Code Constructor User Tool

supported by

- Canadian Foundation for Innovation
- Ontario Innovation Trust (?!)
- Apple Canada
- McMaster University

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3 years Medical Electronics Industry

- 4 patents + 2 pending
- real-time, parallel MRI,
  - rack of PPC604/750s
- best result: 1000X performance
  - mathematical transformation
  - efficient implementation

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HOPS

- term-graph-based
  - program transformation
  - code generation
- derivation of correct programs
- functional programming
- relation-algebraic methods

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- targeting numerical code
  - signal processing
  - image processing
  - math libraries

- goals
  - more reliable
  - faster

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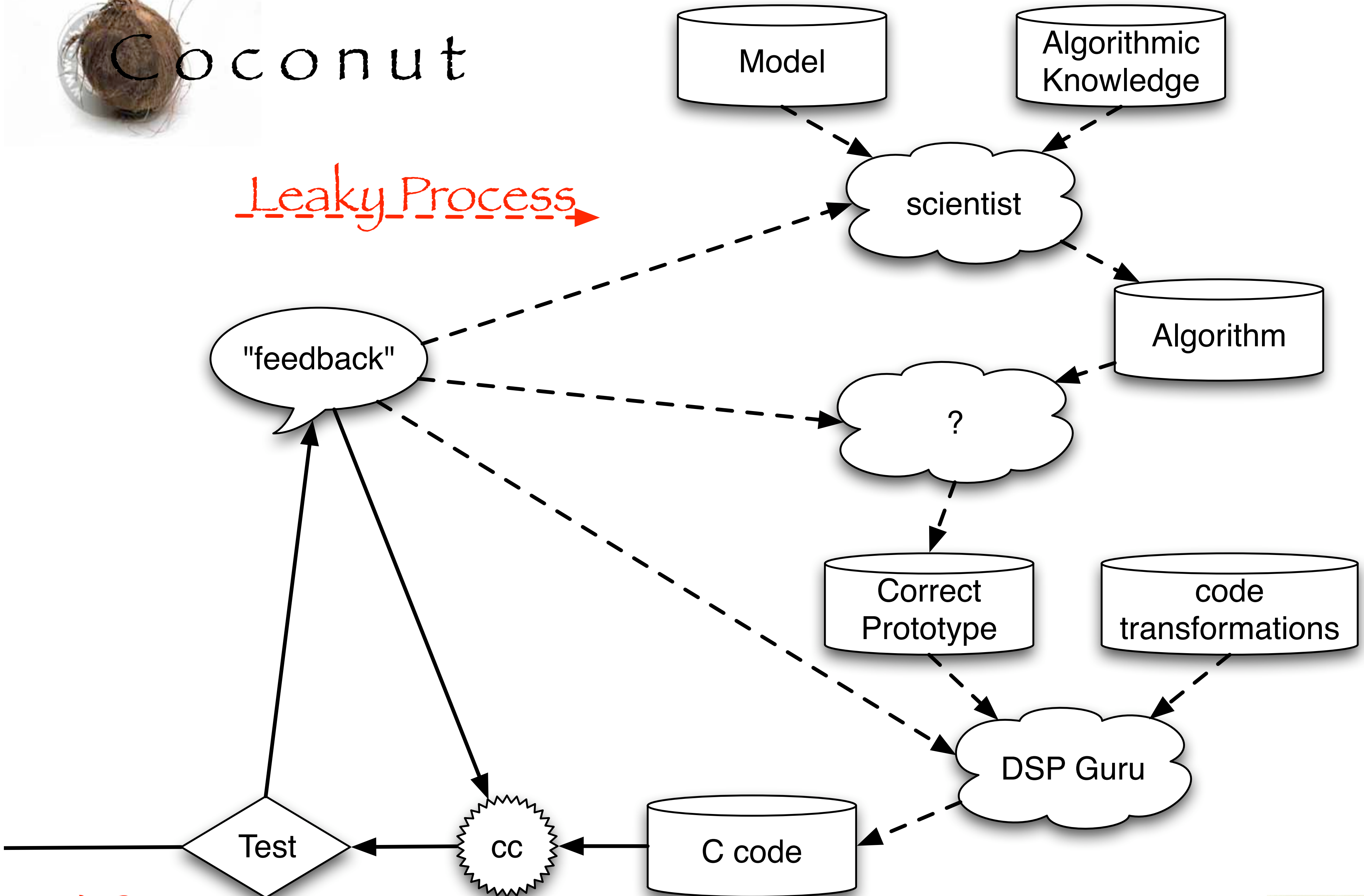
Leaky Process



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Plug leaks!

