Threads and Or-Parallelism Unified

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Abstract

One of the main advantages of Logic Programming (LP) is that it provides an excellent framework for the parallel execution of programs. In this work we investigate novel techniques to efficiently exploit parallelism from real-world applications in low cost multi-core architectures. To achieve these goals, we revive and redesign the YapOr system to exploit or-parallelism based on a multi-threaded implementation. Our new approach takes full advantage of the state-of-the-art fast and optimized YAP Prolog engine and shares the underlying execution environment, scheduler and most of the data structures used to support YapOr's model. Initial experiments with our new approach consistently achieve almost linear speedups for most of the applications, proving itself as a good alternative for exploiting implicit parallelism in the currently available low cost multi-core architectures.

KEYWORDS: Multi-Threading, Or-Parallelism, Implementation.

1 Introduction

One of the main advantages of Logic Programming (LP) is that it provides an excellent framework for the parallel execution of programs. *Implicit* parallelism occurs naturally in logic programs; or-parallelism arises because different alternatives can be run independently; and and-parallelism arises when different goals can be run in different processors (Gupta et al. 2001). On the other hand, as a very high-level language, LP has often been used (and is still indeed being used) to *explicitly* control parallelism and manage tasks (Fonseca et al. 2009). It is therefore unsurprising that parallelism has been an important subject in the development of LP.

Arguably, the high-point of parallel LP were the early nineties. During this period, a number of very sophisticated and well-engineered systems were built and shown to be quite successful at exploiting implicit or-parallelism (Lusk et al. 1988; Ali and Karlsson 1990b; Gupta and Pontelli 1999), implicit and-parallelism (Hermenegildo and Greene 1991; Shen 1992; Pontelli and Gupta 1997), and even a combination of both (Santos Costa et al. 1991). The hard lesson was that although these systems did deliver performance, they never became widely used. We believe this can be explained for a number of reasons: **(i)** only few users had access to the expensive parallel machines of the day; **(ii)** they required significant changes to the Prolog engine, thus becoming complex to maintain and install; and **(iii)** large Prolog programs are hard to parallelize. Thus, interest in the whole area of declarative parallel programming laid dormant for a number of years.

The increasing availability and popularity of multi-core processors has changed this equation: multi-core systems have become a viable high-performance, affordable and standardized alternative to the traditional (and often expensive) parallel architectures. In fact, as the number of cores per processor continues to increase, interest in parallelism expands. This has led to a recent revival of research in the area and motivates a simple question: *Is implicit parallelism worth it in multi-core architectures?*

Answering this question requires a parallel LP system. Unfortunately, building parallel logic programming systems from scratch is *hard*. Ideally, we would like to reuse the vast amount of preexisting work. But, will systems designed and built more than a decade ago still work on the much faster modern architectures? And can we integrate them in modern Prolog (or LP) engines?

We believe that the answer to this question lies in recent progress on supporting *multi-threading* in Prolog engines. Motivated by the desire to support concurrent applications and explicit parallelism in systems such as Ciao (Carro and Hermenegildo 1999) and SWI-Prolog (Wielemaker 2003), multi-threading has now become widely available in Prolog engines, such as YAP (Santos Costa 2008) and XSB Prolog (Marques et al. 2010). Nowadays, supporting threads can be seen as a requirement of modern Prolog engines, not an extension.

To demonstrate the feasibility of implicit parallelism in thread-based systems, we revive and redesign the YapOr system (Rocha et al. 1999) to exploit or-parallelism based on a multi-threaded implementation. YapOr is an or-parallel engine, originally based on the stack copying model, as first implemented in the Muse system (Ali and Karlsson 1990b), that extends the YAP Prolog system to support implicit or-parallelism in logic programs. Our new approach takes full advantage of YAP's state-of-the-art fast and optimized engine and shares the underlying execution environment, scheduler and most of the data structures used to support parallelism in YapOr. Our new design thus unifies YAP's multi-threaded support with YapOr's or-parallelism support. We named our new approach the *Threads and Or-parallelism unified (ThOr)* model.

To put the performance of our new implementation in perspective, we experimented with the system on a number of different computing platforms and compare it against the copy based YapOr. Initial experiments with both systems consistently achieve almost linear speedups for a large number of applications, and good speedups even if parallelism is very fine-grained. On the other hand, ThOr benefits from its simpler architecture and we show ThOr running on two platforms where porting YapOr would be non-trivial. Thus, we believe it is as an excellent alternative for exploiting implicit parallelism in a portable way in the currently available low cost multi-core architectures.

The remainder of the paper is organized as follows. First, we briefly introduce the YapOr model and describe its main data structures, memory organization and scheduler strategies. Then, we present our new multi-threaded implementation, describe its major implementation decisions and discuss its advantages, disadvantages and challenges. At last, we present experimental results and we end by outlining some conclusions.

