Dynamic Compilation

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Overview

- Dynamic Compilation
- Specialisation
  - DyC
  - Calpa
- Dynamic Binary translation
  - Dynamo

Dynamic techniques

- These techniques focus on delaying some or all of the optimisations to runtime
- This has the benefit of knowing the exact runtime control-flow, hotspots, data values, memory locations and hence complete program knowledge
- It thus largely eliminates many of the undecidable issues of compile-time optimisation by delaying until runtime
- However, the cost of analysis/optimisation is now crucial as it forms a runtime overhead. All techniques characterised by trying to exploit runtime knowledge with minimal cost

Background

- Delaying compiler operations until runtime has been used for many years
- Interpreters translates and execute at runtime
- Languages developed in the 60s eg Algol 68 allowed dynamic memory allocation relying on language specific runtime system to mange memory
- Lisp more fundamentally has runtime type checking of objects
- Smalltalk in the 80s deferred compilation to runtime to reduce the amount of compilation otherwise required in the 00 setting
- Java uses dynamic class loading to allow easy upgrading of software

Runtime specialisation

- For many, runtime optimisation is "adaptive optimisation"
- Although wide range of techniques, all are based around runtime specialisation. Constant propagation is a simple example.
- Specialisation is a technique that has been used in compiler technology for many years especially in more theoretical work
- Specialising an interpreter with respect to a program gives a compiler
- Can we specialise at runtime to gain benefit with minimal overhead? Statically inserted selection code vs parametrised code vs runtime generation.

Static code selection, parametrised and code generation

```
IF (N<M) THEN
 DO I =1,N
  DO J =1,M
   ...
  ENDDO
 ENDDO
ELSE
 DO J =1,M
  DO I =1,N
   ...
  ENDDO
 ENDDO
ENDIF
```

```
IF (N<M) THEN
 U1 = N
 U2 = M
ELSE
 U1 = M
 U2 = N
ENDIF
DO I1 =1,U1
  DO I2= 1,U2
   ...
  ENDDO
ENDDO
```

```
gen_nest1(fp,N,M)
(*fp)()
```

DyC

- One of the best known dynamic program specialisation techniques based on dynamic code generation.
- The user annotates the program defining where there may be opportunities for runtime specialisation. Marks variables and memory locations that are *static* within a particular scope.
- The system generates code that checks the annotated values at runtime and regenerates code on the fly.
- By using annotation, the system avoids over-checking and hence runtime overhead. This is at the cost of additional user overhead.