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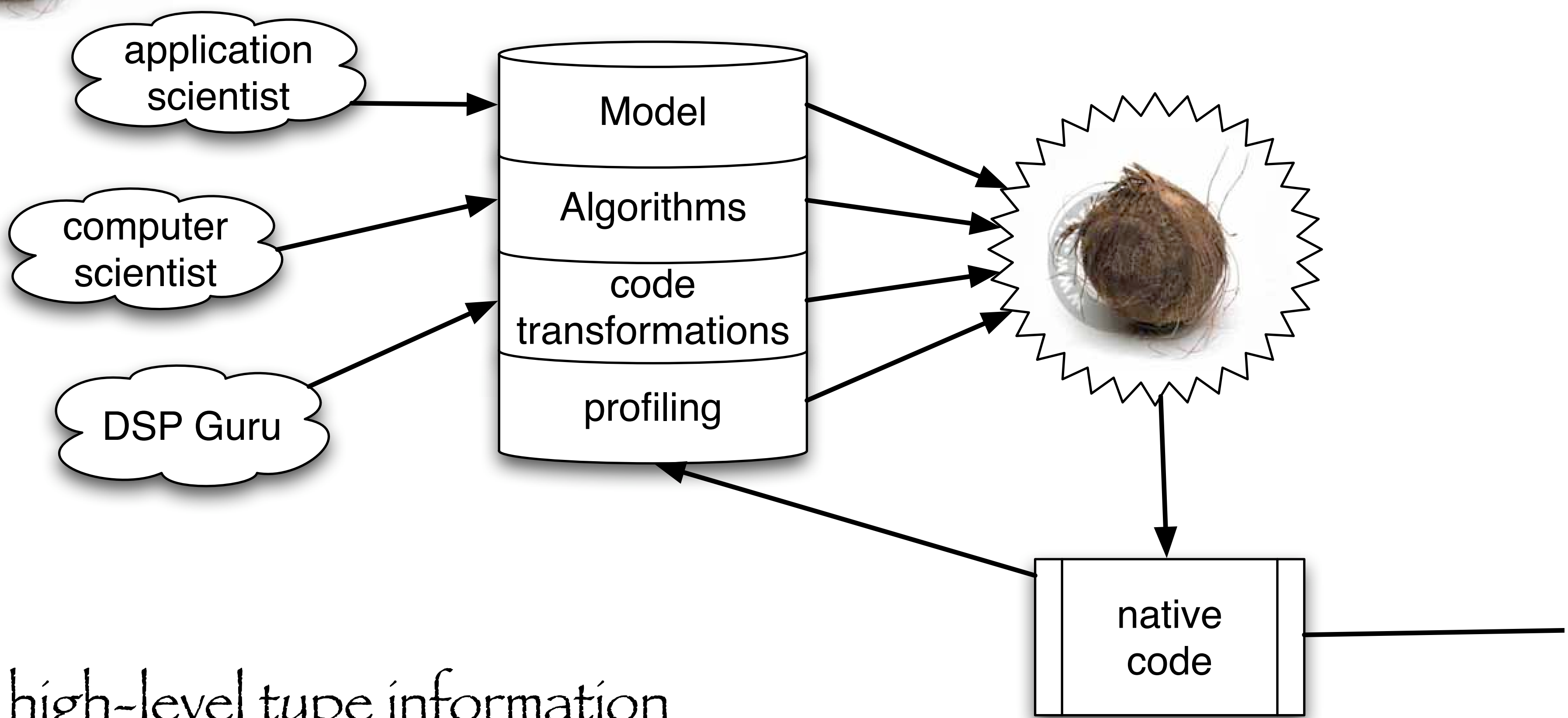
no pipes ⇒ no leaks



high-level type information

+

machine specifics

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- faster via
  - global data transformations
    - arrays of structs of arrays
    - alignment
    - virtual objects
  - leverage
    - SIMD (VMX)
    - cache hierarchy

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- fast via
  - high-level code transformations
    - generic BLAS++
    - pipelining without cleanup
    - reason about precision
    - custom virtual machines
    - tricks !