2 The YapOr Model

The initial implementation of or-parallelism in YapOr was largely based on the *stack copying model* as first introduced by Ali and Karlson in the Muse system (Ali and Karlsson 1990b; Ali and Karlsson 1990a). YapOr is an example of a *multi-sequential* model (Ali 1986). In this approach, each processor or *worker* maintains its own copy of the search tree where it is expected to spend most of its time performing reductions. Only when a worker runs out of work, it searches for work from fellow workers. If a fellow worker has work, it can make some or all of its open alternatives available: this operation is called *sharing.* First, the sharer will make some or all of its choice-points *public*, so that backtracking to these choice-points can be synchronized between different workers. Second, in a copying model, the execution stacks of the sharer are copied to the requester. The sharer then continues forward execution, while the requester backtracks to the shared choice-points and exploits alternatives.

Deciding which workers to ask for work and how much work should be received is a function of the *scheduler.* For stack copying, scheduling strategies based on bottommost dispatching of work have proved to be more efficient than topmost strategies (Ali and Karlsson 1990a). Synchronization between workers is mainly done through choice-points. In an copying model, each worker has a separate copy of the public choice-points. Synchronization requires an auxiliary data structure, called *or-frame*, to be associated with the public choice-points. We next discuss in more detail some of these features and characteristics of the original YapOr model.

2.1 Or-Frames and Public Choice-Points

In order to correctly exploit a shared branch, a fundamental task when sharing work is to turn public the private choice-points. Public choice-points are treated differently because we need to synchronize workers in such a way that we avoid executing twice the same alternative. To do so, the worker sharing work adds an *or-frame* data structure to each private choice-point made public. The or-frames form a tree that represents the public search tree. Figure 1 illustrates the relation between the choice-points before and after that operation.

In YapOr, a choice-point includes eight fields, the first six were inherited from YAP and the last two were introduced by YapOr. The `CP_OR_FR` field points to the corresponding or-frame, if the choice-point is public. Otherwise, it is not used. The `CP_LUB` field (LUB stands for “Local Untried Branches”) stores the number of private unexplored alternatives in the current branch, and it is used to compute the worker’s load. Sharing a choice-point involves updating the `CP_OR_FR` and `CP_ALT` field, respectively, to the newly created or-frame and to the `getwork` pseudo-instruction. Backtracking to a shared choice-point will thus always trigger the exe-

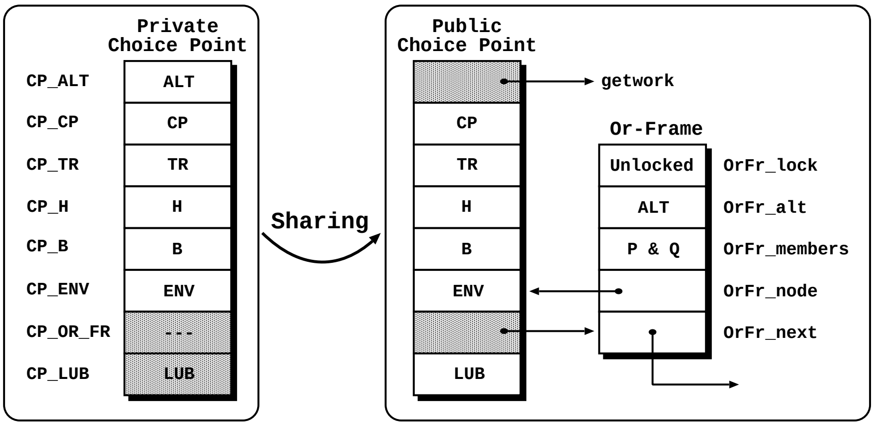


Fig. 1. Sharing a choice-point

cution of the `getwork` instruction and its execution allows for a synchronized access to the untried alternatives among the workers sharing the corresponding or-frame. The or-frame is initialized as follows. The `OrFr_lock` field supports a busy-wait locking mechanism that guarantees atomic updates to the or-frame data. It is initially set to unlocked. The `OrFr_alt` field stores the `ALT` pointer which was previously in the `CP_ALT` choice-point field (i.e., the control of the untried alternatives moves to the or-frame). The workers sharing the choice-point are marked in the `OrFr_members` field. `OrFr_node` is a back pointer to the corresponding choice-point. Last, the `OrFr_next` field is a pointer to the parent or-frame on the current branch.

2.2 Incremental Copying

Sharing work is a major source of overhead in YapOr, as it requires copying the execution stacks between workers. The *incremental copying strategy* (Ali and Karlsson 1990b) is designed to reduce this overhead by allowing the receiving worker to keep those parts of its execution stacks that are consistent with the giving worker, and only to copy the differences between the two workers' stacks.

For example, consider that worker Q asks worker P for sharing and that worker P decides to share its private nodes with Q. To implement incremental copying, Q should start by backtracking to the youngest common node with P, therefore becoming partially consistent with part of P. Then, if Q receives a positive answer from P, it only needs to copy the differences between P and Q. These differences can be easily calculated through the information stored in the common node found by Q and in the top registers of the local, heap and trail stacks of P. Care must be taken about variables older than the common youngest node that were bound by worker P, as incremental copying does not copy these bindings. Worker Q needs to explicitly *install* the bindings for such variables. This process, called the *adjustment of cells outside the increments*, is implemented by searching the trail stack for bindings to variables older than the common node (Ali and Karlsson 1990b).