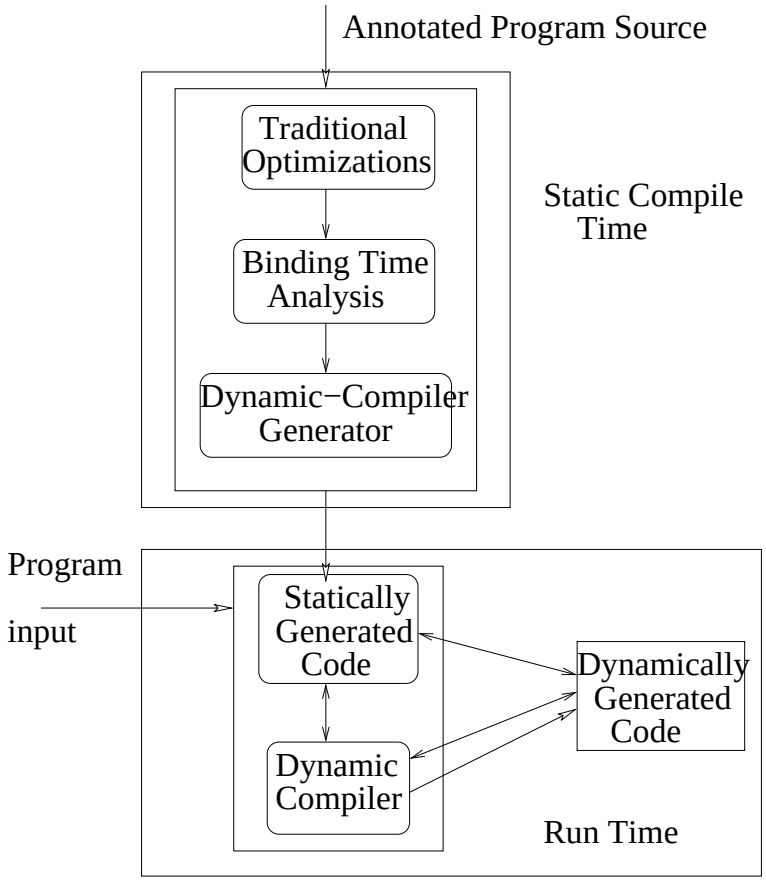
DyC

- Focuses on static runtime values and memory locations. Static binding-time analysis to identify static runtime expressions.
- Polyvariant division and specialisation to replicate control-flow path and divide into static and run-time variable sub-graphs.
- A specialised compiler is inserted at dynamic sub-graphs. At runtime it compiles code with values and stores this in a cache for later use and then executes it.
- Later invocations look up the code and use it. Uses full unrolling, strength reduction, zero/copy propagation, dead-assignment elimination and static loads.

DyC

Binding analysis examines all uses of static variables within scope

Dynamic compiler exploits invariancy and specialises the code when invoked



DyC Example

```
make_static(CMTRIX,CROWS,CCOLS,CROW,CCOL);     -- USER annotation
  CROWSO2 = CROWS/2; CCOLSO2= CCOLS/2;
for(irow=0; irow<irows; ++irow){
  rowbase = irow-CROWSO2;
  for(icol= 0; icol<icols;++icol){
    colbase = icol-CCOLSO2; sum =0.0;
    for (CROW=0; CROW<CROWS; ++CROW){          -- unroll loop
      for (CCOL=0; CCOL <CCOLS; +CCOL){        -- unroll loop
        weight = cmatrix @[CROW]@[CCOL];       -- constant load
        x = image[rowbase+CROW][colbase+CCOL];
        weighted_x = x * weight;
        sum = sum + weighted_x;
    outbuf[irow][icol] = sum;
```

DyC Example

Matrix cmatrix has the following structure :

0	1	0
1	0	1
0	1	0

- When CROW and CCOL loop is unrolled, the static loads from cmatrix will be inlined
- Allows elimination of redundant computation

DyC Example

```
-- crow and ccol unrolled
-- weight accesses static load, is propagated and eliminated
x = image[rowbase][colbase];   -- crow =0, ccol=0
weighted_x = x * 0.0;          -- weight == cmatrix[0][0] ==0
sum = sum + weighted_x;

-- weight accesses static load, is propagated and eliminated
x = image[rowbase][colbase+1]; -- crow =0, ccol=1
weighted_x = x * 1.0;          -- weight == cmatrix[0][0] ==1
sum = sum + weighted_x;
        ...
```

DyC Example

```
for(irow=0; irow<irows; ++irow){
  rowbase = irow- 1;
  for(icol= 0; icol<icols2;++icol){
    colbase = icol-1;

       x = image[rowbase][colbase+1];-- It 1:crow=0,ccol=1
       sum = x;

       x = image[rowbase+1][colbase];-- It 3:crow=1;ccol=0
       sum = sum + x;
         ...
     outbuf[irow][icol] = sum;
```

DyC Example

- Asymptotic speedup and a range programs varies from 1.05 to 4.6
- Strongly depends on percentage of time spent in the dynamically compiled region. Varies from 9.9 to 100 %
- Low overhead from 13 cycles to 823 cycles per instruction generated
- Break-even point low .
- However relies on user intervention which may not be realistic in large applications
- Relies on user *correctly* annotating the code

