite relations:
  =, >, >=, <, <=, <>, <=>
- Transreal arithmetic supports negations of all of the composite relations:
  !=, !>, !>=, !<, !<=, !<>, !<=>
- Transreal arithmetic preserves symmetry (orthogonality) of negation that the IEEE standard breaks, this makes it easier to program with transreal numbers

Floating-Point

- 12 of the IEEE relations can raise an exception:
  >, >=, <, <=, <>, <=>, NOT(>), NOT(>=), NOT(<), NOT(<=), NOT(<>), NOT(<=>)
- Specifically, all of the relations that do not contain the predicate *unordered* can raise an exception on NaN
- None of the transreal relations can raise an exception so it is easier and safer to program with transreal numbers

Floating-Point

- The IEEE standard defines that $\mathrm{NaN}_i \neq \mathrm{NaN}_j$ so that it is false that $x = x$ for some floating-point objects, x
- The above breaks a cultural stereotype that everything is equal to itself and destroys equality in mathematical physics so that mathematical physics does not work with NaN

Floating-Point

- Transreal arithmetic has $x = x$ for all transreal numbers, x
- The above preserves a cultural stereotype that everything is equal to itself and maintains equality in mathematical physics

High Performance Computing

I have designed a new computer architecture and I have built a team to design, manufacture, test, and sell it!

- Pass tokens on a pipeline so that all cores can simultaneously receive and transmit tokens in every direction with zero Input/Output (I/O) latency
- Hold all working memory on-chip, thereby accessing memory at processor speeds
- Run I/O from every edge of the chip with zero latency so that there is no memory wall

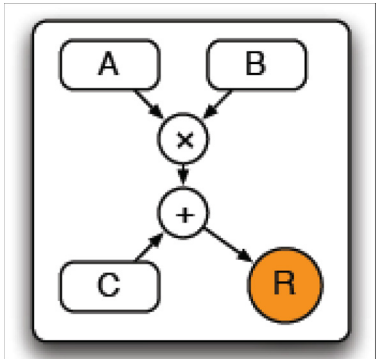
High Performance Computing

Hardware layouts say we can achieve:

- Order 10 k double-precision floating-point cores on a chip
- Order 10 kW per PFLOP of double-precision floating-point arithmetic

High Performance Computing

- The only arithmetical operation is $A \times B + C \rightarrow R$:



High Performance Computing

- All other arithmetical operations are synthesised from this one, because fabricating them would waste space in most of the processors on a chip
- The floating-point chip also has one non-arithmetical operation

High Performance Computing

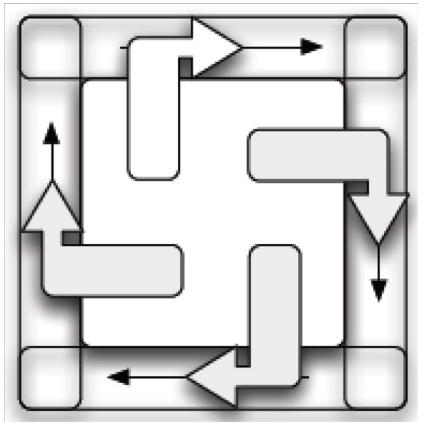
Fetchless architecture:

- Minimises circuitry
- Reduces on-chip fetch-latency to zero

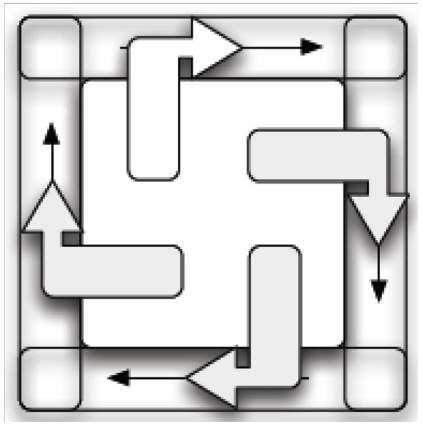
Achieved by token passing

High Performance Computing

- Tokens transmitted, conditionally on the sign of $A \times B + C \rightarrow R$, through every edge of the square processor and internally (Grey arrow blocked, white transmitted)

