Parallel Implementation of Large Scale Agent-based Models in Economics

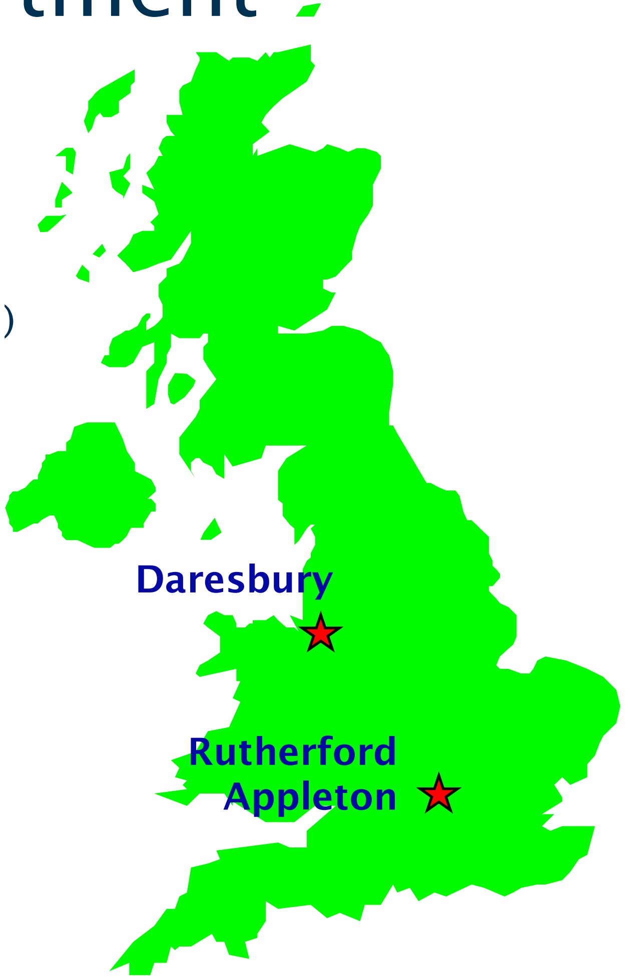
Prof C Greenough, LS Chin and Dr DJ Worth
Software Engineering, STFC Rutherford Appleton Laboratory

Prof M Holcombe, Dr Simon Coakley and Dr Mariam Kiran
Computer Science, Sheffield University

Contents

The Computational Science and Engineering Department

- STFC (Science and Technology Facilities Council) has two main Laboratories with around 1500 staff in total:
  - Daresbury Laboratory (near Warrington) and at
  - the Rutherford Appleton Laboratory (near Oxford)
- Computation Science & Engineering has around 100 research and support staff
- Development and application simulation codes
  - Usually collaborating with Universities
  - Emphasis on high performance
- Interests in Science and Engineering



Large Scale Facilities at the Rutherford Appleton Laboratory

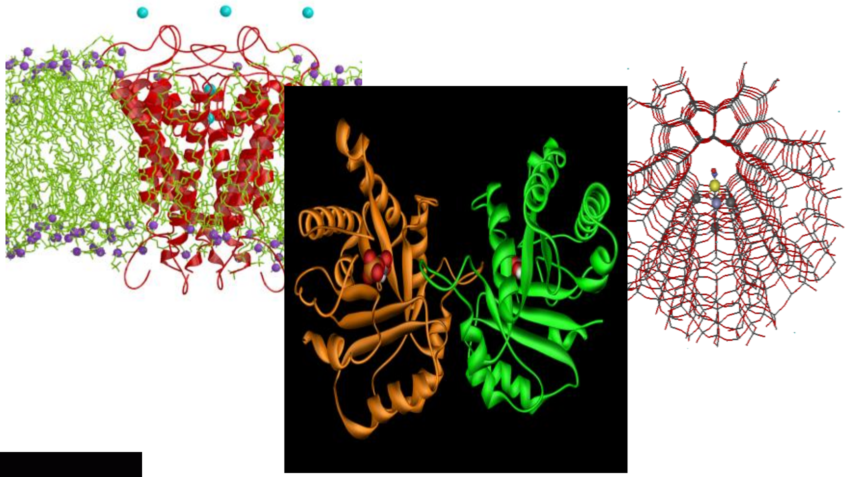
Rutherford Appleton Lab

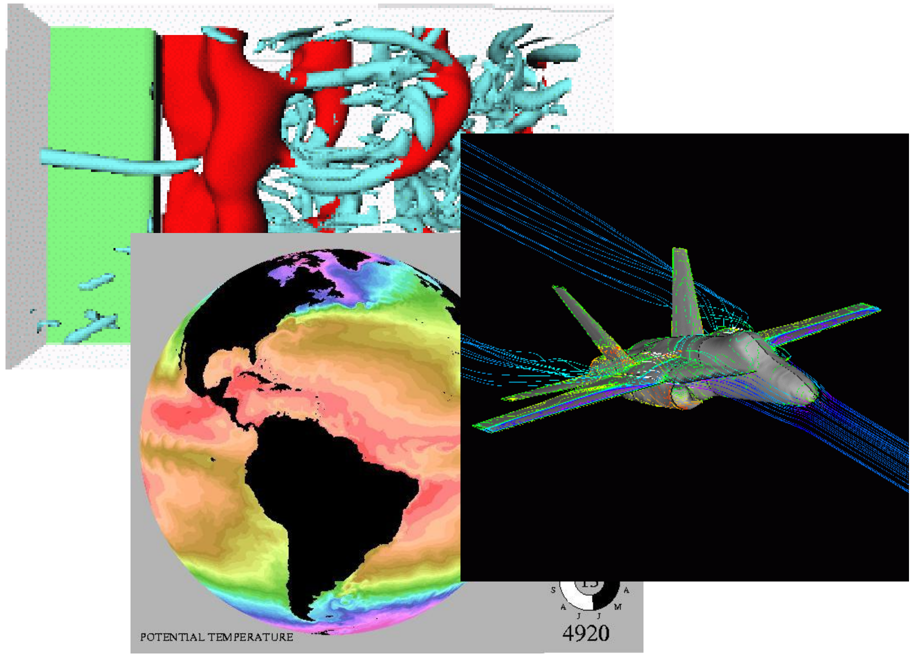
ISIS Neutron Source

Diamond Light Source

Computational Science & Engineering

- Material Sciences
- Life Sciences
- Systems Biology

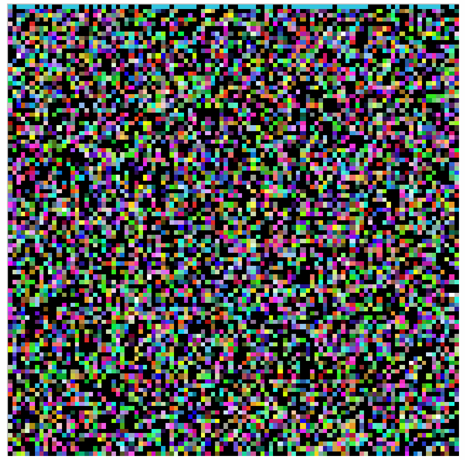


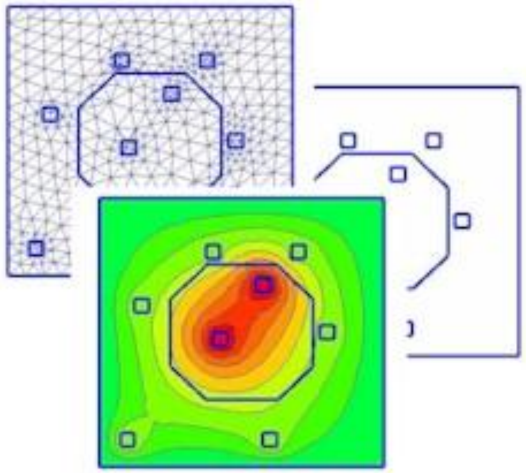


- Computational Engineering
- Ocean/Climate Modelling
- Advanced Algorithms
- Numerical Analysis
- Software Engineering
- Novel Hardware

Software Engineering Group

- Software Engineering Support Programme (SESP)
  - Practical/Pragmatic software engineering methods
  - Development of software engineering tools
  - Education – workshop, seminars, tech reports...
- Intelligent Agent Technology
  - Agent-based frameworks and algorithm
  - Biological Systems
  - EURACE – EU Economic Modelling





- Applications
  - CFD
  - Heat transfer
  - Electromagnetics
  - Semi-conductors
  - Space detectors
- Parallel Algorithms

Acknowledgements

This research is funded by the European Union via the EURACE project (No 035086) which aimed to build a large scale agent-based model of the European economy to aid economic policy design.

The project required the development of an integrated multi-agent model of economic and financial markets and the development of software techniques and a software platform for large-scale agent-based economic simulations.

Acknowledgements

The EURACE Project Partners:

- Economics/Finance
  - Università degli Studi di Genova (UG) Italy (*Coordinator*)
  - Universitaet Bielefeld (UNIBI) Germany
  - Université de la Méditerranée (GREQAM) France
  - Università Politecnica della Marche (UPM) Italy
- Software Engineering:
  - University of Sheffield (USFD) UK
  - Università degli Studi di Cagliari (UNICA) Italy
  - STFC Computational Science & Engineering Dept (STFC) UK
  - National Research Institute of Electronics and Cryptology (UEKAE) Turkey

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Why High Performance Computing?