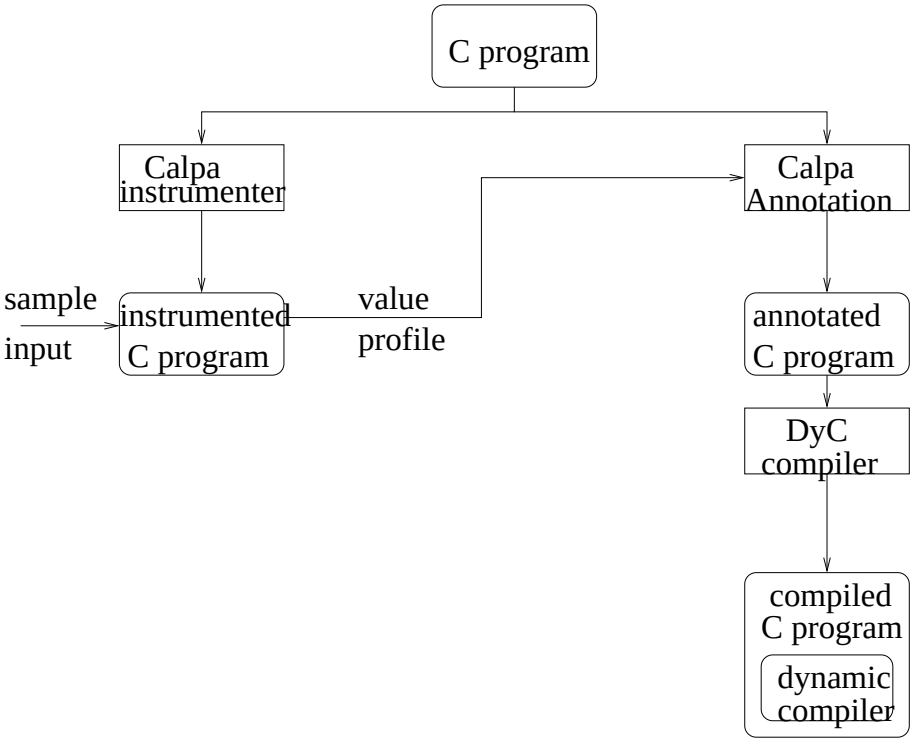
Calpa for DyC

- Calpa is a system aimed at automatically identifying opportunities for specialisation without user intervention
- It analyses the program for potential opportunities and determines the possible cost vs the potential benefit
- For example if a variable is multiplied by another variable which is known to be constant in a particular scope, then if this is equal to 0 or 1 then cheaper code maybe generated
- If this is inside a deep loop then a quick test for 0 or 1 outside the loop will be profitable

Calpa for DyC

Calpa is a front end to DyC

It uses instrumentation to guide annotation insertion



Calpa for DyC

`i=0`	$\emptyset$
`L1: if i >= size goto L2`	$i, size$
`uelem = u[i]`	$i, u[]$
`velem = v[i]`	$i, v[]$
`t = uelem * velem`	$i, u[], v[]$
`sum = sum + t`	$i, sum, u[], v[]$
`i = i + 1`	i
`goto L1`	$\emptyset$
`L2:`	

- At each statement calculate candidate static variables .

- Over larger region determine candidate division - all possible sub sets. Search for the best set based on value profile data using gradient search.

Calpa for DyC

- Instruments code and sees have often variables change value. Given this data determined the cost and benefit for a region of code
- Number of different variants, cost of generating code, cache lookup. Main benefit determined by estimating new critical path
- Explores all specialisation up to a threshold. Widely different overheads 2 seconds to 8 hours. Finds user choices and in two cases improves - from 6.6 to 22.6
- Calpa and DyC utilise selective dynamic code generation. Next look at fully dynamic schemes.

