POET:
Parameterized Optimizations For Empirical Tuning

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Extracting high performance through empirical tuning

- Producing high-performance applications is hard
  - It is increasingly hard to predict

    how machines will behave

    how applications will behave

    how compilers will behave

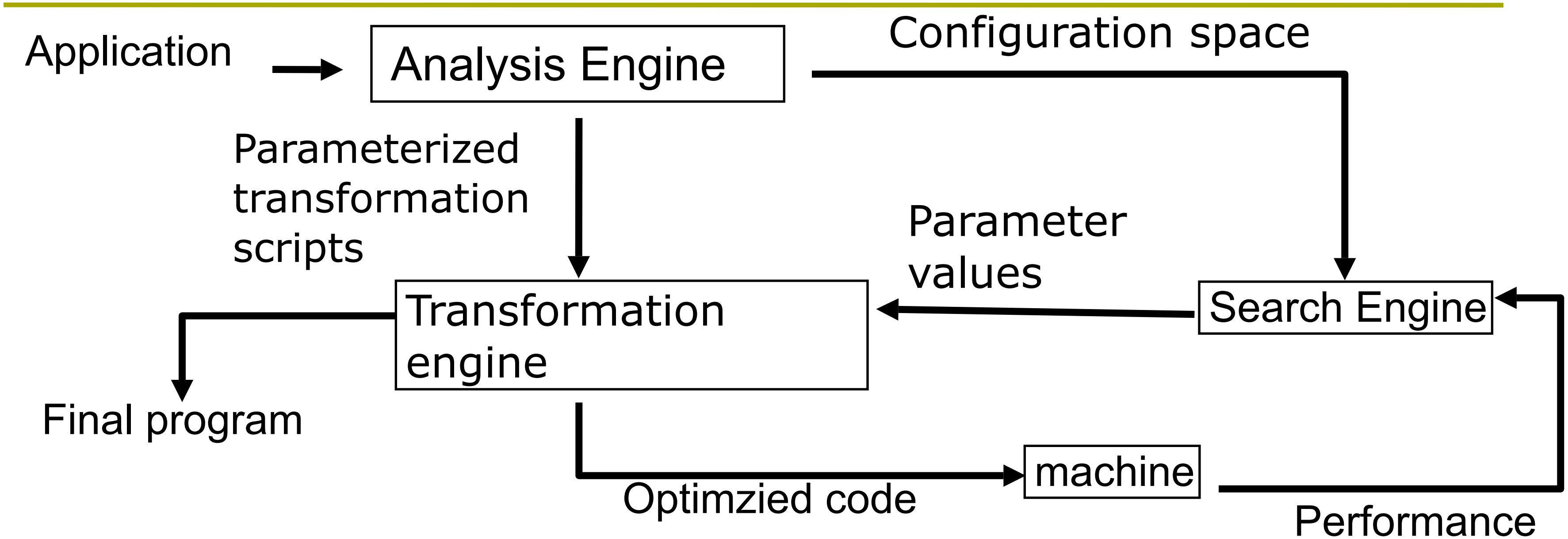
    how the network will behave ...

- The promising solution: empirical tuning
  - Experiment with different transformations to the application
  - Collect performance feedback
  - Adjust transformations and re-experiment