- Implementing software on an high performance system is difficult and time consuming so there must be a good reasons to embark on the task:
  - Application can not be run on a conventional computing system – insufficient power and/or memory:
  - Agent population to large (m/p)
  - Agents are too complex (m/p)
  - Number of simulations to large (p)
    - ➔ Policy experiments
    - ➔ Validation process
    - ➔ Optimisation

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Some Issues in High Performance Computing

- Parallel systems are in constant development
- Their hardware architectures are ever changing
  - simple distributed memory on multiple processors
  - share memory between multiple processors
  - hybrid systems –
    - clusters of share memory multiple processors
    - clusters of multi-core systems
  - the processors often have a multi-level cache system

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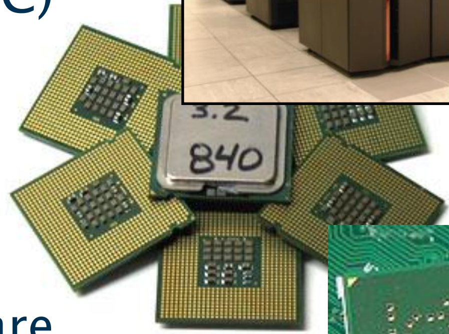
Some More Issues in High Performance Computing

- Most have high speed multi-level communication switches
- Cloud/GRID architectures are now being used for very large simulations
  - many large high-performance systems
  - loosely coupled together over the internet
  - Specialised programming interfaces – no standards
- Performance can be improved by optimising to a specific architecture
- Can very easily become architecture dependent
- Cost – most serious HPC machines can be very expensive

Computing Systems

- Workstations/Desktop Systems:
  - Multi-core processors (4,8....)
  - Add-on processors (GPGPU..)
- High Performance Computing (HPC) Systems:
  - Large multi-processor system (thousands of processors)
  - Coupled Multi-core systems
  - Complex communications hardware
  - Specialised attached processors (vector units, cells..)



Parallelism does not come for free!!

- Cannot magically transform a program to run efficiently on a parallel system
- Algorithm must be suitable for parallelisation
- There are such things as non-parallelisable algorithms
- Elements of work must localised – minimal dependencies on other task!
- Communication and synchronisation between processors significant overheads – so communication between task must be minimised

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FLAME
Flexible Large-scale Agent Modelling Environment

- An agent-based modelling framework
- Initially developed by Simon Coakley (University of Sheffield). Extended in collaboration with STFC.
- Originally targeted at biological systems
- Developed further under the EURACE project:
  - Now support larger class of models (e.g. economic models)
  - Extension of the X-Machine Markup Language (XMML)
  - Optimised performance (serial and parallel)
  - Ported to various HPC machines (supercomputers) and Operating Systems

How is FLAME different?

- It is a generic ABM program generator
- It has been design with HPC in mind – written in C using MPI to manage communications
- Components are: model parser, a template library and a run-time library
- Uses a model definition written a dialect of XML together with user provided C code for agent functions
- It uses the concept of *Message Boards* for inter-agent communication
- Uses an agent dependency graph to schedule and optmise agent function (state change) activations
- Generates: the application and builder files for serial and parallel execution

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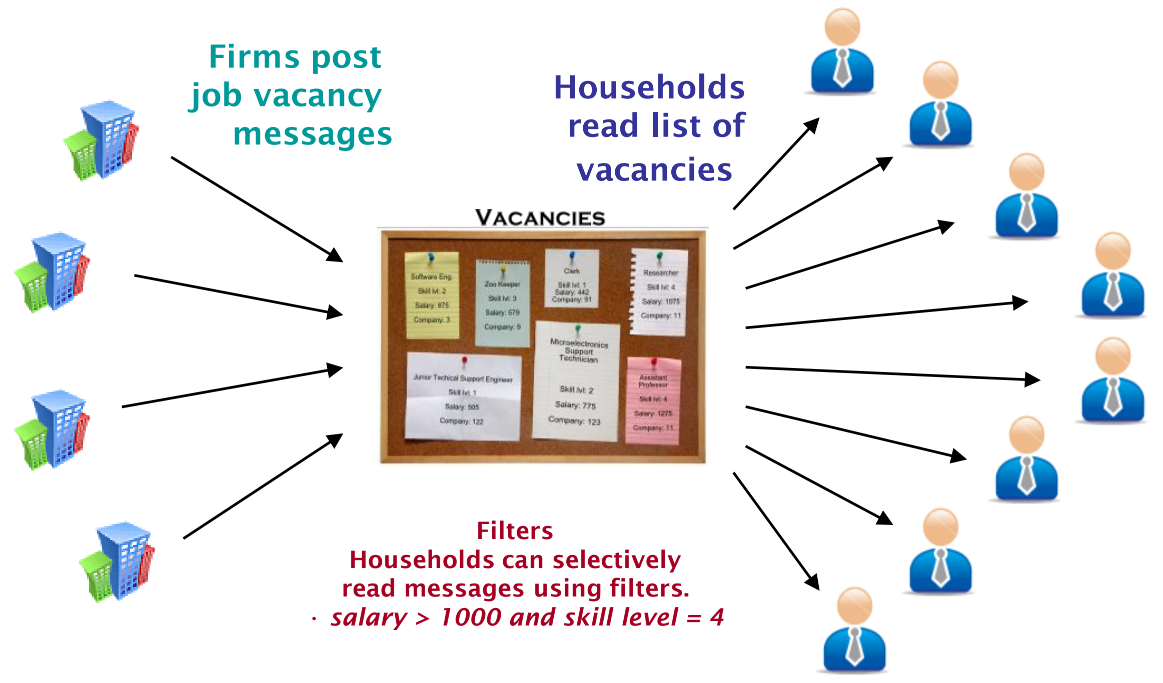
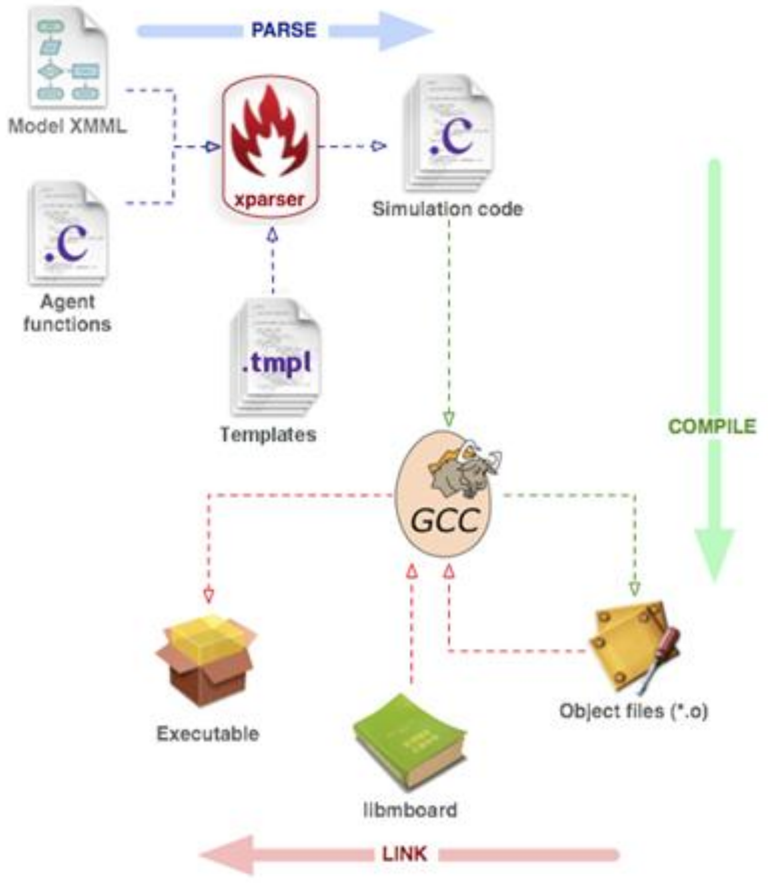
Message Boards


Firms post job vacancy messages
Households read list of vacancies
VACANCIES
Filters
Households can selectively read messages using filters.
· *salary > 1000 and skill level = 4*

- All inter-agent communications are through messages boards
- There is a message board each message type within the model
- Messages only have two states – *read* or *write* (*no read/write*).
- The *message board library (libmboard)* manages these

The FLAME Process

- Input from the modeller:
  - Model – XMML file
  - C-code for functions
- Input from FLAME
  - *Template* file
  - Header files
- Output from FLAME
  - Applications code
  - State diagram



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Creating a model

- What do we need to define:
- **Agents**
  - Memory
  - Behaviour – functions/states/communications
- **Messages** (information flow between agents)
- **Optional extras**
  - Environment constants
  - Custom data types
  - Custom time units

Specifying a Model using XMML

- XMML is a dialect of XML (X-Machine Agent Mark-up Language)
- Standard set of XML tags
- Simple editable text file
- File has three main sections: *models, environment*, *agents* and *messages*
- EURACE develop a tool set to help model developers and users

XMML – Overall Structure

```
<xmodel >
    <name>circles</name>
    <models>
      <model>.... </model>
    </models>
    <environment>
      <constants>.... </constants>
      <functionfiles>.... </functionfiles>
      <timeUnits>.... </timeUnits>
    </environment>
    <agents>
      <xagent>.... </xagent>
    <messages>
      <message>....      </message>
    </messages>
</xmodel>
```

Programmers FLAME API

- Interface to agents and Framework
- Sending & receiving messages
  - *get_next_<message name>_message*
  - *add_<message name>_message*
- Accessing agent memory
  - *get_<variable>*
  - *set_<variable>*
- Creating & removing agents

Application Programmers Interface

The programmers interface to agent memory and to message board information is through the FLAME Programmers API.