Dynamic Binary Translation

- The key idea is to take one ISA binary and translate it into another ISA binary at runtime.
- In fact this happens inside Intel processors where x86 is unpacked and translated into an internal RISC opcode which is then scheduled. The TransMeta Crusoe processor does the same. Same with IBM legacy ISAs.
- Why don't we do this statically? Many reasons!
- The source ISA is legacy but the processor internal ISA changes. It is impossible to determine statically what is the program. It is not legal to store a translation. It can be applied to a local ISA for long term optimisation

DYNAMO

- Focuses on binary to binary optimisations on the same ISA. One of the claims is that it allows compilation with -01 but overtime provides -03 performance.

- Catches dynamic cross module optimisation opportunities missed by a static compiler. Code layout optimisation allowing improved scheduling due to bigger segments. Branch alignment and partial procedural inlining form part of the optimisations

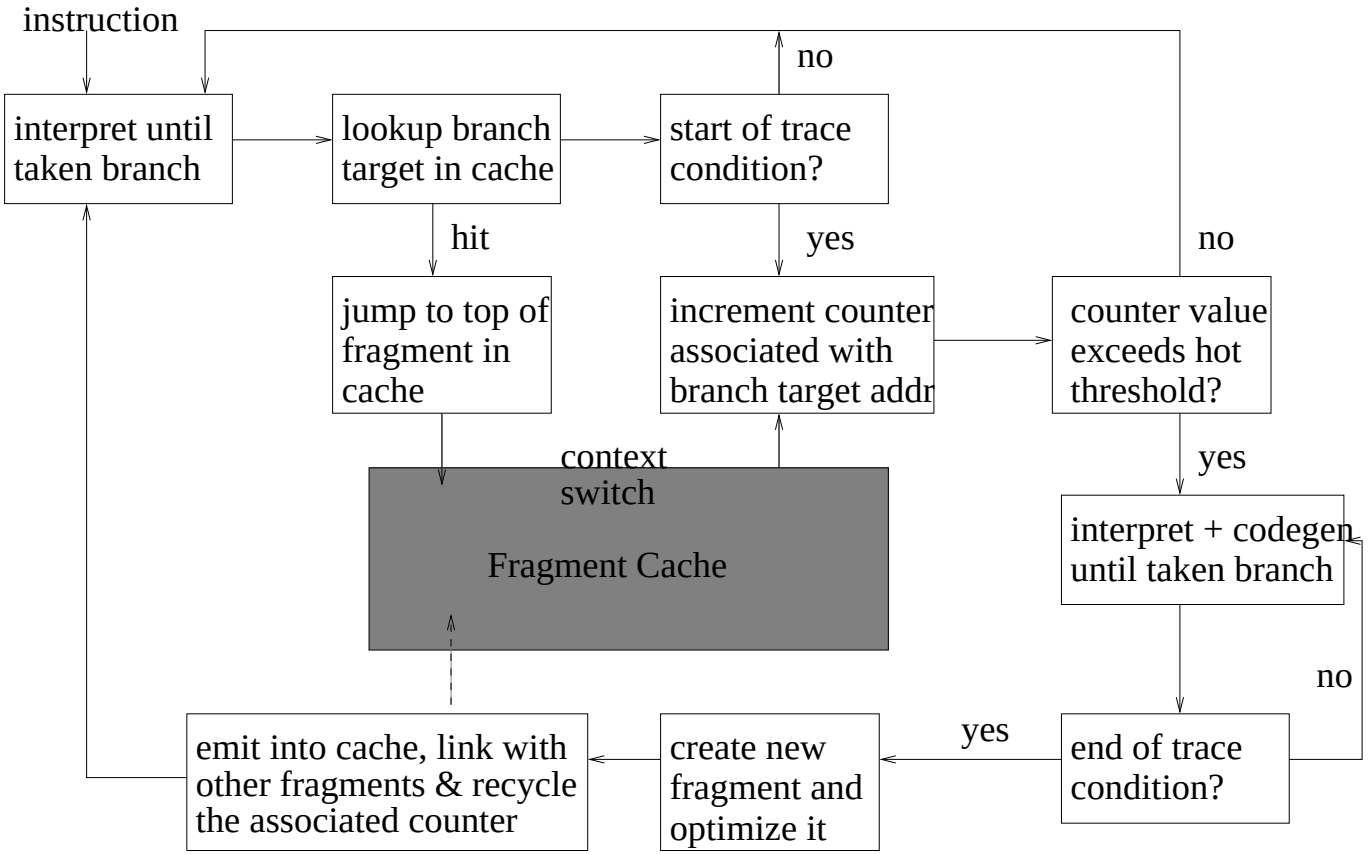
- Aimed as way of improving performance from a shipped binary overtime.