2.3 Memory Organization

The YapOr memory is divided into two major *shared* address spaces: the *global space* and a collection of *local spaces*. The global space contains the code area inherited from YAP and all the data structures necessary to support parallelism. Each local space represents one system worker and contains the four execution stacks inherited from YAP: heap, local, trail, and auxiliary stack.

In order to efficiently meet the requirements of incremental copy, the set of local spaces are mapped as follows. The starting worker asks for shared memory in the system's initialization phase. Afterwards, the remaining workers are created and inherit the previously mapped address space. Then, each new worker rotates the local spaces, in such a way that all workers will see their own spaces at the same virtual memory addresses.

Figure 2 helps to understand this remapping scheme. It considers 3 workers and it illustrates the resulting mapping address view of each worker after rotating the inherited local spaces. The global space is shared at the same virtual address ($Addr_0$ in Fig. 2) for the 3 workers and each worker accesses its own local space starting from the same virtual address ($Addr_1$ in Fig. 2). The figure also shows an example or-frame (as an oval) allocated in the global space and the corresponding choice-points (as squares) for the workers sharing it, workers 1 and 3. Notice that this virtual memory trickery allows the same or-frame to point to different copies of the same choice-points, depending on the worker. This mapping scheme also allows for efficient memory copying operations during incremental copying because no reallocation of address values in the copied segments is necessary. To copy a stack segment between two workers, we simply copy directly from one worker space to the relative virtual memory address in the other worker's space.

In YapOr, this memory scheme is implemented through two different and alternative UNIX shared memory management functionalities, the *mmap()* and *shmget()* functions (Stevens 1992). These functions allow us to map shared memory segments at given addresses, and unmap and remap them later at new addresses.

2.4 Scheduling Strategies

When a worker runs out of work, first the scheduler tries to select a busy worker with excess of work load to share work. There are two alternatives to search for busy workers in the search tree: search below or search above the current node. Idle workers always start to search below the current node, and only if they do not find any busy worker there, they search above. The main advantage of selecting a busy worker below instead of above is that the idle worker can request immediately the sharing operation, because its current node is already common to the busy worker, which avoids backtracking in the tree and undoing variable bindings.

When the scheduler does not find any busy worker with excess of work load, it tries to move the idle worker to a better position in the search tree. By default, the idle worker backtracks until it reaches a node where there is at least one busy worker below. Another option is to backtrack until reaching the node that contains

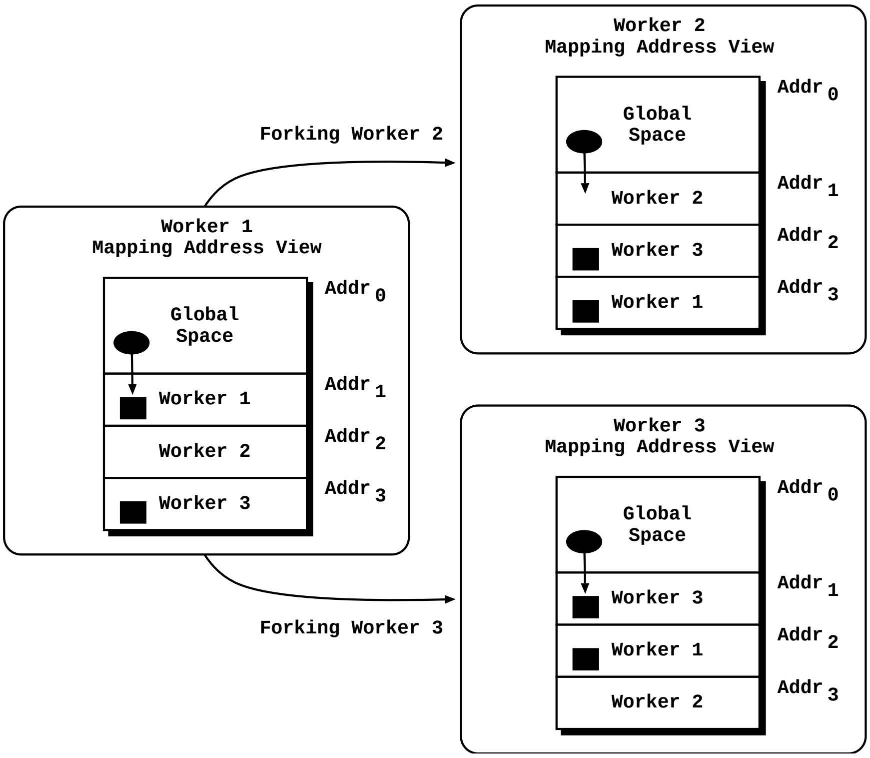


Fig. 2. YapOr's memory organization for 3 workers

all the busy workers below. The goal of these strategies is to distribute the idle workers in such a way that the probability of finding, as soon as possible, busy workers with excess of work below is substantially increased.