Example 1: Circle agent with memory of *x*, y, id and *radius* communicating through the *location* message.

```
int outputdata()
{
      double x, y, radius;
      int id;

      x  = get_x();    y = get_y();
      id = get_id();  radius = get_radius();

      add_location_message(id, (radius * 3), x, y, 0.0);

      return 0;
}
```

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Application Programmers Interface

Example 2: Circle agent *get*-ing and *set*-ing memory values *x*, *y*, *fx* and *fy* using API functions.

```
int move()
{
      double fx, fy;

      fx=get_fx();
      fy=get_fy();

      set_x(fx);
      set_y(fy);

      return 0;
}
```

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API - *MACROS*

The FLAME parser generates predefined macros which allow the programmer to generate loops over message boards.

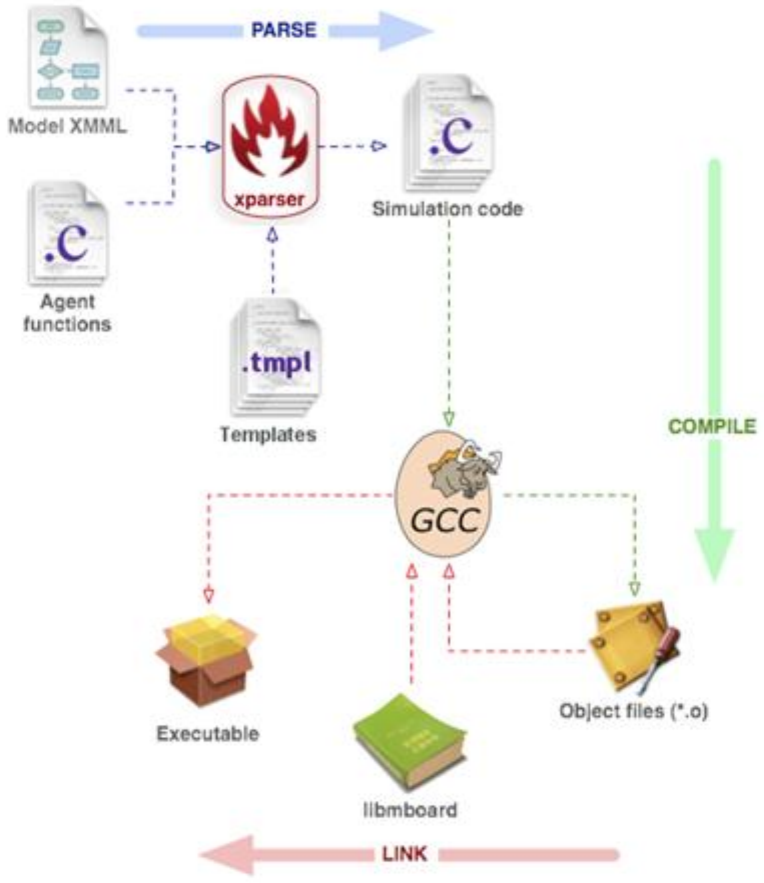
Example 3: A loop to scan over *LOCATION* message board

```
#define START_LOCATION_MESSAGE_LOOP
for ( location_message = get_first_location_message();
        location_message != NULL;
        location_message = get_next_location_message(location_message))
     {

#define FINISH_LOCATION_MESSAGE_LOOP
     }
```

The FLAME Process

- Input from the modeller:
  - *Model – XMML file*
  - *C-code for functions*
- Input from FLAME
  - *Template* file
  - Header files
- Output from FLAME
  - Applications code
  - State diagram



Two simple models

C@S Model

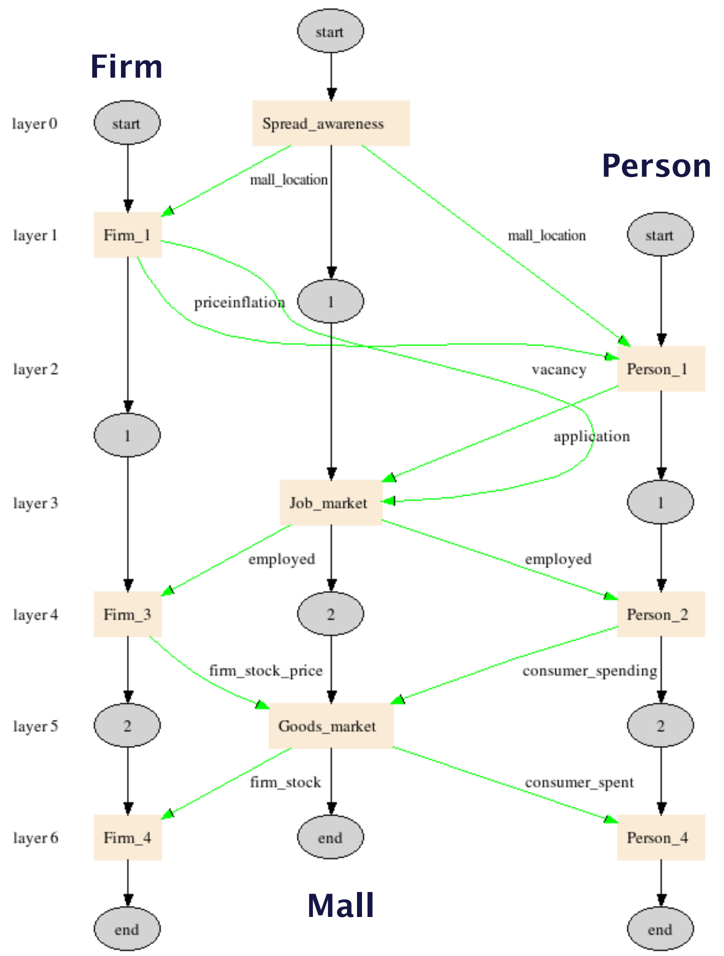
- mix of agents: *Malls, Firms, People*
- a mixture of state complexities
- all have position data
- agents have range of influence
- 9 message types
- 9 functions

Circles Model

- very simple agent
- all have position data
- *x, y, fx, fy, radius* in memory
- moves by repulsion from neighbours
- 1 message type
- 3 functions