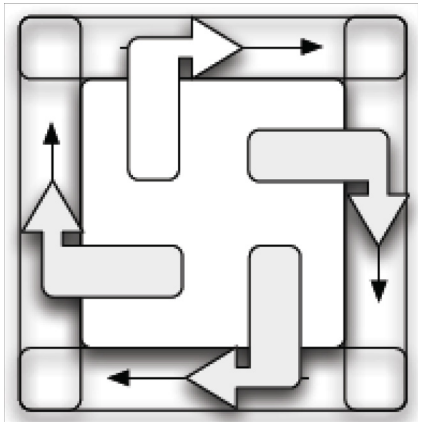


High Performance Computing



- There are four signs – negative, zero, positive, nullity – encoded in two sign bits so all selectors are maximally efficient

High Performance Computing



- If desired, each of the four separate signs can transmit a token in a different direction

High Performance Computing

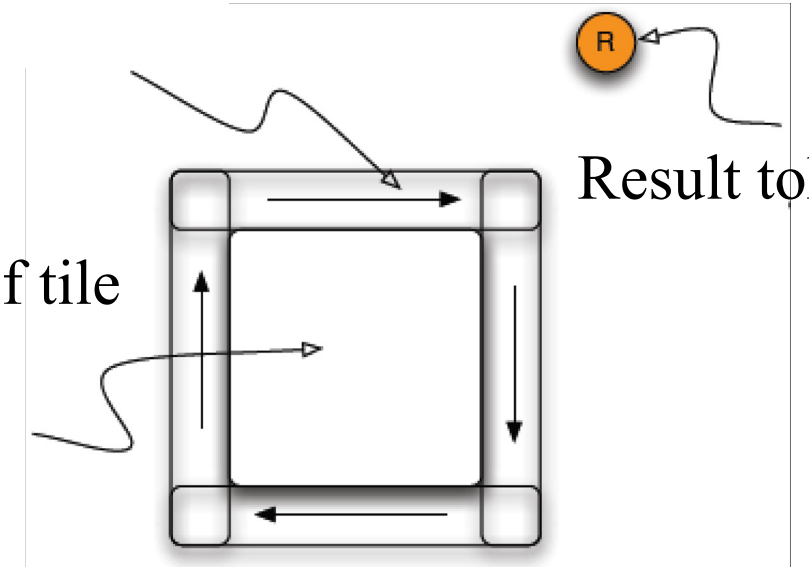
There are no arithmetical error states so:

- There is no arithmetical error handling circuitry on a processor
- Program execution is more secure