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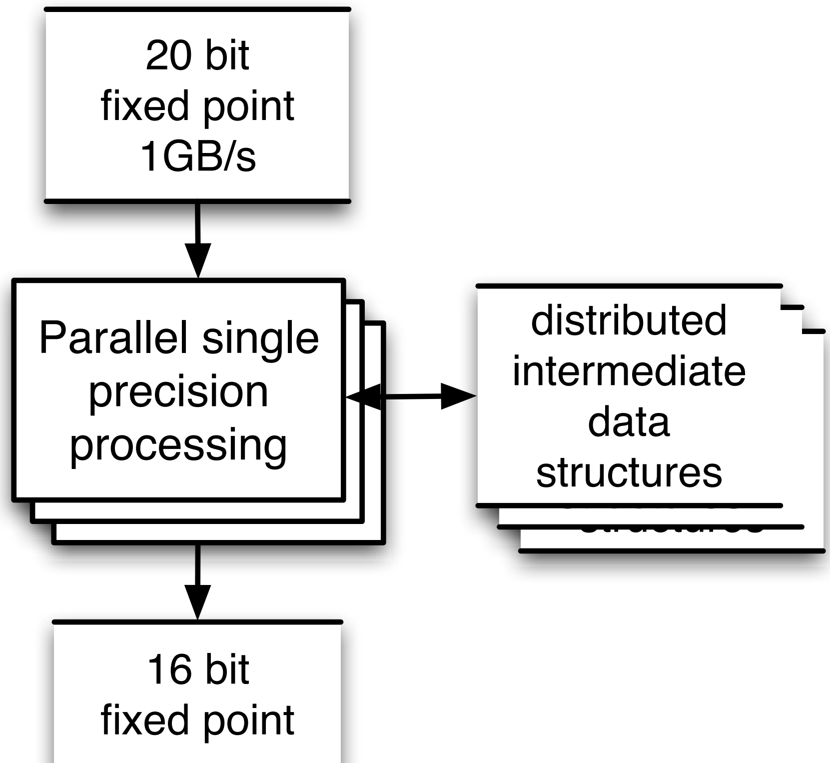
Magnetic Resonance Imaging



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fast imaging ⇒ nonuniform Fourier Transform ⇒

```
void    vexpif(     float *thetas, int quarterSize, float *sines, float *cosines) {
  int index;
  for (index = 0; index < 4*quarterSize; index++) {
    sines[index] = sin(thetas[index]);
    cosines[index] = cos(thetas[index]);
  }
}
```

want to

- inline
- eliminate storage for thetas
- use VMX/Altivec
- prefetch data

(use VMX/Altivec, prefetch data) } 12X acceleration

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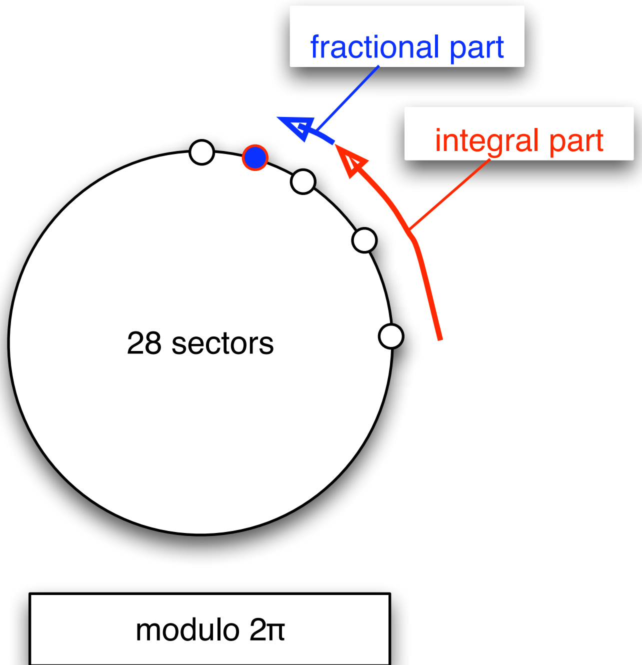