Empirical tuning systems

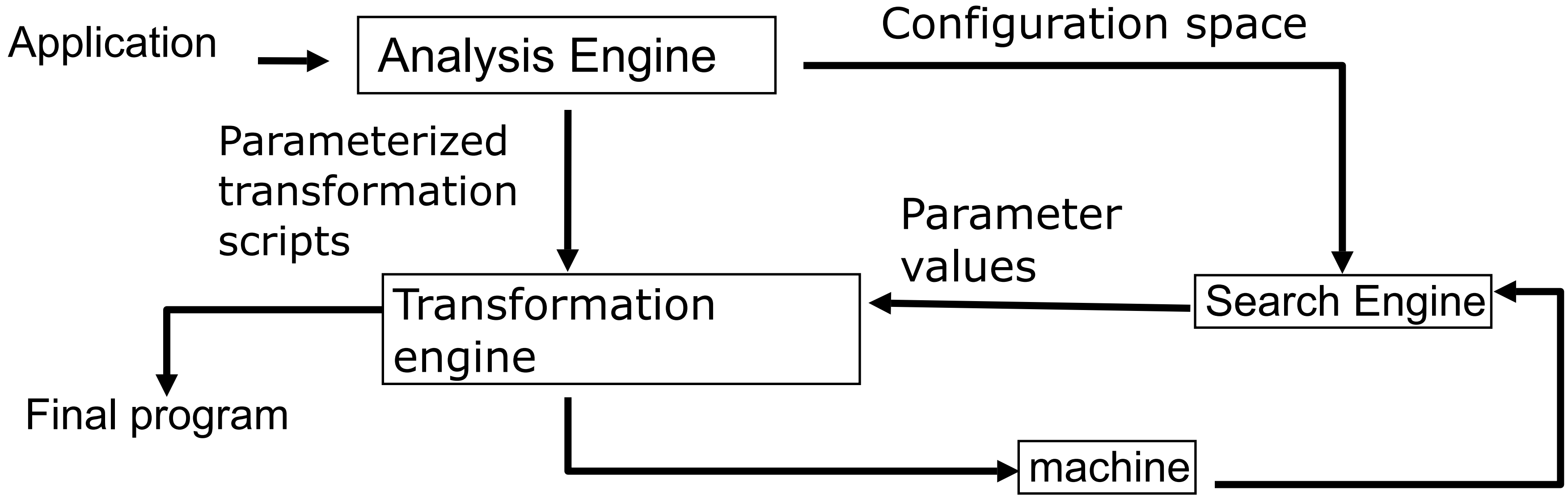
- Domain-specific libraries
  - Many highly successful
    - ATLAS, PHiPAC, FFTW, SPIRAL...
  - Time consuming: needs to manually orchestrate specialized optimizations
  - Not reusable across different problem domains
- Empirical optimizing compilers
  - Compilers trying to automate the tuning process
  - Hard to incorporate customized optimizations
  - Does not allow human intervention in general
- POET is trying to provide
  - A tool box for programmers to easily build high-performance kernels
  - A communication interface among all components of a tuning system

Empirical tuning approach



- Analysis engine/ Human
  - Understand application and machine, choose optimizations to apply
- Search engine exploits the configuration space
  - Use info from program analysis (encoded in configuration space)
- Transformation engine
  - Transforms application code based on transformation script and search configuration

The POET Language



- Language for expressing result of analysis engine
  - Parameterized code transformation scripts
  - Parameterized configuration space
- Interpreted by search engine and transformation engine
  - Configuration space interpreted by independent search engine
    - Sequence of parameters, constraints on parameter values
  - Transformations applied by transformation engine
    - Configuration determined by search engine

Flexibility, Modularity and Efficiency

- Portability --- applications can be shipped in POET representation
  - Tuned by independent search and transformation engines on different platforms
- Efficiency --- both transformation and search engines are light-weight
  - Heavy weight analysis optimizations done only once in analysis and optimization engine
  - Result parameterized to be tuned many times on different platforms
- Flexibility --- analysis engine and transformation/search engine can reside on different machines
  - Analysis engine not involved in the tuning process
  - Analysis and tuning research is separate and independent
  - Different optimizations can be combined through an external common language

POET: Describing Structure of Input computation

Example: code templates for C in POET

```
<code Nest pars=(loop, body) >
@loop@ {
  @body@
}
</code>

<code Sequence pars=(s1,s2) >
@s1@
@s2@
</code>

<code Loop pars=(i,start,stop,step) >
@init=(if start=="" then "" else (i "=" start ));
 test=(if stop=="" then "" else (i "<=" stop ));
 incr=(if step=="" then "" else (i "+=" step ));
@for (@init@; @test@; @incr@)
</code>
```

- POET: scripting language to be embedded in arbitrary languages
  - Syntax of source language described in a collection of code templates
  - Support strings, integers, lists, tuples, tables, AST based on code templates
  - Support loops,conditionals, recursion
  - Predefined library of code transformation routines
- Analysis engine
  - Decompose application into code templates
  - Specify transformations