Although other memory organization models have performed well for smaller numbers of workers, stack copying has consistently shown to provide better scalability, while achieving low overheads.

3 The ThOr Model

The ThOr model builds upon two major components of YAP: the YapOr implementation, as discussed in the previous section, and the threads library (Santos Costa 2008). The YAP thread library can be seen as a high-level interface to the POSIX threads library, where each thread runs on a separate stack but shares access to the global data structures (code area, atom table and predicate table). As each thread operates its own stack, thus, it is natural to *associate* each parallel worker to a thread: threads can run in parallel and they already include the machinery to support shared access and updates to the global data structures and input/output structures.

Notice however that not all threads have to be workers: some threads may be used to support specialized tasks, possibly running in parallel with the workers. We believe this is an important advantage of ThOr. Traditionally, we expect to find a single *or-parallel* program, and issues such as side-effects must be addressed within the or-parallel system. In ThOr, we can easily construct independent threads that *collaborate* or even *control* the workers (or-parallel threads). Natural applications are the collection of solutions, and performing input/output tasks.

3.1 Memory Model

Three different or-parallel models have been implemented for YAP: the Sparse Binding Array (SBA) model (Correia et al. 1997), the α-COW model (Santos Costa 1999) and YapOr's copying model. Of the three models, the α-COW relies on process forking and is therefore not suitable for a thread-based implementation. This leaves us with two choices: models sharing as much data structures as possible, such as the SBA; and copying based models, such as the default YapOr model. We chose to use copying for ThOr for several reasons:

1. Copying allows us to preserve a key notion in the thread library: independent and separate workers have a *private* stack. In this way, we can reuse the existing code for threads so that workers can independently perform garbage collection and stack shifting.
2. Because workers see a contiguous stack, copying imposes less overheads on the engine and has high performance compared to the other approaches (Santos Costa et al. 2000).
3. Ultimately copying is less intrusive on the sequential engines. As a small experiment, we explored what kind of changes would be needed in the emulator. In both models, support for or-parallelism, including copying, requires about 60 changes to the emulator, mostly in order to adapt choice-point manipulation and to perform pruning on the shared tree. Support for the SBA model requires 90 additional changes that affect a complex operation, unification.

On the other hand, YapOr's copying model relies on every worker *having its own stacks at the same virtual address position.* This clearly will not work with threads. Next, we discuss how we have addressed this problem.

3.2 Shifted Copying

In a thread-based model, all memory areas should be visible to all threads *at the same virtual memory address positions.* Moreover, in order to take full advantage of memory (especially on 32 bit machines), it is convenient not to assume any preconditions on memory organization. In YAP, threads may actually move their stacks in the virtual memory space during execution.

The α-COW, SBA and copying models share most of the scheduling and work management code and all models assume that every worker has its own stacks at the same virtual memory addresses. ThOr has also been designed to take advantage of the existing code-base but, having each own stack at the same virtual memory addresses, does not hold true in ThOr. Namely, to share work we need to have several copies of the same choice-point at different virtual memory addresses. To

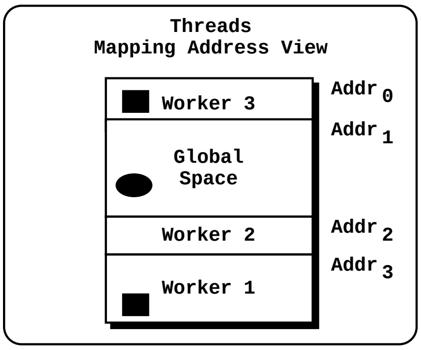


Fig. 3. ThOr's memory organization for 3 workers

address this problem, our key idea is *shifted copying*, which essentially consists of two steps: copy the memory between the workers sharing work and then adjust pointers. Although shifted copying adds a linear overhead to copying operations, it offers some important advantages:

1. it allows using the thread infra-structure as is;
2. it allows shifting between stacks *with different sizes*, and we can actually reuse preexisting code from the YAP stack shifter.

The resulting memory model for ThOr is presented in Fig. 3. Notice that we do not assume any fixed order addresses between stacks, and that we do not assume equal stack sizes. Initialization code now consists of creating $N-1$ or-parallel threads (and it is in fact simpler than the initialization code for the other models). Choice-points in ThOr are stored as *offsets* from the top of stack: ThOr takes advantage of the fact that YAP does not perform garbage collection on the local stack. Translation between addresses and offsets is performed by a *setter* and a *getter* method. As in YapOr, one can copy the whole stacks, or perform *incremental copying.* The latter is quite often much more efficient, and we discuss it in some more detail next.

3.3 Work Sharing Algorithm

We next describe the work sharing algorithm used in ThOr. We assume that worker P gives work to worker Q. The algorithm for P is shown in Fig. 4 and the algorithm for Q is shown in Fig. 5. Notice that the *signal[]* array is used to synchronize between the two workers and that, by default, all entries are in *ready* mode.