Core Tile

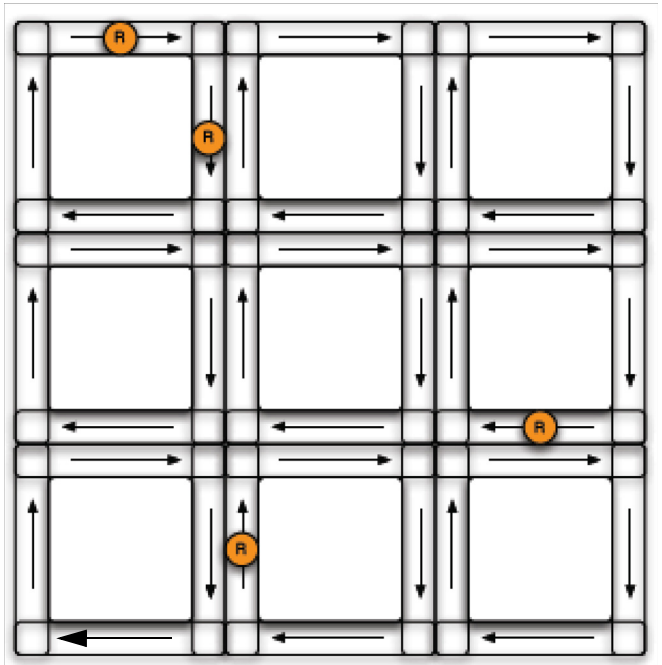
Pipeline
N, S, E, W

Processor in centre of tile



Result token

Pipeline

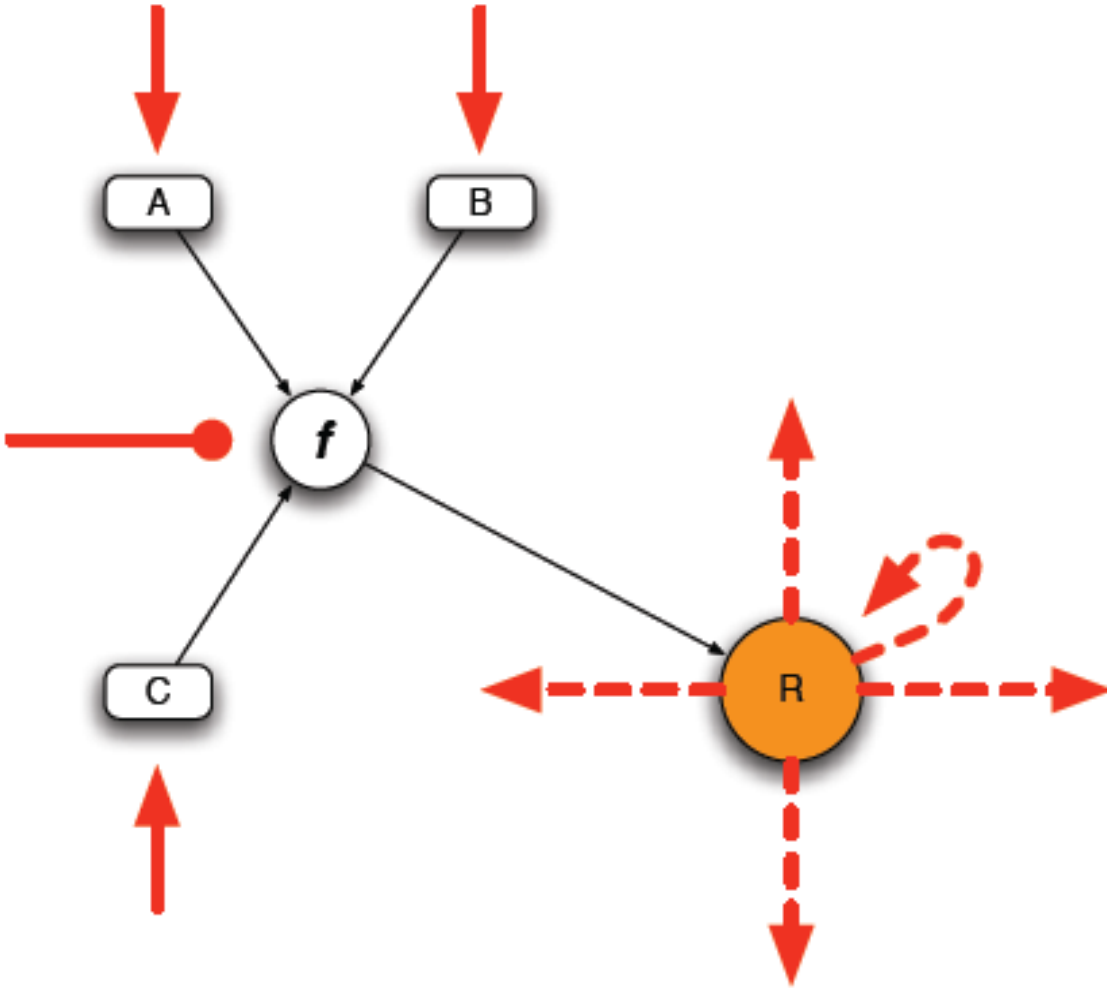


- Pipeline emerges from the processor tiles

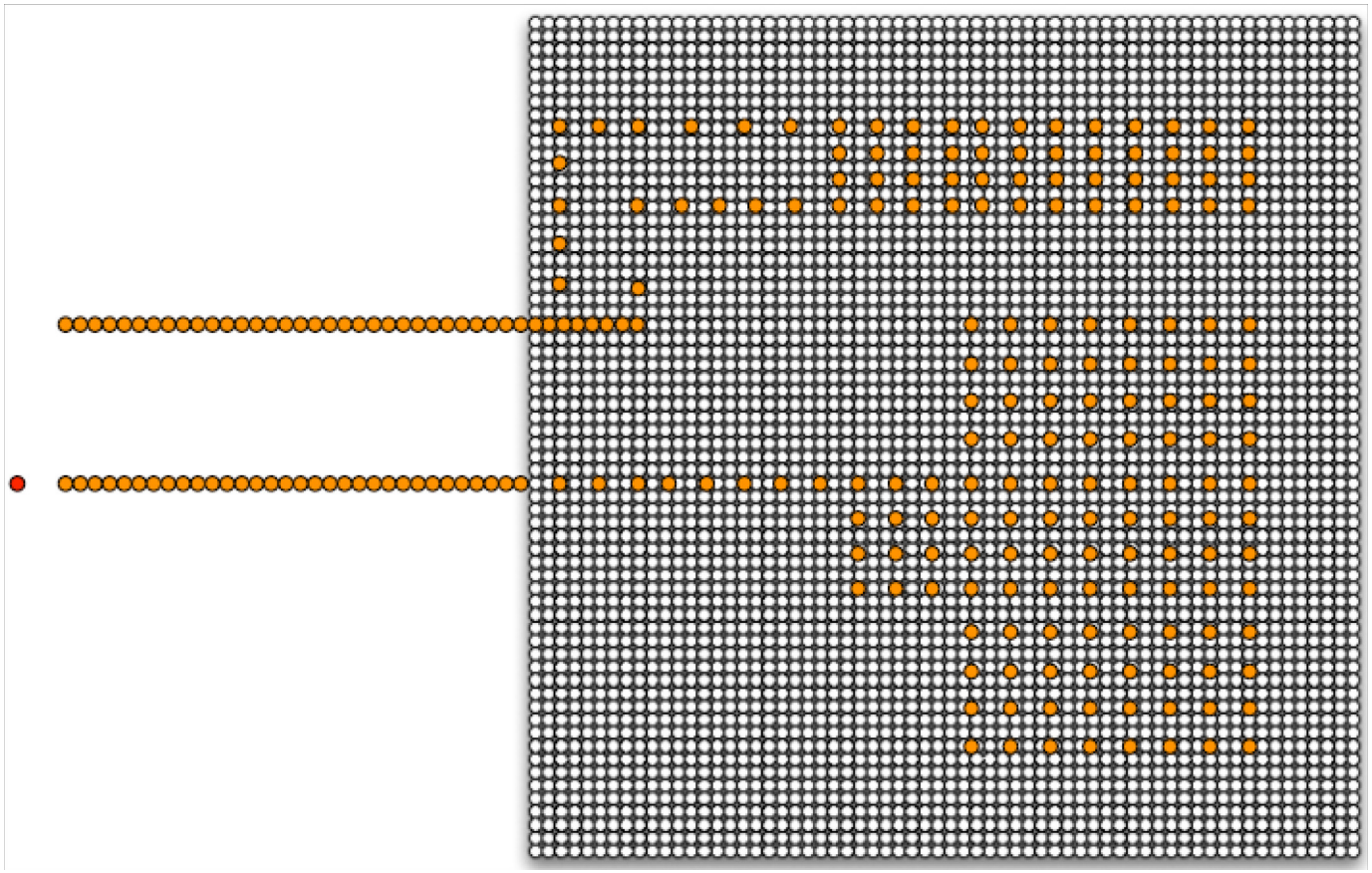
Pipeline

- Every core can simultaneously read from and write to the pipeline on every processor clock cycle with zero latency

Programming: an Army of Ants



Programming: Initial Orders



Programming: Is it Possible?

We have programmed these machines:

- Emulated a Turing complete machine
- Eliminated race conditions by using a single thread
- Eliminated race conditions by travel-time inequalities
- Implemented fully pipelined, mathematical functions with a throughput of one result per clock tick, and a latency down to half that of the Itanium 2 on: reciprocal, reciprocal square root, square root, exponential

Programming: Is it Possible?