POET: Describing Structure of Input computation

Example: the input specification for dgemm

```
 //@; BEGIN(gemm)
void ATL_USERMM(const int M, const int N, const int K,
        const double alpha, const double *A, const int lda,
        const double *B, const int ldb, const double beta,
        double *C, const int ldc)            //@=>_:Exp
{                                            //@; BEGIN(_)
 int i, j, l;                                //@=>gemmDecl:Stmt; BEGIN(gemmBody)
 for (j = 0; j < N; j += 1)                  //@ =>loopJ:Loop BEGIN(nest3)
 {                                           //@; BEGIN(body3)
   for (i = 0; i < M; i += 1)                //@=>loopI:Loop BEGIN(nest2)
    {                                        //@;BEGIN(body2) BEGIN(parse)
     C[j*ldc+i] = beta * C[j*ldc+i];         //@END(parse) =>_:Stmt
     for (l = 0; l < K; l +=1)               //@=>loopL:Loop BEGIN(nest1)
     {                                       //@;BEGIN(parse)
      C[j*ldc+i] += alpha * A[i*lda+l] * B[j*ldb+l];  //@END(parse) =>stmt1:Stmt
     }                                       //@END(nest1:Nest) END(body2:Sequence)
    }                                        //@END(nest2:Nest) END(body3:Nest)
 }                        //@END(nest3:Nest) END(gemmBody:Nest) END(_:Sequence)
}                                            //@END(gemm:Function)
```

Define transformations in POET

```
<xform Stripmine pars=(inner,bsize,outer)
                    tune=(unroll=0,split=0)
 output=(_nvars,_bloop,_tloop,_cloop,_body)>
 switch outer {
  case inner : ("","","","",inner)
  case Loop#(i,start,stop,step): ......
  default:  ......
  }
</xform>

<xform BlockHelp
  pars=(bloop,tloop,rloop,bbody,cbody,cloop)>
 if (bloop == "") ... <*base case*>...
 else { ...<*recursively call BlockHelp*>... }
</xform>

<xform BlockLoops
 pars=(inner,outer,decl,input)
 tune=(bsize=16, split=0, unroll = 0) >
   ... = Stripmine[unroll=unroll,split=split]
                   (inner, bsize,outer);
   ... call BlockHelp ...  ... modify input ...
</xform>
```

- POET is a dynamic functional language designed for the ease of writing code transformations
  - Supports pattern matching, code traversal, replacement, and duplication
  - Support control flows and recursion
  - support auto tracing of code fragments going through transformations
- Libraries to support most existing code transformations known to be important

POET: What Analysis Engine Needs to Write?

```
<parameter SSELEN=16, SSENO=16 />
<parameter mu=6, nu=1, ku=36, NB=36, MB=36, KB = 36, PF=1 />

<trace nest3,loopJ,body3,nest2,loopI,body2,
       nest1,loopL,stmt1,gemm,gemmDecl,gemmBody/>

<define Specialize DELAY {
  if (SP) {
    REPLACE("N",NB,loopJ); REPLACE("M",MB,loopI); REPLACE("K",KB,loopL);
    REPLACE("lda",MB, gemmBody);  REPLACE("ldb",NB, gemmBody);
    if (alpha == 0) {  REBUILD(REPLACE("alpha",1, gemmBody) }
} } />

<define nest3_UnrollJam  DELAY {
   if (mu > 1 || nu > 1) {
       UnrollJam[factor=(nu mu)](nest1,nest3,gemmBody);
} } />

<define nest1_Unroll  DELAY {  if (ku > 1) {
     UnrollLoops[factor=ku](stmt1,nest1,body2);
} }/>
......
```