Worker P uses $share\_private\_nodes()$ to make all its choice-points public. In practice this entails creating a new or-frame per choice-point and waiting for worker Q. Our implementation moves most of the work to worker Q: this worker is the one who actually copies the stacks and adjusts the cells in the stacks. Copying may be done incrementally or the full stacks may be copied. By default, ThOr uses incremental copy, but full copy may be required after a garbage collection. Last, for incremental copy ThOr copies *and adjusts* cells outside the increments (mentioned in Section 2.2), as required by the copying model.

```
P_SHARE $(p, q)$ {
  $share\_private\_nodes(q)$
  $signal[q] = nodes\_shared$
  wait_until $(signal[q] == ready)$
}
```

Fig. 4. Giving Work

```
Q_SHARE $(p, q)$ {
  wait_until $(signal[q] \neq ready)$
  $copy\_registers(p, q)$
  if $(INCREMENTAL\_COPY)$
    $copy\_stacks(p, q, deltas)$
    $copy\_trailed\_entries(q, p)$
    $signal[q] = ready$
    $adjust\_stacks(deltas)$
  else
    $copy\_stacks(p, q, full\_stacks)$
    $signal[q] = ready$
    $adjust\_stacks(full\_stacks)$
  endif
}
```

Fig. 5. Receiving Work

3.4 ThOr in Practice

We have so far discussed the main principles of ThOr implementation. Next, we discuss some important practical questions that we should address to make ThOr usable in practice.

Sequential and Parallel Predicates One major burden for or-parallel systems has been the need to fully support Prolog semantics. We believe we should follow a different approach. In ThOr, or-parallel execution is a component in a multi-threaded system, and should focus on executing pure Prolog programs.

Therefore, ThOr will not impose sequential execution of system built-ins. Notice that synchronization of side-effects was already supported in YapOr, and it is still possible, just it is not the default execution mode.

Locking ThOr allows for two types of locking: low-level high-performance code, and POSIX threads locks. The low-level locks are busy-waiting locks written in assembly. We should observe that the locking and scheduling protocols used in YapOr rely extensively on busy-waiting. As a result, workers that are waiting for new tasks will still consume CPU resources. This is a reasonable solution for dedicated hardware, but it is not acceptable for personal workstations. In this case, the scheduling code must be rewritten so that idle workers will not hog the CPU.

Global Variables The `nb_` and `b_` primitives maintain global variables (Demoen et al. 1998), by associating a name, represented as a Prolog atom, to a term. In the backtrackable version, or `b_`, the association is discarded on backtracking; in the non-backtrackable version, the association can be seen as a global property. These primitives are quite widely used, e.g., they are crucial in the implementation of constraint libraries.

The SWI-Prolog (and YAP) thread libraries deem global variables to be *thread-private*. Each thread maintains separate lists of different global variables, and threads cannot access other thread's global variables. The current implementation of ThOr follows this approach: we simply keep global variables on the original thread. We believe this approach does not correspond well with or-parallelism, as each thread now logically implements a snapshot of the *same* stack:

- `b_` variables are in fact just a different way of accessing stack objects, and should be copied as any other variables by the stack copying mechanism.
- `nb_` variables should be seen as shared between all threads that work together in or-parallel. This suggests that these variables should be stored in a common area.

In order to provide support for `nb_` variables, a separate data area for global variables should exist and be shared between threads.

4 Experimental Results

Our performance evaluation focuses on three aspects:

- Performance of well known Prolog on the ThOr implementation.
- Performance of ThOr in comparison with that of YapOr and sequential YAP.
- Scalability of ThOr on a multi-core machine of reasonable size.

The following programs were used as benchmarks:

- `cubes`: a known benchmark taken from Tick's book (Tick 1987). This program implements the solution of a magic cube of size 7.
- `fp`: this is an implementation of a floor plan design, originally implemented by Kovács (Kovács 1992), which represents a real-world application. The task is to partition a floor rectangle according to a room request list consisting of room sizes and constraints such as rooms that face north or have natural light.
- `ham`: checks if a given graph forms a Hamiltonian cycle.
- `magic`: a solution to the 3x3x3 magic cube.
- `map` and `mapbigger`: a solution for the map coloring problem using 4 colors. We used two maps representing diverse size and graph density. The smaller version has 10 nodes and the bigger version has 17 nodes.
- `puzzle`: one version of sudoku where the diagonals must add up to the same amount.
- `puzzle4x4`: a solution for a 4x4 maze.
- `queens`: a solution for the n-queens problem using forward checking. The size of the board used in testing was 13x13.

We performed our experiments on 2 different machines. The first is an Intel(R) Core(TM)2, quad-core CPU Q9450 with 4 GBytes of RAM and running Mandriva Linux in 32-bit mode. The second machine is a Dell Poweredge R905, 4 six-core Opteron 8425HE (2.1Ghz) with 64 GBytes of RAM and running Fedora 12 in 64-bit mode.