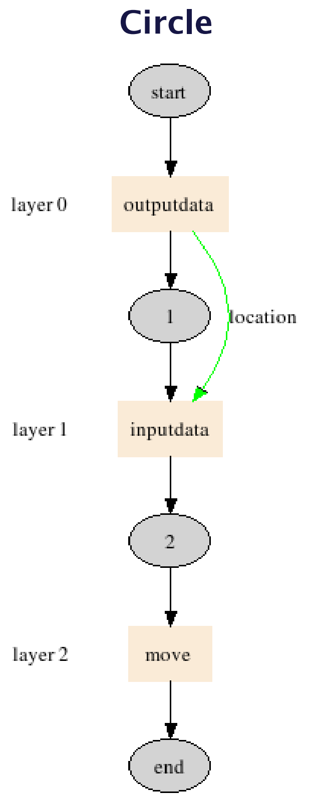
Dependency Graphs

Simple three-agent model



→ Communications

→ State changes



Circle agent model

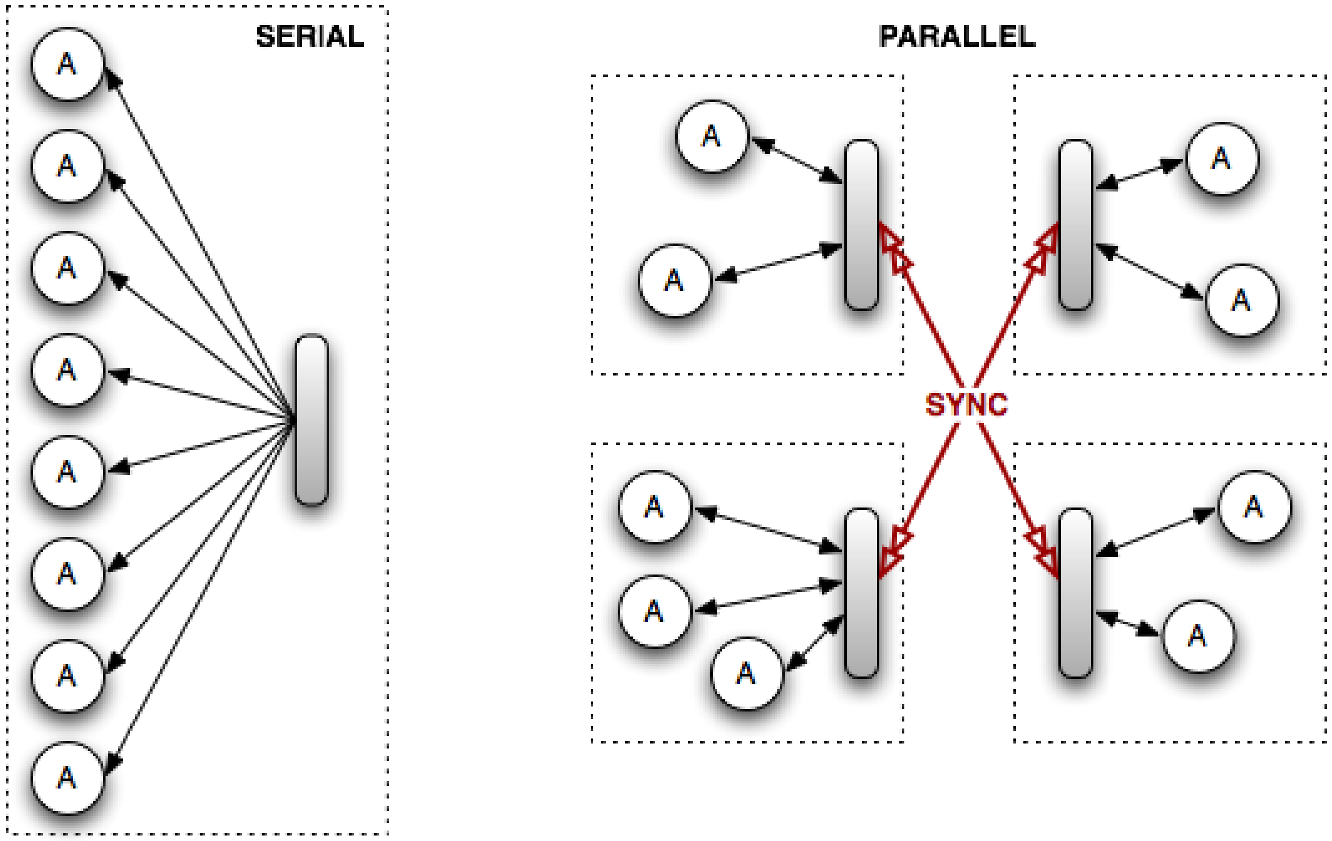
Issues with HPC and FLAME

- FLAME is a applications generator
- Parallelism is hidden in the XML model and the modeller provided C-code – this is in term of agent locality or population groupings
- Inter-agent communications captured in XML
  - In agent function descriptions
  - In message descriptions
  - The frequency of messages is not known
- The *agent functions* are the computational load
  - Their weight not known until run time
  - They could be fine or course grained
  - Their activation is irregular – not lock stepped

Parallel Implementation

- Based on :
  - the distribution of agents – ***computational load***
  - distribution of message boards (MB) – ***data load***
- Agents only communicate via MBs
- Cross-node message information is made available to agents by message board synchronisation
- FLAME uses MPI to manage inter-node communications
- Communication between nodes are minimised
  - Multi-threading on computation and communication
  - Message filtering
  - Domain/group halos

Parallelism in FLAME



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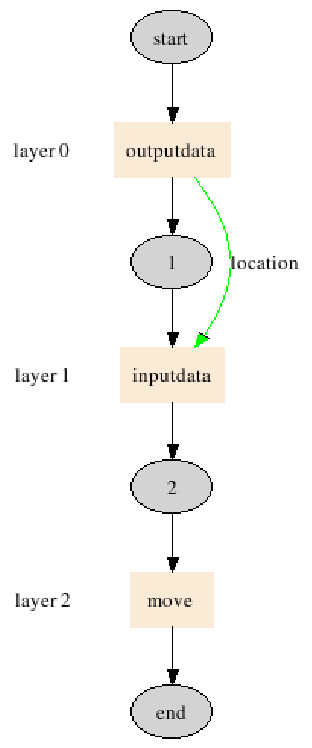
Initial Problem Distribution

- The goal of using a high performance parallel computer is to minimise the time taken to perform a simulation.
- We must balancing the use of resources available to achieve this
- Some issues:
  - communicating between processors takes time
  - communication must overlap computation
  - the model must contain parallelism
  - the model must be sufficiently large
- Using all the available processors is not the solution

A Very Simple Model

The *circle* agent is our basic test agent

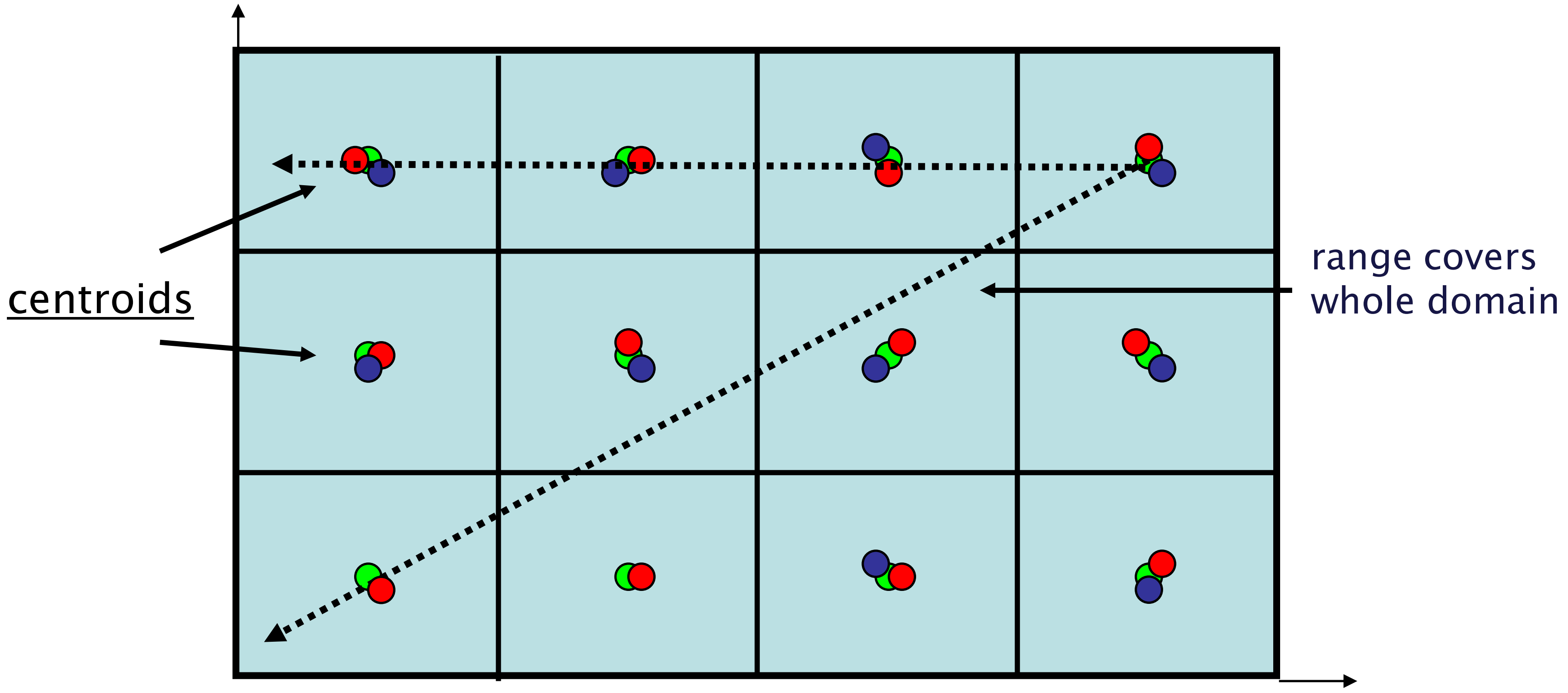
- Very simple agents – zero size points in 2D space
- all have a 2D (*x*,*y*) positional data
- all have a *radius* of influence
- values of *x*, *y* and *radius* are in memory
- they move by repulsion from neighbours
- there is only 1 message type
- there are 3 functions