- Has to use existing hardware - no additional fragment cache available

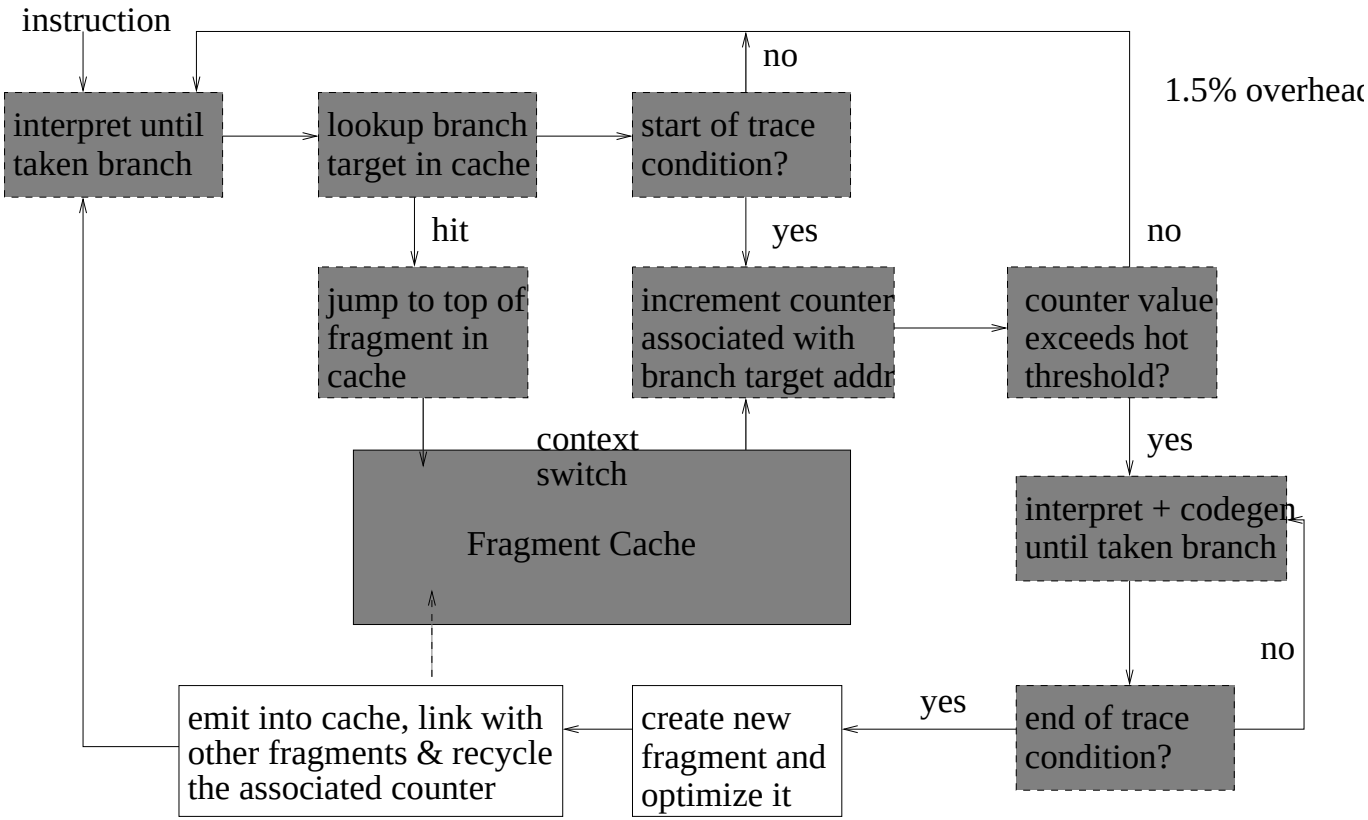
DYNAMO

- Initially interprets code. This is very fast as the code is native. When a branch is encountered check if already translated
- If it has been translated jump and context switch to the fragment cache code and execute. Otherwise if hot translate and put in cache.
- Over time the working set forms in the cache and Dynamo overhead reduces -less than 1.5% on specint.
- Cheap profiling, predictability and few counters are necessary.
- Linear code structure in cache makes optimisation cheap. Standard redundancy elimination applied.

DYNAMO


instruction
interpret until taken branch
lookup branch target in cache
start of trace condition?
no
hit
yes
no