Table 1 shows the base execution times (running on a single core), in seconds, for all benchmarks in both machines. Each benchmark was run at least 20 times. The results shown in the Table 1 are the averages of these runs. In this Table, we also show the base execution times of sequential YAP. The numbers between parentheses correspond to the overhead imposed by YapOr or Thor when compared with sequential YAP.

Table 1. *Average execution times, in seconds, for single core of YapOr and ThOr on a Linux quad-core desktop machine and on a Linux 4 six-core server machine, compared with sequential YAP*

Benchmark	**Quad-Core**			**4 Six-Core**		
	YAP	**ThOr**	**YapOr**	**YAP**	**ThOr**	**YapOr**
`cubes`	0.11	0.11 (1.00)	0.11 (1.00)	0.20	0.23 (1.15)	0.20 (1.00)
`fp`	1.47	2.36 (1.61)	1.71 (1.16)	2.51	3.29 (1.31)	2.67 (1.06)
`ham`	0.15	0.29 (1.93)	0.19 (1.27)	0.33	0.46 (1.36)	0.34 (1.03)
`magic`	25.07	27.55 (1.10)	27.80 (1.11)	40.29	48.88 (1.21)	41.16 (1.02)
`map`	12.20	20.25 (1.66)	14.60 (1.20)	24.06	30.45 (1.26)	23.94 (0.99)
`mapbigger`	33.01	55.26 (1.67)	39.63 (1.20)	64.46	81.09 (1.25)	65.90 (1.02)
`puzzle`	0.08	0.13 (1.63)	0.08 (1.00)	0.15	0.20 (1.34)	0.17 (1.13)
`puzzle4x4`	6.02	7.18 (1.19)	6.47 (1.07)	9.17	10.34 (1.12)	9.38 (1.02)
`queens`	21.79	24.54 (1.13)	24.12 (1.11)	48.10	51.63 (1.07)	48.73 (1.01)
Average		(1.44)	(1.12)		(1.23)	(1.03)

Table 1 shows a higher significant distance between base execution times of YapOr and ThOr on the quad-core desktop than the distance observed on the 4 six-core server. One important difference between the two machines is that the quad-core is running in 32-bit mode, and the 4 six-core in 64-bit mode. In general, YAP has been better optimized for 32-bit mode, and the overhead of supporting YapOr is more noticeable in this mode. Namely, the parallel code always tests for work requests, even if there is a single worker.

In the 4 six-core server, the YapOr version almost has no overheads in these benchmarks. These overheads range from 0 (for `map`, where the performances of Yap and YapOr are practically the same plus or minus a rounding error) to 13% (for `puzzle`). ThOr incurs a higher overhead that ranges from 7 to 36%. This is partly because threads need to disable some optimizations in YAP (namely, abstract machine arguments cannot be at fixed addresses). But, most importantly, threads require indirect access to thread-private global variables, including the abstract machine registers. This overhead can be reduced by ensuring that every function has a local variable pointing to the abstract machine, but the optimization is currently only implemented in the emulator, but not in the built-in predicates compiled inline.

Figures 6 and 7 compare the speedups of YapOr and ThOr for each benchmark in the quad-core and in the 4 six-core server. We achieve quasi-ideal speedups for almost all benchmarks in the quad-core machine. In the 4 six-core server, ThOr and YapOr manage to achieve quasi-linear speedups in all applications that have enough parallelism for 24 processors. Amongst the real-world applications, `fp` achieves very good speedups even for 24 processors. It is interesting to notice that ThOr is capable of extracting parallelism and achieving good speedups even from the smallest benchmarks.

Obviously, for larger numbers of cores, one may eventually observe a drop in performance as is the case of `fp`, in the quad-core machine, with 4 processors (Figure 6(b)).

The threaded version may produce results such as the ones observed for the application `map`, in Figure 7(e), where it achieves super-linear speedups. The application has no pruning, and the speedups tend to improve as we add more cores. This suggests the speedup may be memory related, and caused by cache effects.

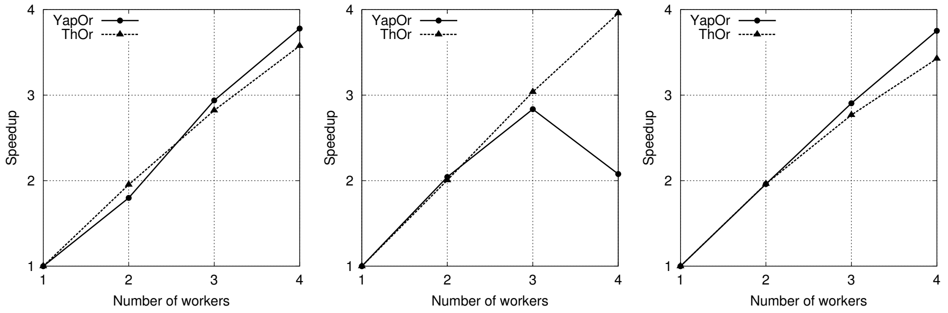
It is also interesting to show performance results on a dual-core laptop. In this case, we use an Apple MacBook Pro 2.5 GHz Intel Core 2 Duo with 4 GBytes of RAM. The machine can run two operating systems: Mac OS X version 10.6.2 and Windows Vista. We experiment with both operating systems on a relatively idle machine (although not in single user) and report average run-time for one and two workers (please see Table 2). Notice that YapOr requires Unix, so it could not run in either of these two configurations.