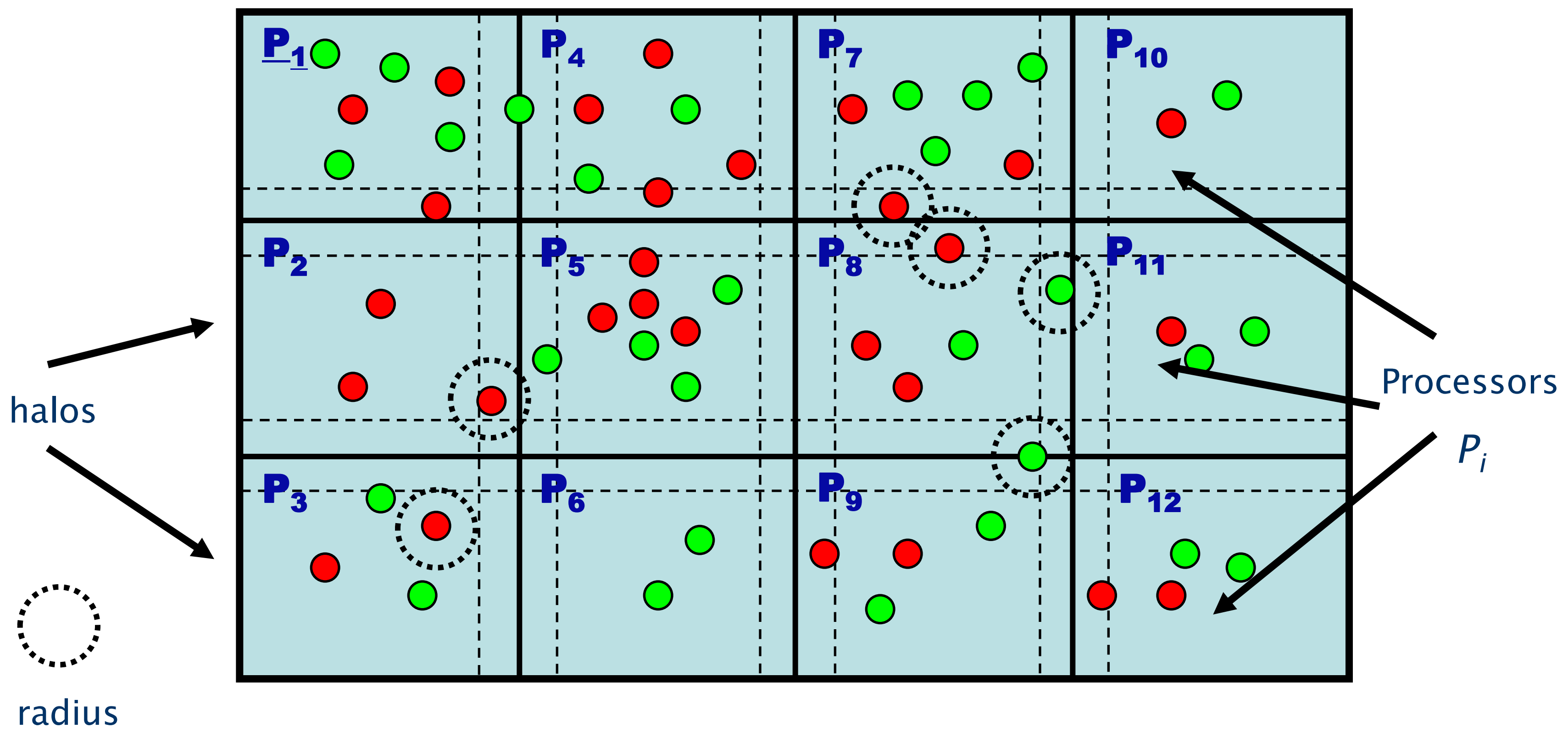
Model Partitioning

- Round-robin: simple agent by agent allocation
  - partitions are given a geometry
  - agents are allocated to partition's centroid
  - agents distributed for load balance
- Geometric: based on prime factors
  - using position as separator
  - partitions are defined uniformly over *x* and *y* space
  - for prime numbers *x* is preferred direction
  - could be used of multi-variable separators

Round-Robin Partitioning



Geometric Partitioning



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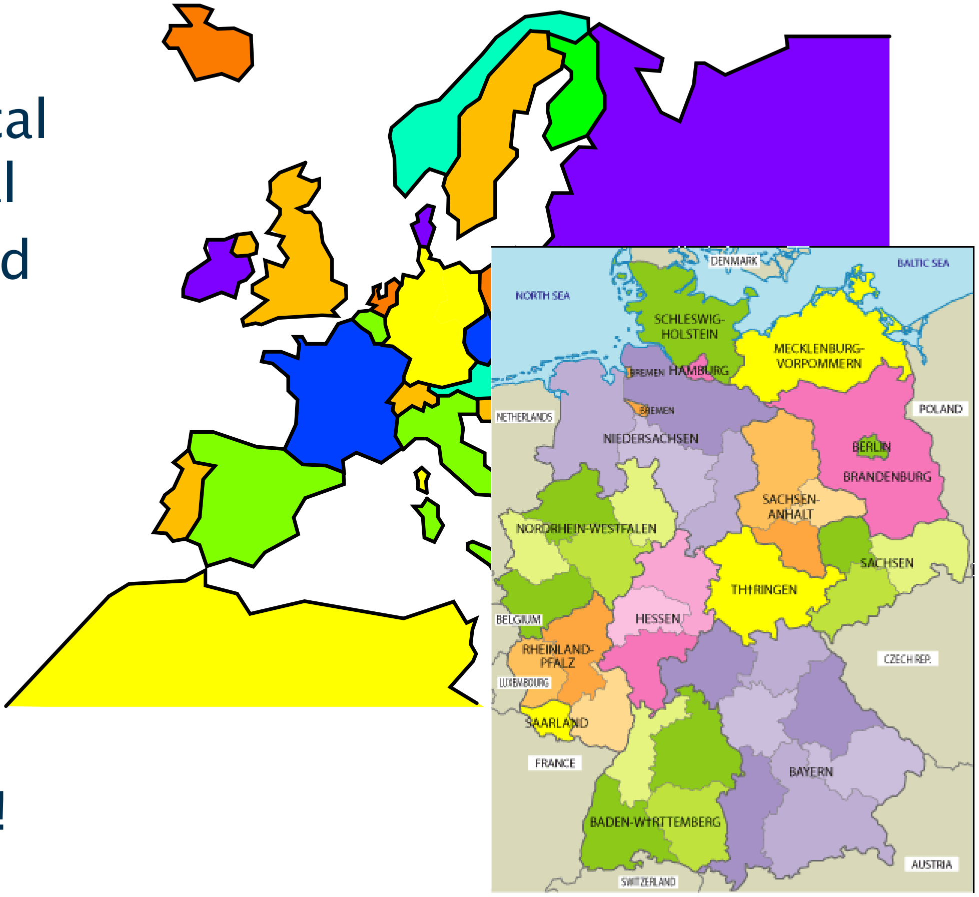
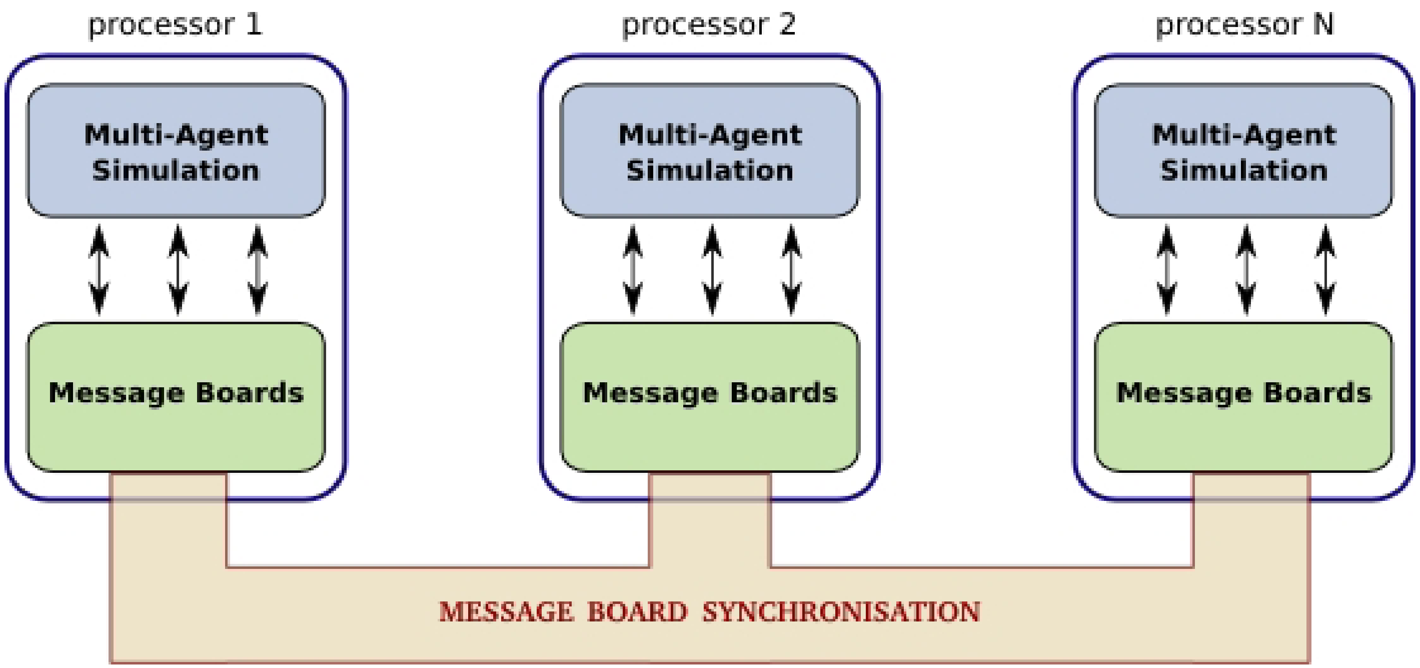
Partitioning by Region

- For economics geographical regions seem to be natural
- We still need to understand the agent interaction the work they perform – the communication and computation load
- Very difficult in unsteady multi-agent systems
- Multiple agent weights
- Start with a static analysis!