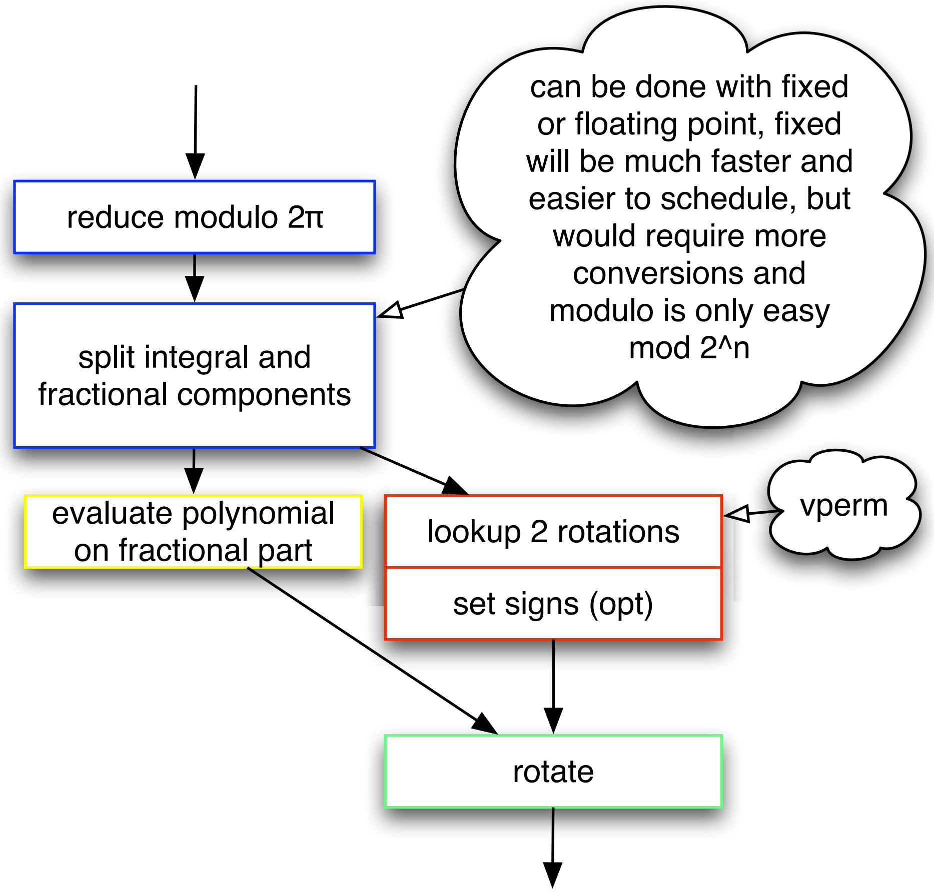

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```
static unsigned char staticsinLookupLookup[] = {
  0*4,1*4,2*4,3*4,4*4,5*4,6*4,7*4,6*4,5*4,4*4,3*4,2*4,1*4,                        // positive lookups
  0*4,1*4+1,2*4+1,3*4+1,4*4+1,5*4+1,6*4+1,7*4+1,6*4+1,5*4+1,4*4+1,3*4+1,2*4+1,1*4+1, // negative lookups
  0,0,0,0  //unused
};
static unsigned char staticcosLookupLookup[] = {
  7*4,6*4,5*4,4*4,3*4,2*4,1*4,0*4,1*4+1,2*4+1,3*4+1,4*4+1,5*4+1,6*4+1,
  7*4+1,6*4+1,5*4+1,4*4+1,3*4+1,2*4+1,1*4+1,0*4,1*4,2*4,3*4,4*4,5*4,6*4,
  0,0,0,0  //unused
};
static unsigned char staticpartialSplat[] = {
  3,3,3,3,7,7,7,7,11,11,11,11,15,15,15,15
};
static unsigned int staticotherConstants[] = {
  0x3E22F983,//.1591549431,    // oneOverTwoPi
  0x3C924925,//.1785714286e-1, // oneOver56
  0x40C90FDB,//6.283185308,         // twoPi
  0x3E65C8F0,//.2243993266,  // sin1

  0xBAF6999E,//-.1881409241e-2, // sin3
  0x3F800000,//0.9999999996880272,  // cos0
  0xBCCE4126,//-.2517754893e-1, // cos2
  0x38DD614C,//.1055622430e-3  // cos4