jump to top of fragment in cache
increment counter associated with branch target addr
counter value exceeds hot threshold?
context switch
Fragment Cache
yes
interpret + codegen until taken branch
no
emit into cache, link with other fragments & recycle the associated counter
create new fragment and optimize it
yes
end of trace condition?

DYNAMO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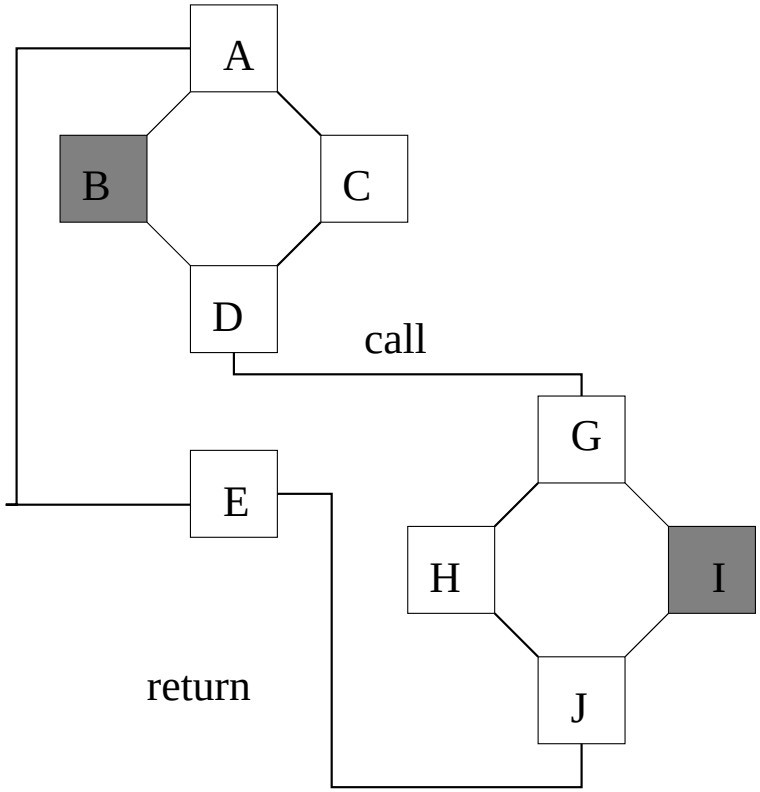
start of trace condition?
no
yes
increment counter associated with branch target addr
context switch
Fragment Cache
counter value exceeds hot threshold?
no
1.5% overhead
yes
interpret + codegen until taken branch
end of trace condition?
yes
no
create new fragment and optimize it
emit into cache, link with other fragments & recycle the associated counter