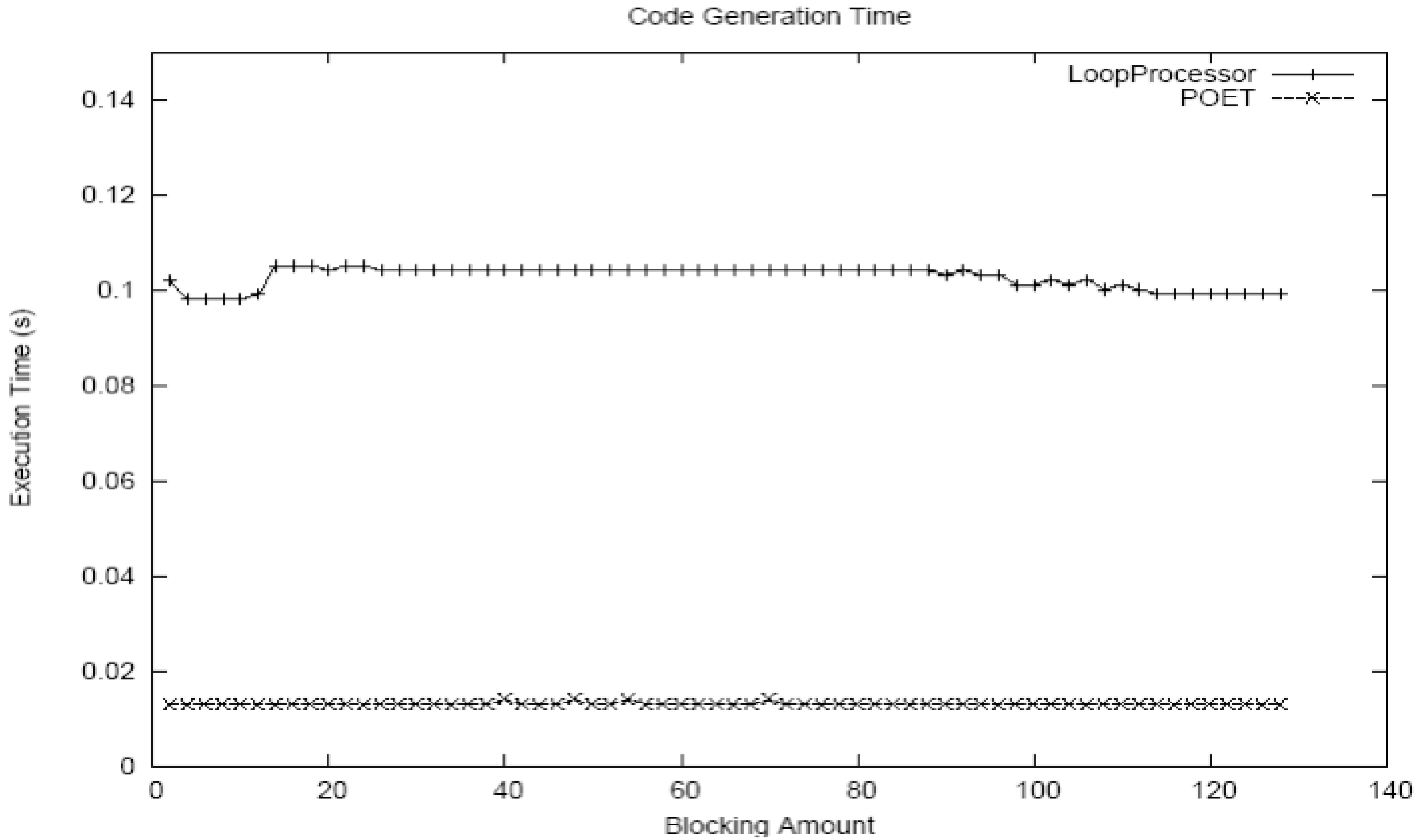
POET: Applying Transformations

```
.......

<output dgemm_kernel.c (
   TRACE gemm;
   APPLY Specialize;
   APPLY A_ScalarRepl;
   APPLY nest3_UnrollJam;
   APPLY B_ScalarRepl;
   APPLY C_ScalarRepl;
   APPLY array_ToPtrRef;
   APPLY Abuf_SplitStmt;
   APPLY body2_Vectorize;
   APPLY array_FiniteDiff;
   APPLY body2_Prefetch;
   APPLY nest1_Unroll;
   gemm
) />
```

- Writing a POET script
  - Define transformation parameters
  - Define the input computation
  - Define tracing variables
  - Define each transformation independently
  - Apply transformations and output

Empirical tuning using POET



Compared to empirical tuning using a source-to-source loop optimizer
Collaborated work with You, Seymour (UTK), Quinlan and Vuduc (LLNL)