  0x41E00000,//28.
  0x00010203,//0..3
  0x0000001C,//28
  0x3E65C8FA,//2PiOver28
};
```


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```
for (count = quarterSize / refreshSize; count--; ) {
  vec_dst(pInput,GetPrefetchConstant(8, 2 * refreshSize * 2 / (8), 8*16),0);
  for (subcount = refreshSize; subcount--; ) {
    theta = vec_ld(0,pInput);
    vfp(theta);
    vOneOver56 = vec_splat(vOtherConstants1,1);
    vOneOver2Pi = vec_splat(vOtherConstants1,0);
    pInput++;
    theta = vec_madd(theta,vOneOver2Pi,vOneOver56);
    intPart = vec_floor(theta);
    v28f = vec_splat(vOtherConstants3,0);
    theta = vec_sub(theta,intPart);     // got (theta/2Pi + 1/2/28) mod 1, offset by 1/2 a segment length
    theta = vec_madd(theta,v28f,vZero);
    intPart = vec_floor(theta);
    theta = vec_sub(theta,intPart);
    (vector unsigned int)temp = vec_splat_u32(1);  // make .5f
    temp = vec_ctf((vector unsigned int)temp,1);
    theta = vec_sub(theta,temp);
    (vector unsigned int)intPart = vec_ctu(intPart,0);
    v28 = vec_splat((vector unsigned int)vOtherConstants3,2);
    vOneToFour = vec_splat((vector unsigned int)vOtherConstants3,1);

    asm("dcbz %0, %1" : : "O" (0), "b" (pCosines));
    asm("dcbz %0, %1" : : "O" (0), "b" (pSines));

    sinSign = vec_perm(vSinLookupLookup1,vSinLookupLookup2,(vector unsigned char)intPart);  // now we have 0x000000PosSign
    sinMap = vec_and(sinSign,(vector unsigned char)v28);
    sinMap = vec_perm(sinMap,sinMap,vPartialSplat);
    sinMap = vec_add(sinMap,vOneToFour);
    sinRot = vec_perm(lookup1,lookup2,sinMap);
    vOne = vec_splat_u32(31);
    (vector unsigned int)sinSign = vec_sl((vector unsigned int)sinSign,vOne);
    sinRot = vec_or((vector float)sinSign,sinRot);

    (vector unsigned char)cosSign = vec_perm(vCosLookupLookup1,vCosLookupLookup2,(vector unsigned char)intPart);  // now we have 0x000000PosSign
    cosMap = vec_and(cosSign,(vector unsigned char)v28);
    cosMap = vec_perm(cosMap,cosMap,vPartialSplat);
    cosMap = vec_add(cosMap,vOneToFour);
    cosRot = vec_perm(lookup1,lookup2,cosMap);
    (vector unsigned int)cosSign = vec_sl((vector unsigned int)cosSign,vOne);
    cosRot = vec_or((vector float)cosSign,cosRot);
    cos4 = vec_splat(vOtherConstants2,3);
    cos2 = vec_splat(vOtherConstants2,2);
    square = vec_madd(theta,theta,vZero);
    cos = vec_madd(square,cos4,cos2);
    cos0 = vec_splat(vOtherConstants2,1);
    cos = vec_madd(square,cos,cos0);
    sin1 = vec_splat(vOtherConstants1,3);
    sin3 = vec_splat(vOtherConstants2,0);
    sin = vec_madd(square,sin3,sin1);
    sin = vec_madd(sin,theta,vZero);
    cosOut = vec_madd(cos,cosRot,vZero);
    sinOut = vec_madd(cos,sinRot,vZero);
    cosOut = vec_nmsub(sin,sinRot,cosOut);
    sinOut = vec_madd(sin,cosRot,sinOut);
    vec_stl(cosOut,0,pCosines);
    vec_stl(sinOut,0,pSines);
    pCosines++;
    pSines++;
  }
```

now

- inline
- pipeline / unroll
- tune prefetch

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Design Patterns for Signal Processing

"in functional languages Design Patterns are executable"

- less programmer intervention = fewer errors
- type checking = almost as good as model checking
- provably correct implementations
- inheritance replaced by Haskell type classes

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Haskell

- functional: functions as first-class citizens
- pure: no side-effects
- non-strict: unneeded arguments may be undefined
  - implemented usually via lazy evaluation
  - enables separation of concerns, e.g., generate/prune
- strongly typed
- safe overloading (type classes)
- accessible for correctness proofs and program derivation
- compiled mostly by transformation
- large, active community; open definition and compilers

Haskell

static typing
no side-effects } $\Rightarrow$ verifiably correct code by construction

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Domain-Specific Languages (DSLs) in Haskell

- Embedded DSLs
  - built from primitives and combinators defined in Haskell
  - compiled by Haskell compiler
- Wrapping DSLs
  - wrap other libraries via the foreign-function interface (FFI)
  - from immediate wrappers to high-level abstractions
- Arbitrary DSLs
  - represented by Haskell data structures
  - the compiler will be a special Haskell program
  - Haskell is an excellent language for writing compilers

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Domain Specific Language

inside Haskell ⇒ open, extensible

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High Level DSL

mathematical specification of algorithms

Low Level DSL

high-performance, parallel vector, target-specific implementation

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High level DSL

- containers (matrices, structures)
- precision
- approximation
- derivatives
- special functions
- polynomials
- linear programming
- Newton's method

80% grammar
Oct 2003

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Low level DSL

- includes High Level DSL
- cache hierarchy
- cache hinting
- instruction scheduling
- storage classes
- page sizes
- inter-processor messaging
- SIMD

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Example: Interior Point Method for LP

key step: $A^{*}\,\mathrm{diag}(x)\,\mathrm{diag}(s)^{-1}\,A$

sparsity $\notin$ BLAS

BLAS	custom
$n \times m \times m \times m \times n$	$n \times m \times n$
	cache s^{-1}

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