Parallelism in FLAME



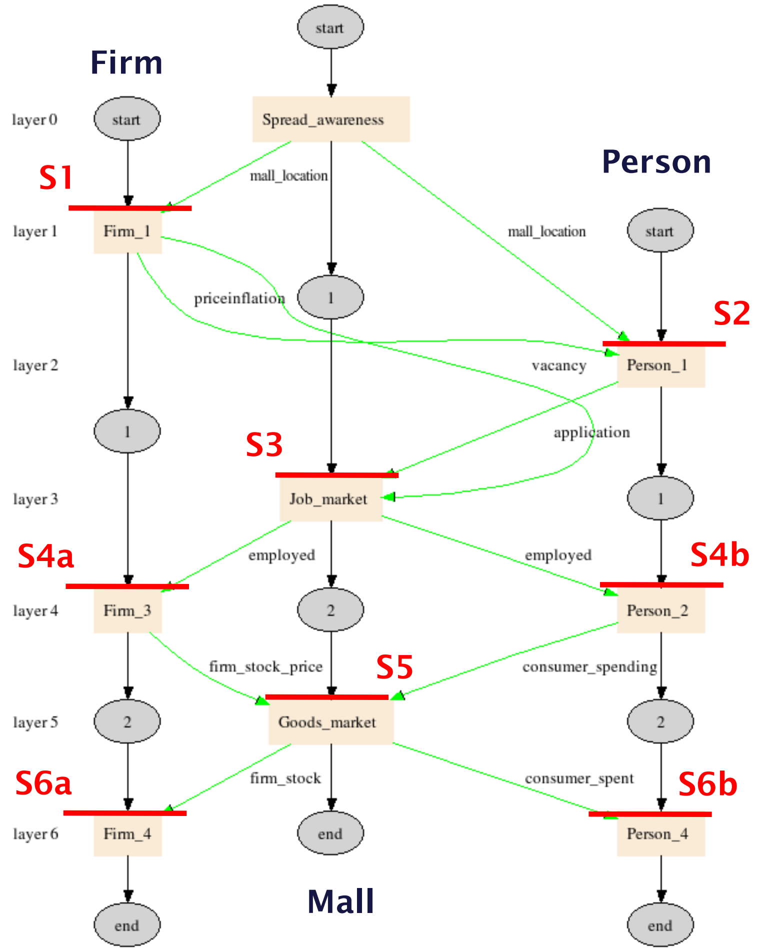
Parallel agents grouped on parallel nodes.

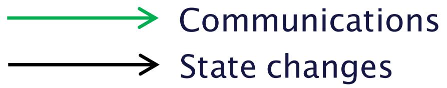
Messages synchronised across nodes as necessary

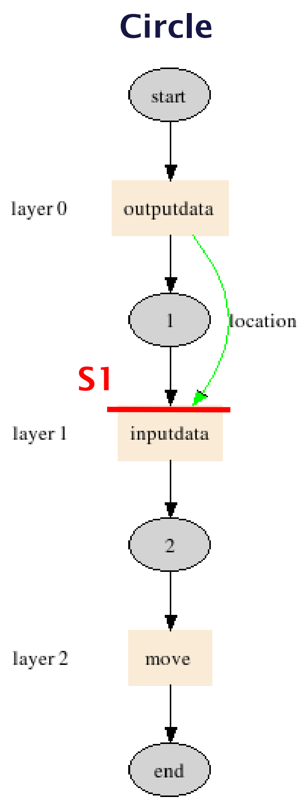
Message board library allows both serial and parallel versions to work

Dependency Graphs

Simple three-agent model







Circle agent model

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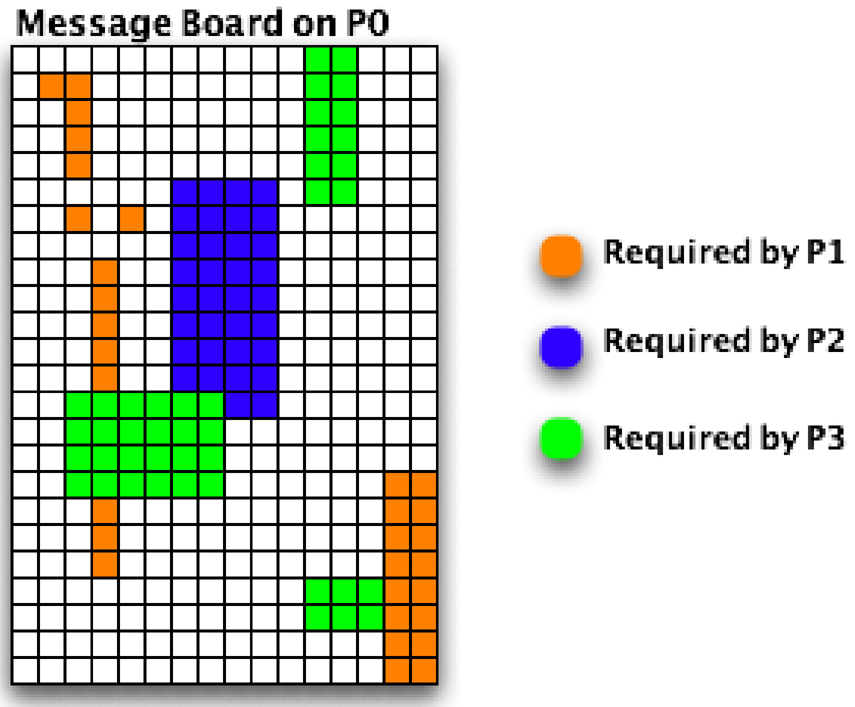
Message Filtering

- The XMML *filter* provides a way of selecting only the required data is transferred

```
<function><name>inputdata</name>
<currentState>1</currentState>
<nextState>2</nextState>
<inputs><input>
<messageName>location</messageName>
  <filter>
    <lhs><value>a.id</value></lhs>
    <op>NEQ</op>
    <rhs><value>m.id</value></rhs>
  </filter>
</input></inputs>
</function>
```

- Used to control scanning loops
- Used in message board synchronisation



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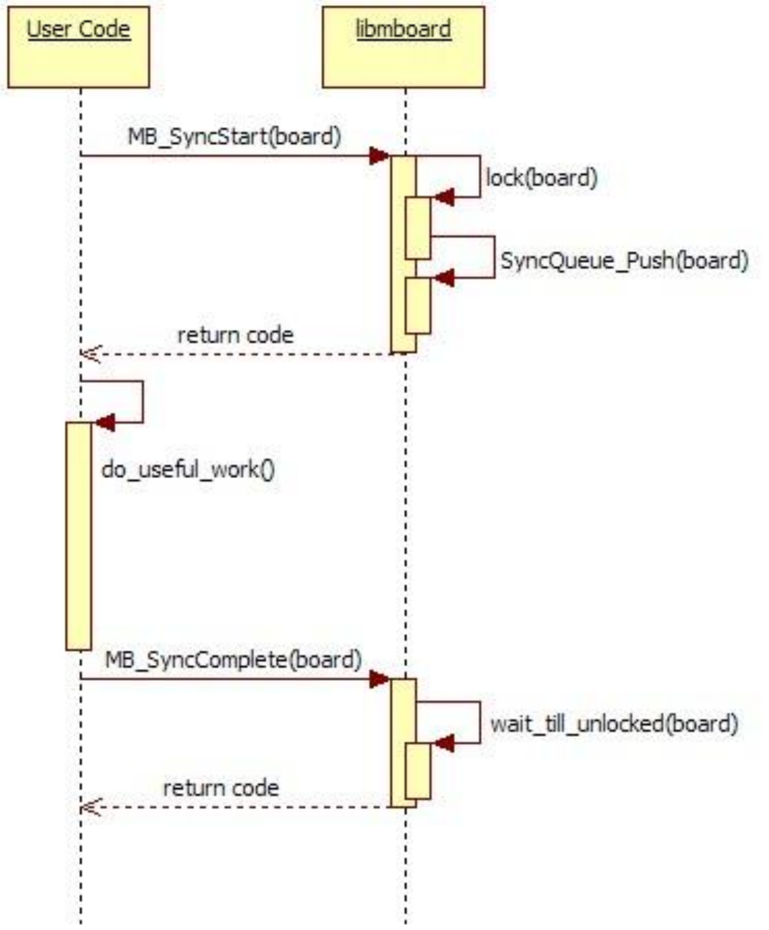
Message Board Synchronisation

- At these critical points we need to synchronise the message information
- To continue every agent must have in place the information it needs before the simulation can continue
- Local message boards must be updated with necessary current information
- In its simplest form synchronisation by full replication of all messages within each node – cannot be done in large populations – insufficient memory
- We only transfer the information required as defined in the model XMML.