Automatic production of ATLAS library kernels

- Library kernels are
  - Computational intensive routines
  - invoked by higher-level procedures
  - Assumptions can be made about pre-applied optimizations, e.g., specialization on matrix sizes, array copy
- Using POET to automatically produce ATLAS library kernels
  - Define the input computation in C with POET annotations
    - Define global variables to trace fragments to be optimized
  - Define a collection of potential optimizations independently
    - Invoke the optimizations and output
  - Parameterization: precision of kernel, how to apply optimizations
- Automatically produced ATLAS kernels: gemm, gemv, ger
  - Encoded the relevant ATLAS optimizations in POET
    - specialization, unroll-and-jam, loop unroll, scalar repl, strength reduction, SSE vectorization

Experimental Design

Platform	Compiler	Flags
2.66GHz Core2Duo	icc 9.1	-xP -msse3 -O3 -mp1 -fomit-frame-pointer
	gcc 4.0.1	-mfpmath=sse -msse3 -O2 -m64 -fomit-frame-pointer
2.2GHz Athlon 64 X2	gcc 4.2.0	-mfpmath=387 -falign-loops=4 -fomit-frame-pointer -O2

Peak performance of machines

	Core2Duo Peak MFLOPS		Athlon-64 X2 Peak MFLOPS	
precision	scalar Unit	vector Unit	scalar Unit	vector Unit
single	5320	21280	4400	8800
double	5320	10640	4400	4400

ATLAS version 3.7.30;   Collaborated work with Clint Whaley

Result for Level-3 BLAS

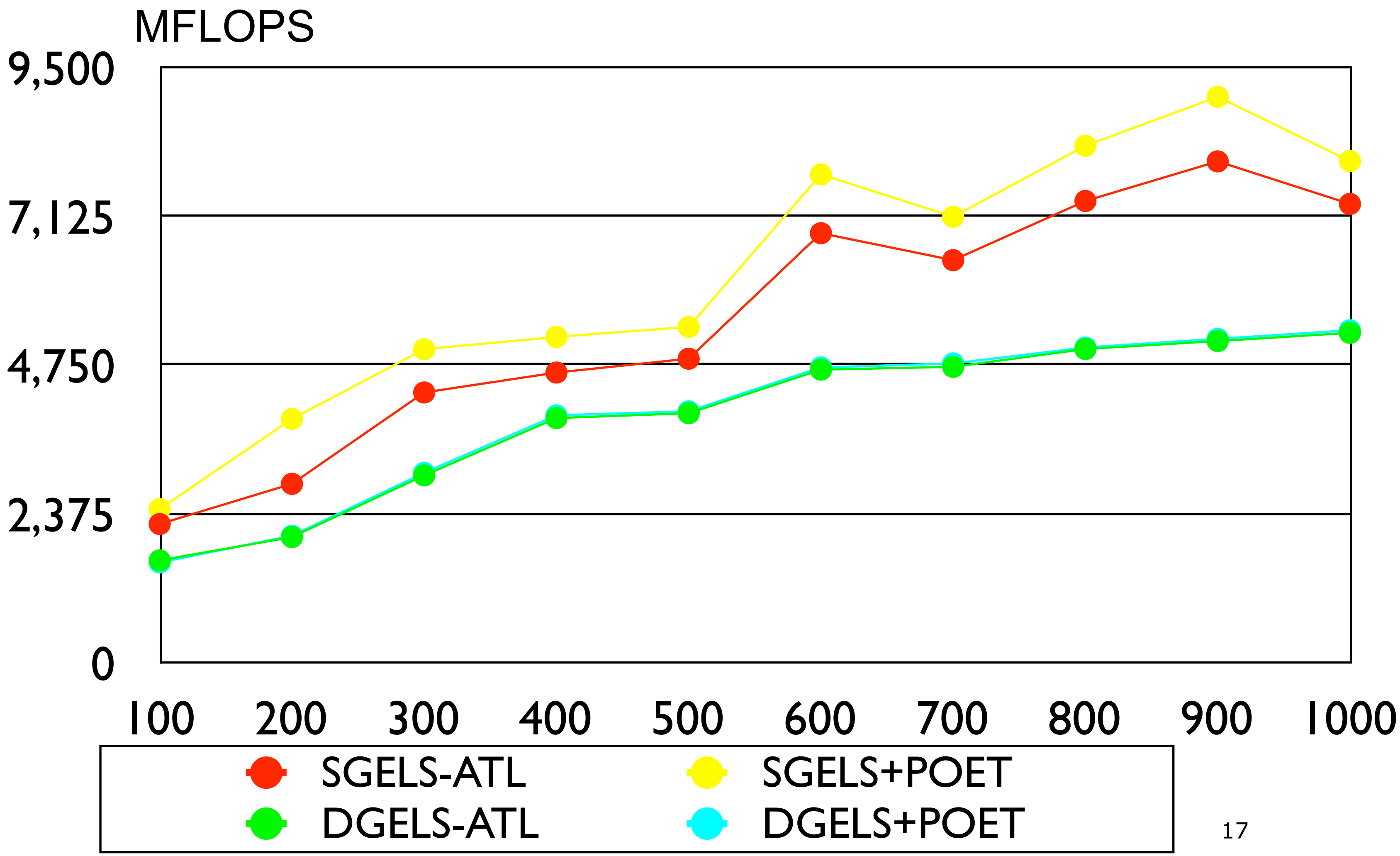
MFLOP/ %PEAK	Core2Duo MFLOPS					Athlon-64 MFLOPS			
	gcc +ref	icc +ref	ATLAS gen	ATLAS full	POET +ref	gcc +ref	ATLA S gen	ATLAS full	POET +ref
sgemmK	571/ 2.7%	6226/ 29.3%	4730/ 22.2%	13972/ 65.6%	15048/ 70.7%	1009/ 11.5%	4093/ 46.5%	7651/ 86.9%	6918/ 78.6%
dgemmK	649/ 6.1%	3808/ 35.8%	4418/ 41.5%	8216/ 77.2%	7758/ 72.9%	939/ 21.3%	3737/ 84.9%	4009/ 91.1%	3754/ 85.3%