DYNAMO

Control-flow
in binary

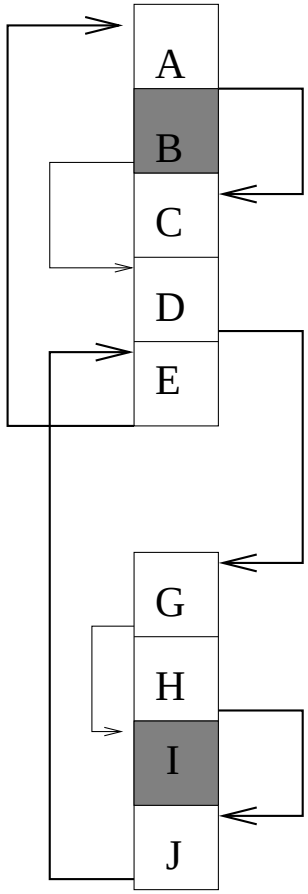
Cross-module
flow not
picked up
by compiler



DYNAMO

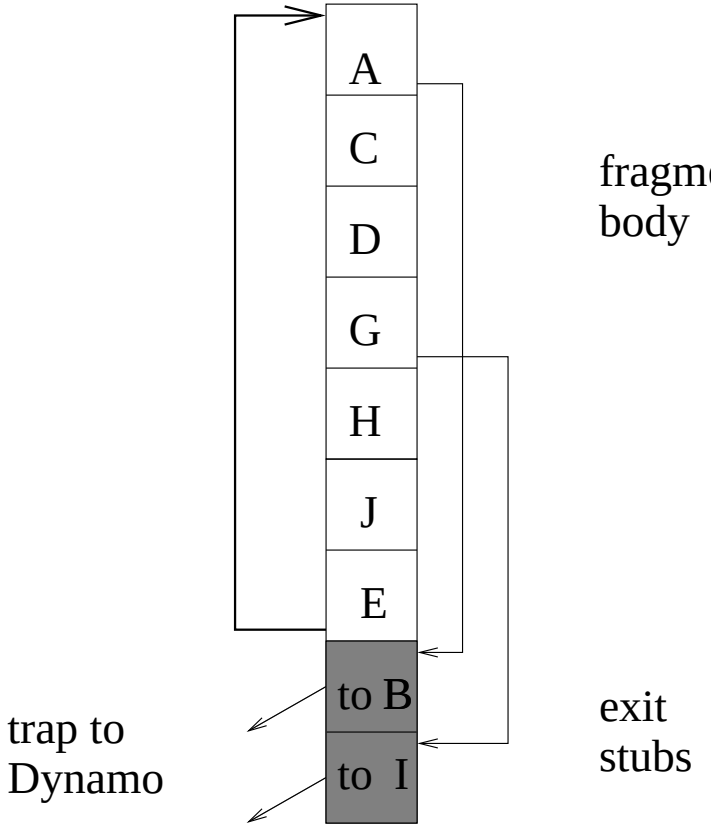
Layout of code in memory

The two functions may be very far apart in memory



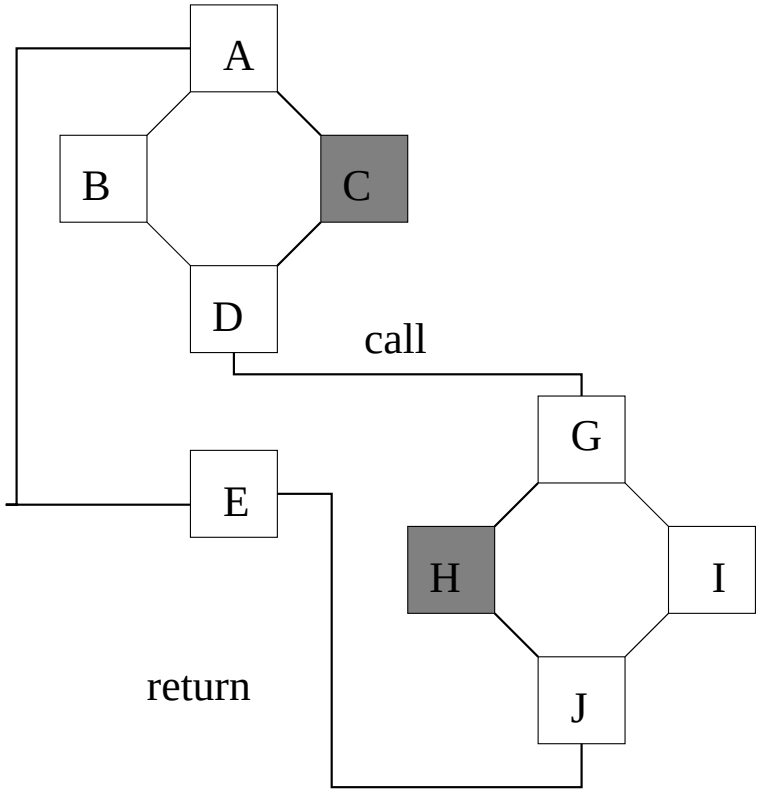
DYNAMO

Layout of trace in Dynamo's fragment cache



DYNAMO

When there is a change of control-flow it is important to avoid returning to interpreter if at all possible

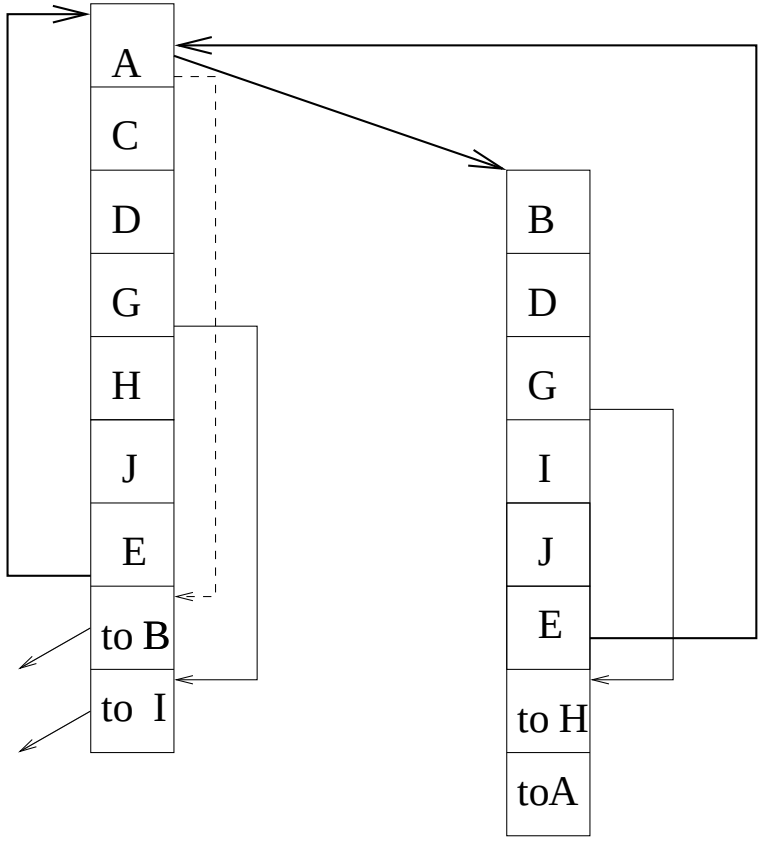


DYNAMO

Achieved by fragment linking

Also provides an opportunity for eliminating redundant compensation code

Essential optimisation factor 40!



DYNAMO percentage improvement

	trace selection	optimisation
compress	7	7
go	-2	0
ijpeg	-2	0
li	16	6
mk88	18	5
perl	12	16
vortex	-1	0
def	2	2
avg	6	3

- Flush cache at phase change. Bail out if no steady control-flow. Optimising at a very low level. Complementary to DyC

Summary and conclusions

- All schemes allow specialisation at runtime to program and data
- Staged schemes such as DyC are more powerful as they only incur runtime overhead for specialisation regions
- JIT and DBT delay everything to runtime leaving little optimisation opportunities
- DyC focused on reducing ops - no investigation of processor behaviour
- Dynamo trace approach basis for JIT compilers