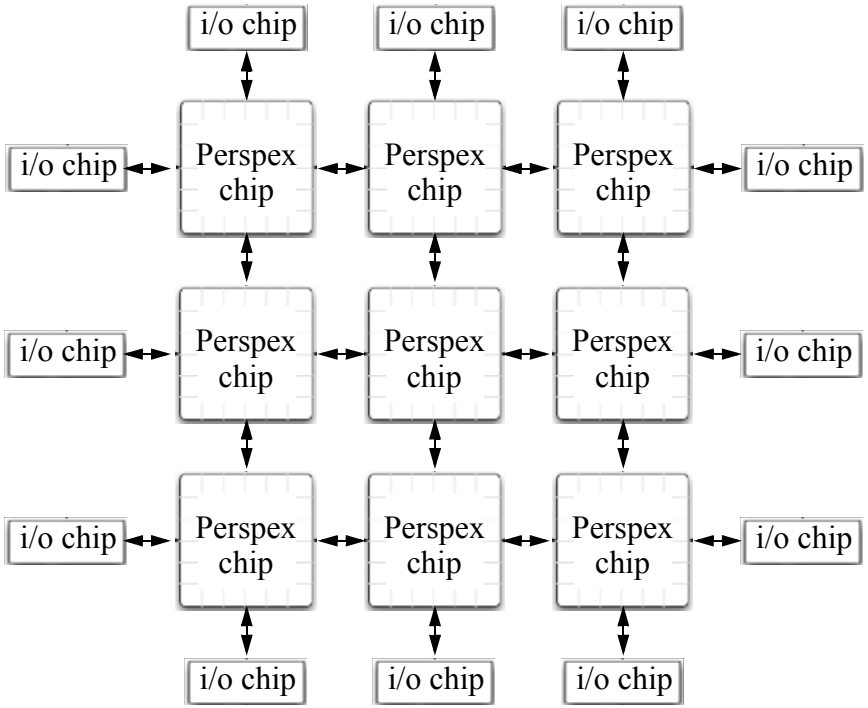
- Pipelines do not break on branches, they just tee-off in some city-block direction within the 2D surface of a chip
- Non-recursive subroutines have call and return implemented by branching so when they are in-lined they do not break pipelines
- Multiple calling points for a single subroutine introduce bubbles in each pipeline, and may break the pipeline – but code replication prevents this
- Loops force pipeline data into blocks of a size that will fit inside the loop, this breaks the pipeline unless the machine is huge or the problem is small

Compilation

- General compilation is straightforward, but uses our high performance computer as a co-processor
- Compilation via single assignment (functional programming) is attractive because of pipelining
- Systolic programming is highly applicable, but with a different I/O model
- Pipeline programming is highly applicable

I/O

- Chips can be tiled together with one pipeline input and one pipeline output per edge of the chip, each running at 250 M Tokens Per Second



I/O

- Chips have an address horizon, not an address space, so arbitrarily many chips can be tiled together
- Hence the performance of the architecture scales linearly

Performance

The current specification of the chip has:

- Order 10 k cores
- Cores clocked at 250 MHz
- 4 input channels, and 4 output channels, each running at 250 M Tokens Per Second
- Power consumption of order 10 kW per PFLOP

Performance

- We have implemented conventional programs
- We have implemented systolic programs
- We have implemented pipelined programs
- We get better pipeline latencies than other architectures
- We get better pipeline throughput than other architectures
- We can sometimes match, but can never beat, systolic architectures

Performance

- It is not practical to implement *programmable* systolic arrays in ASIC, but our chip is a viable alternative
- Compiling by travel-time inequalities builds in some robustness to asynchronous operation of the array of processors
- Asynchronicity can be built into the array to smooth power usage
- Our power consumption is of order 1% of competing architectures

Offer

- We plan to sell high performance computers at 5 M US Dollars (USD) per PFLOP, in the fourth year after funding a start-up company
- We offer a discount of two, 1 PFLOP machines for 5 M USD for anyone willing to make staged payments of one third on contract, one third on tape out, and one third on delivery
- We plan to accept discounted orders for 5 to 10 PFLOPs
- If the project fails, we will return all unspent monies – this spreads the risk between early adopters

The Future

- Transmathematics and its application to transphysics will develop slowly
- Transcomputation can deliver benefits now
- The first company to sell a trans-floating-point chip will kill its competition on marketing strengths: more precision for the same bits and astronomically fewer error states
- The first company to deliver massively pipelined transreal computers will transform the market for high performance computing, signal processing, cryptanalysis, and so on …

The Future

- What would you do with a 1 PFLOP machine that fits in your spare bedroom and runs on your domestic electricity supply?