PEAK: using vector (SSE) units

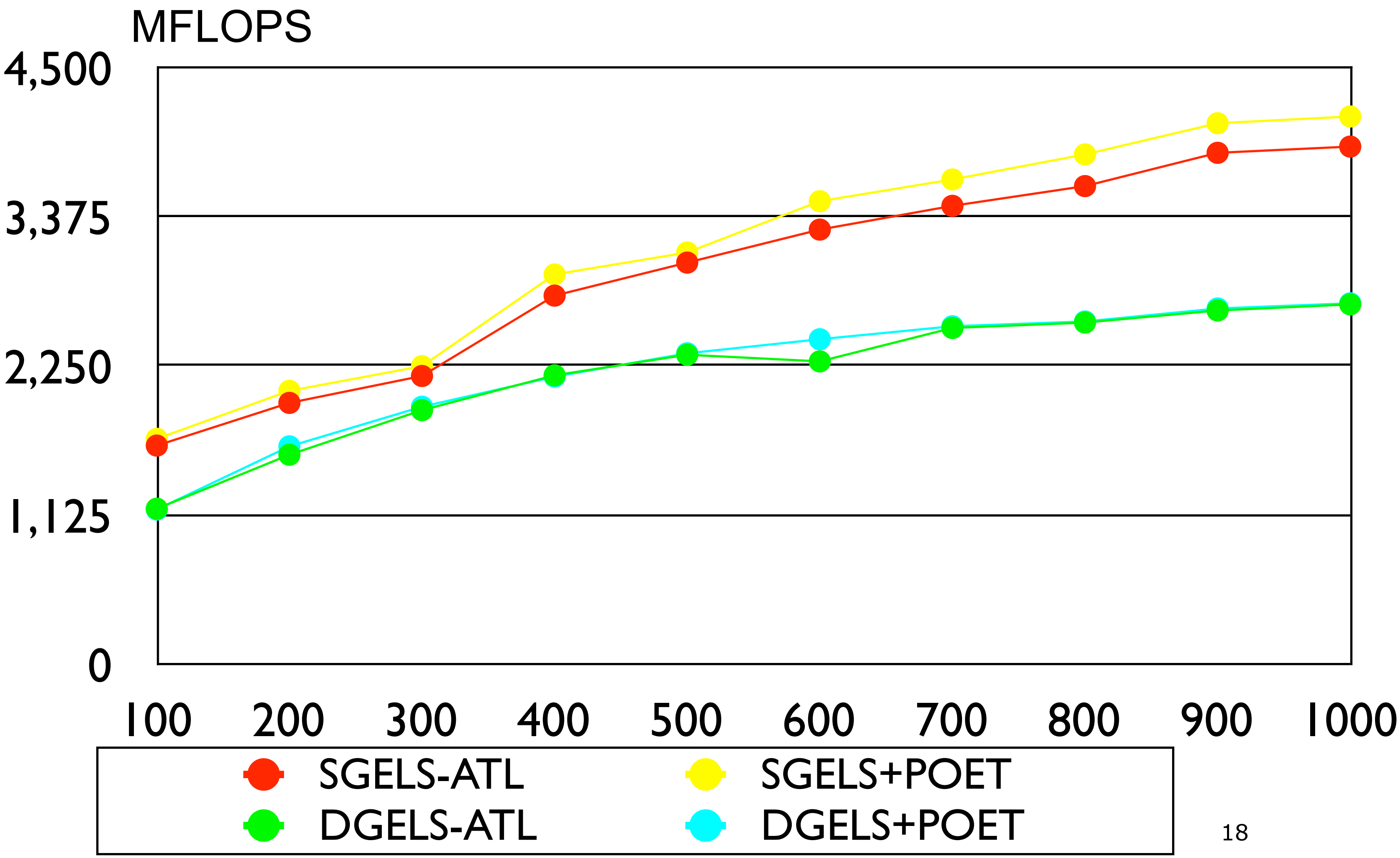
Result for Level-2 BLAS

	Core2Duo MFLOPS/ %PEAK				Athlon-64 MFLOPS/ %PEAK		
	gcc+ref	icc +ref	ATLAS full	POET +ref	gcc+ref	ATLAS full	POET +ref
sgerK	1230/ 5.7%	2927/ 13.7%	3751/ 17.6%	3400/ 15.9%	639 / 7.3%	1005/ 11.4%	962/ 10.9%
dgerK	439/ 4.1%	438/ 4.1%	462/ 4.3%	519/ 4.9%	411/ 9.3%	518/ 11.8%	500/ 11.4%
sgemvTK	556/ 2.6%	1826/ 8.6%	1752/ 8.2%	2171/ 10.2%	835/ 9.5%	1389/ 15.8%	2056/ 23.4%
dgemvTK	556/ 5.2%	574/ 5.4%	835/ 7.8%	1079/ 10.1%	579/ 13.2%	739/ 16.8%	1049/ 23.8%
sgemvNK	438/ 2.1%	859/ 4.0%	1838/ 8.6%	2097/ 9.8%	529/ 6.0%	1185/ 13.5%	1986/ 22.6%
dgemvNK	382/ 3.6%	574/ 5.4%	939/ 8.8%	1069/ 10.0%	408/ 9.3%	799/ 18.2%	902/ 20.5%

Improvement For LAPACK (Core2Duo)



Improvement For LAPACK (Athlon X2)



Summary

- POET targets
  - General-purpose compiler transformations
    - Separate transformation from program analysis
      - They are separated within compilers anyway
      - Each transformation:replace an AST fragment with a new one
    - Parameterized interface for applying transformations
      - Loop fusion, interchange, blocking, unroll-and-jam, unrolling, scalar replacement, array copy, SIMD vec., prefetching, strength reduction ...
  - Domain-specific transformations
    - Equivalent algorithms that might return different results
      - precision of floating point numbers, error analysis
    - Using POET to define customized transformations
      - Write transformation routines
      - Can operate on high-level concepts

POET in Empirical Tuning

- Compilers/analyzers => POET transformation engine
  - Compilers/analyzers
    - Discover performance-critical routines; apply outlining; insert POET computation annotations
    - Discover profitable optimizations; produce parameterized transformation scripts (invocations to POET libraries)
    - Export program analysis results to POET
      - Dependence constraints, insight about programs
      - Information useful to the empirical search engine
  - POET transformation engine
    - Interpret the POET scripts; apply transformations; output result
- POET transformation engine => Empirical tuning
  - Search driver decides configuration of transformation parameters
  - POET transformation engine acts as the code generator