Multi-threading

- Synchronisation is a potential bottleneck as the simulation must wait for inter-node communication
- To reduce this problem libmboard runs multiple threads:
  - one for communication – data transfer
  - one for computation – doing agent based work
- MB_SyncStar and MB_SyncComplete control this process



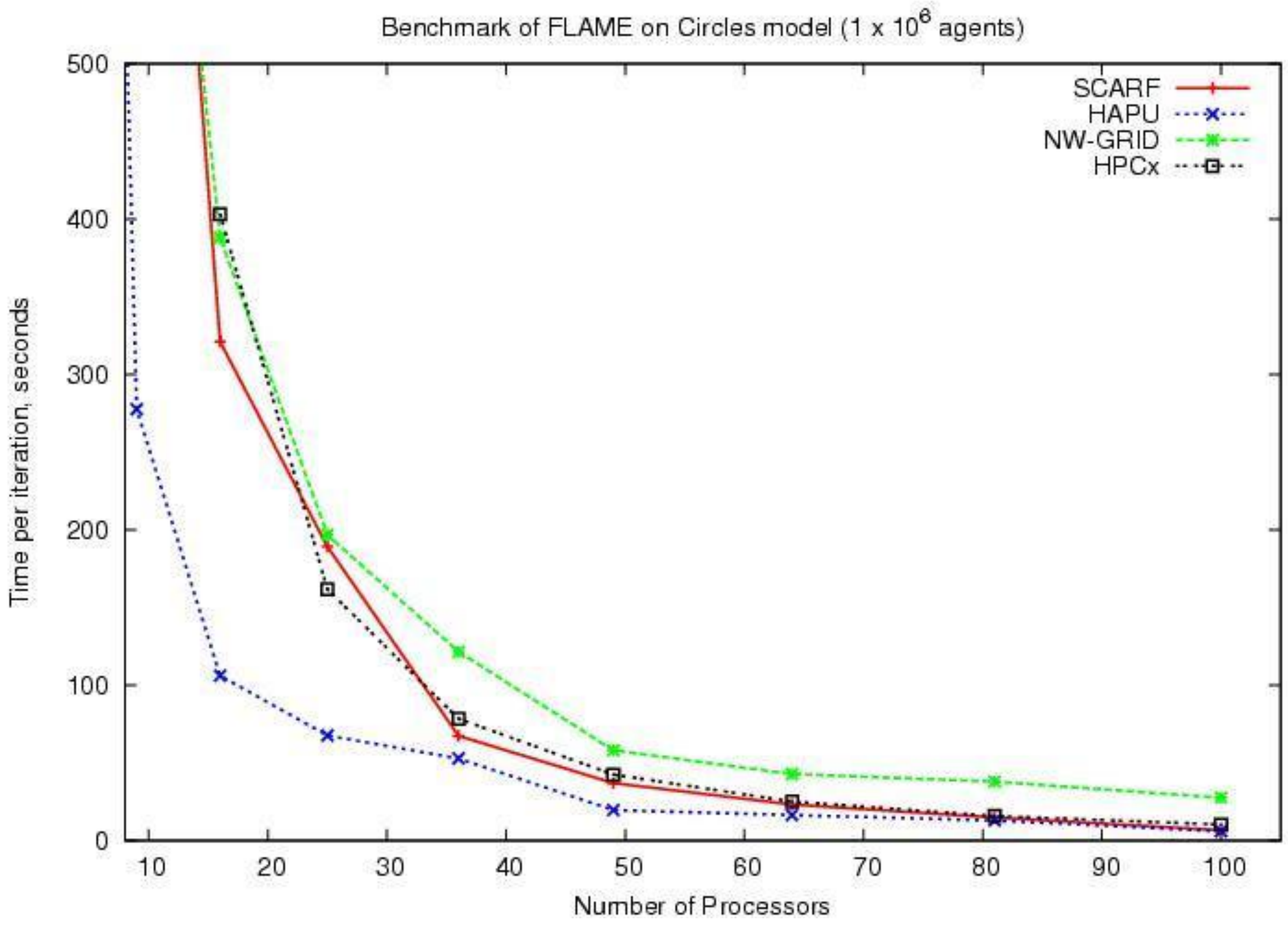
Parallel Platforms

- The FLAME framework has been successfully ported to various HPC systems:
  - SCARF – 360x2.2 GHz AMD Opteron cores, 1.3TB total memory
  - HAPU – 128x2.4 GHz Opteron cores, 2GB memory / core
  - NW-Grid – 384x2.4 GHz Opteron cores, 2 or 4 GB memory/core
  - HPCx – 2560x1.5GHz Power5 cores, 2GB memory / core
  - Legion (Blue Gene/P) – 1026xPowerPC 850 MHz; 4,096 cores
  - HECToR (Cray XT4) – 1416xQuad Core Opterons, 2GB / core, 22,656 cores
  - Leviathan (UNIBI) – 3xIntel Xeon E5355 (Quad Core), 24 cores

Verification and Validation

- It is important to ensure that applications generated by the FLAME framework execute correctly in both their serial and parallel modes.
- A set of simple test models and problems have been developed based on the Circles agent:
  - Test 1: single Circles agent type; Initial population of no agents.
  - Test 2: single Circles agent type; Initial population of one agent at (0,0).
  - Test 3: Two Circles agent type; Initial population of agents at (-1,0) and (+,0).
  - Test 4: Four Circles agent type; Initial population of one agent at (+/-1,+/-1).
  - Test 5: Four Circles agent type; Initial population of one agent at (0,+/-1) and (+/-1,0).
  - Test 6: Four Circles agent type; Initial population of one agent at random positions.
- In each of these models the expected results can be specified and they can provide a very simple check of the correctness serial and parallel implementations.

Circles Model (1 Million Agents)



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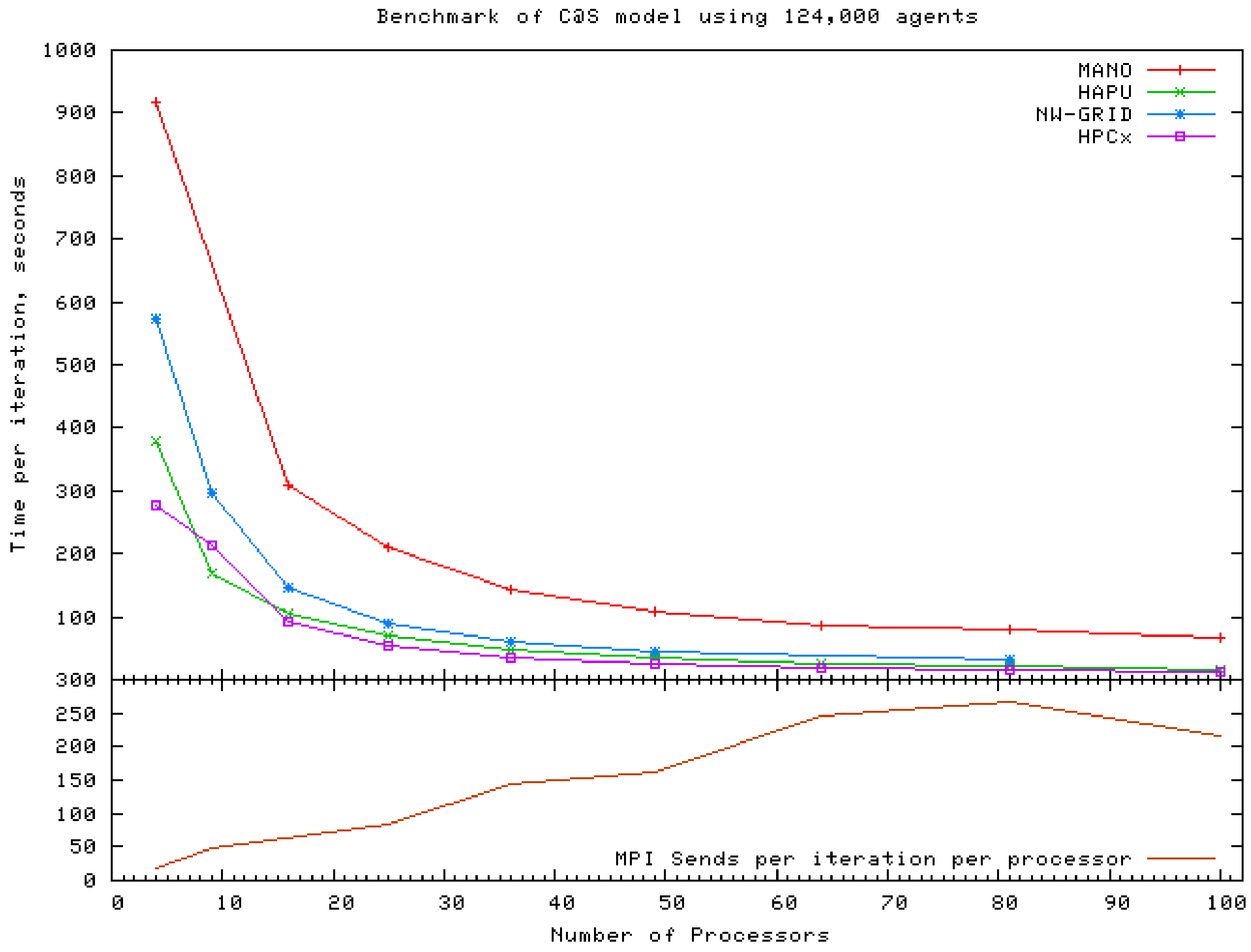
C@S Model (124,000 agents)