Table 2. *Average execution times, in seconds, for one and two cores of ThOr on an Apple laptop machine running OS X and Windows Vista*

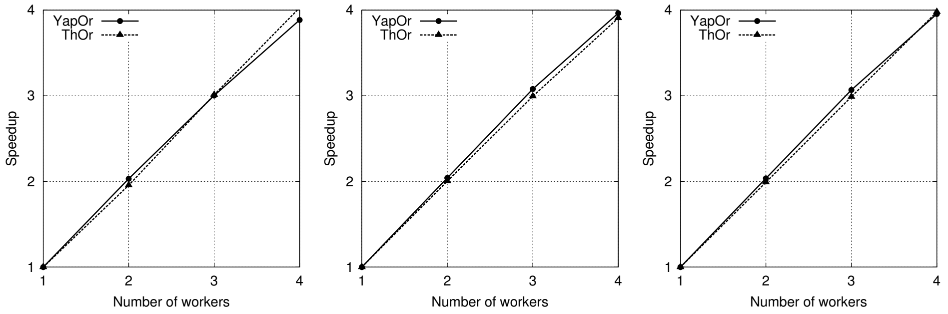
Benchmark	**OS X**		**Windows Vista**	
	1	**2**	**1**	**2**
`cubes`	0.103	0.056 (1.84)	0.156	0.078 (2.00)
`fp`	1.930	1.040 (1.86)	3.500	1.790 (1.96)
`ham`	0.220	0.110 (2.00)	0.530	0.280 (1.89)
`magic`	27.500	15.000 (1.83)	30.700	15.600 (1.97)
`map`	15.800	9.000 (1.76)	33.500	17.700 (1.89)
`mapbigger`	43.500	23.500 (1.85)	92.900	49.000 (1.90)
`puzzle`	0.100	0.055 (1.82)	0.220	0.110 (2.00)
`puzzle4x4`	6.900	3.700 (1.86)	8.980	4.600 (1.95)
`queens`	24.100	13.200 (1.83)	29.700	15.000 (1.98)
Average		(1.85)		(1.94)

Our results clearly show significant speedups in exploiting or-parallelism on modern multi-core architectures. In fact, we obtain linear speedups for some applications up to very larger number of cores. It is impressive that these speedups were based on what is a twenty years old design. The key ideas, copying and bottom-most sharing, seem to perform as well today as they did when they were proposed.

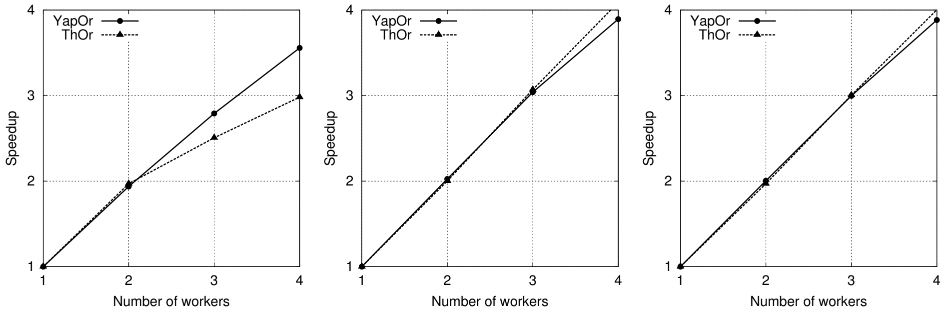
A second observation is that there is a wide variation on the baseline, depending on the operating system and execution mode. A deeper analysis shows that this variation largely depends on execution mode, compiler used, and support for threads. Support for threads in YAP is quite expensive, because YAP was designed



(a) `cubes` (b) `fp` (c) `ham`



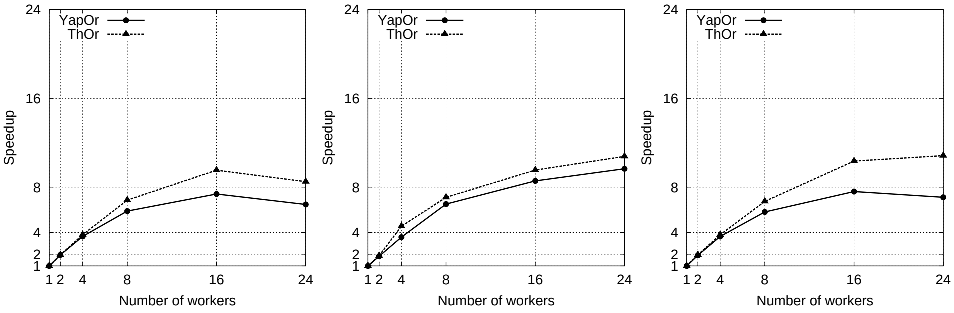
(d) `magic` (e) `map` (f) `mapbigger`



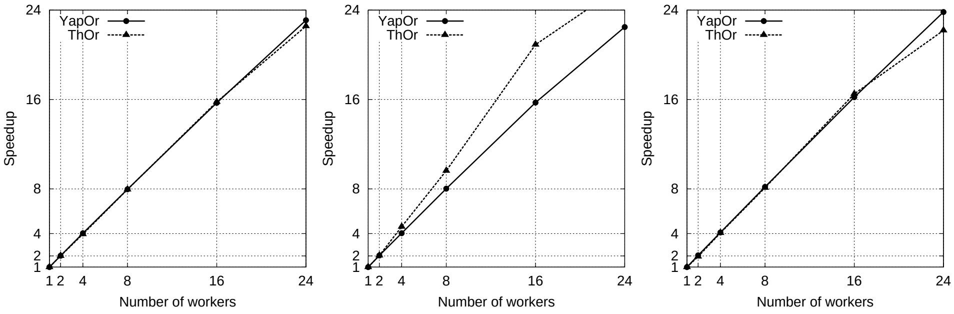
(g) `puzzle` (h) `puzzle4x4` (i) `queens`

Fig. 6. Speedups for benchmark applications on the Linux quad-core desktop machine

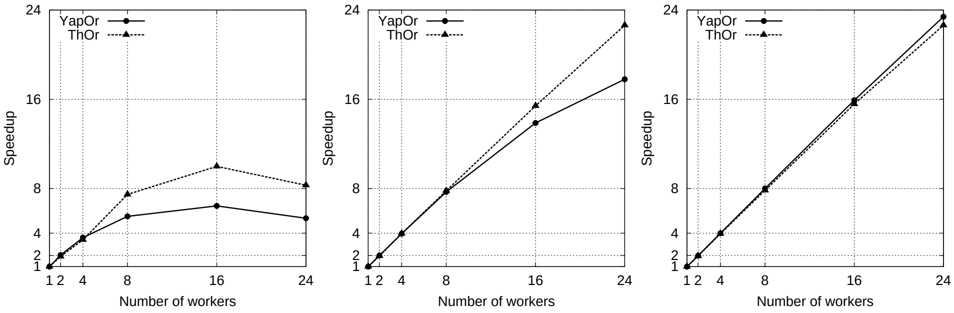
around global variables and multiple threads require the use of private variables for each thread. On the other hand, we believe that ThOr overheads can be easily reduced, and ThOr guarantees speedup on a wide range of machines and operating systems.



(a) `cubes` (b) `fp` (c) `ham`



(d) `magic` (e) `map` (f) `mapbigger`



(g) `puzzle` (h) `puzzle4x4` (i) `queens`

Fig. 7. Speedups for benchmark applications on the Linux 4 six-core server machine

We also observe that both ThOr and YapOr yield very close speedups for almost all applications. This is partly because some of these applications are relatively small, and incremental copying makes the cost of copying and adjusting addresses a very minor component of the cost equation. Indeed, in examples such as `queens`, the overheads are not very noticeable because the parallel work is coarse-grained thus minimizing the number of copies. For a run of 13 queens we measured from 4 to 7 work sharing operations between two workers during the run-time of approximately 20 seconds. On the other hand, ThOr seems to be doing better than YapOr even in fine grained benchmarks. This deserves further investigation, but is probably because its baseline performance is worse.

One important advantage of ThOr is that it relies only on thread support: nowadays, POSIX thread support can be found even in Windows systems, although the significant loss of performance we found suggests POSIX thread implementations may not always be up to the best. The fact that ThOr can run in a wide variety of platforms, and achieves good speedups, is a major advantage of this proposal over previous systems.

5 Conclusions and Further Work

We presented ThOr, a novel system for the exploitation of or-parallelism in logic programming systems. Our approach is based on threads, but differs from other proposals (Casas et al. 2008; Moura et al. 2008; Moura et al. 2009) in that, instead of building a system from scratch by using a high-level approach, we reuse as much possible the excellent previous work in parallel logic programming. Our results indicate that our approach has three main advantages: it allows excellent scalability, and the trend is to expect more cores per computer; it allows good performance on fine-grained tasks, with such speedups being quite useful for users running laptops or personal desktops; it provides an excellent parallel engine with dynamic scheduling for irregular applications.

We can see a large number of future paths for ThOr. One obvious path is to make the system more robust and to experiment with different scheduling strategies, such as stack-splitting (Pontelli et al. 2006). A second direction is to experiment with more applications, namely with tabled programs and with constraint programs. We believe our task will be simplified by the fact that YAP already supports a number of constraint solvers. Last, but not least, we believe our approach gives logic programming a strategy to combine both implicit and explicit parallelism. Our goal is to have specialized threads that can do input/output or that can just take care of sequential execution and offload parallelizable tasks to or-parallel servers. We believe that such a flexible approach will be a key for parallel logic programming to fulfill its great promise.

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