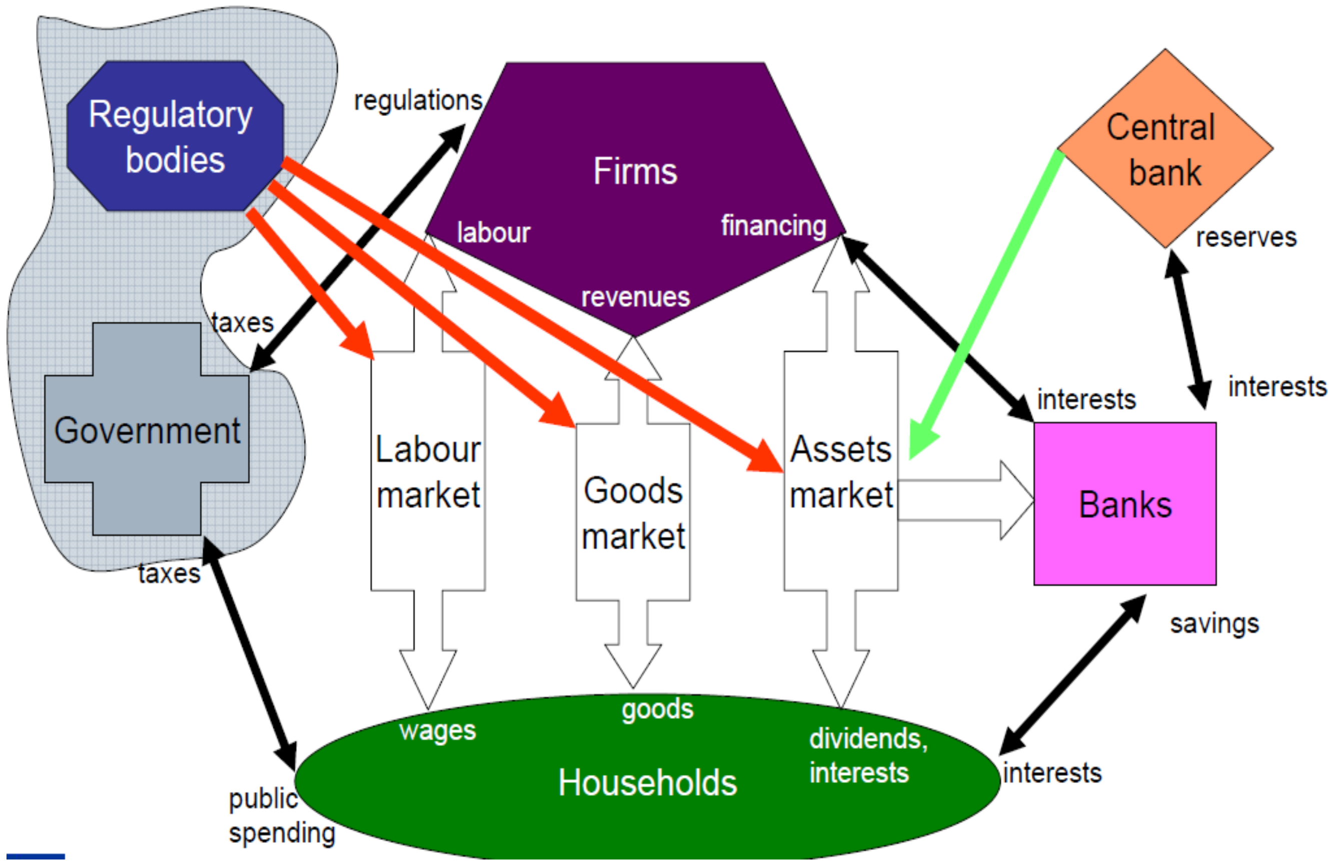
What we don't know!

- Size of agent population – agent could be created and/or destroyed
- Granularity of agents
  - Is there a large computational load
  - How often do they communicate
- Inherent parallelism (locality) in model
  - Are the agents in groups
  - Do they have short range communication

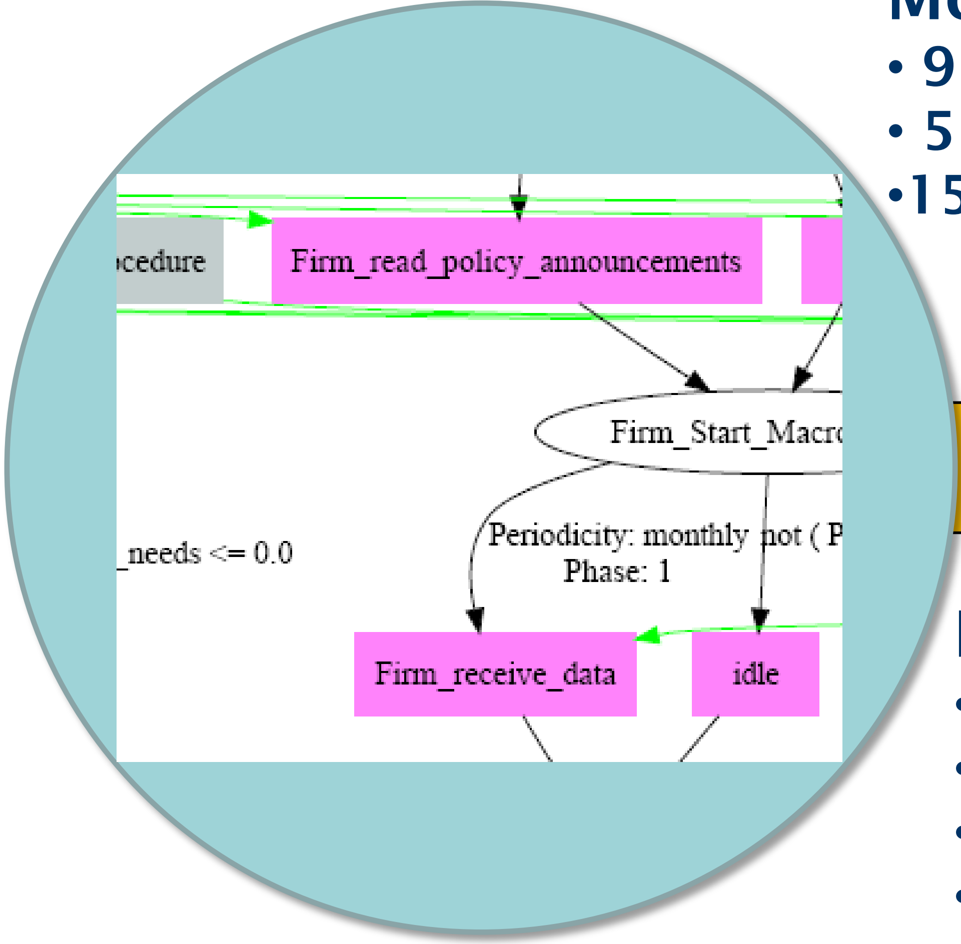
The EURACE Model

- The main goal of EURACE was to develop:
  - an agent-based software platform for European economic policy design with heterogeneous interacting agents
  - discover new insights from a bottom up approach to economic modeling and simulation.
  - multi-agent
  - multi-market
  - regional and global effects

EURACE markets and their interactions

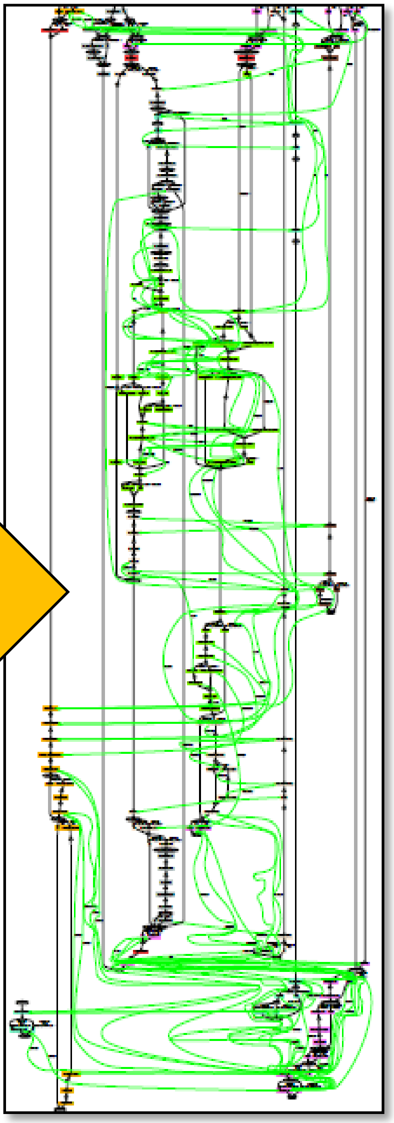


The EURACE Model



Model Stats

- 9 Agent
- 55 Messages
- 159 Functions



Markets

- Labour
- Goods
- Credit
- Financial

EURACE Agent Populations

- Default unit of population
- 5 fixed national agents
- 4 regional agent groups
- Larger populations are cloned using the this basic population unit and replicating the regional agents

Agent type	**Number of agents**
National	
Government	1
Central_Bank	1
Clearinghouse	1
Eurostat	1
IGFirm	1
Regional	
Mall	1
Bank	2
Firm	80
Household	1600

Performance analysis tools

- Two types of analysis tools have been developed for FLAME generated applications: *static* and *dynamic*. Static analysis tools process the model XMML and the C-code. The dynamic analysis tools provide information on the code during execution.
- ***Static Analysis Tools:***
  - ***Analyses_model.py*** : a static analysis of the FLAME model which gives detailed information on the components of a model: agent, function and messages types, number and sizes, a static communications table, a weighted communications table.
  - ***Check_message_consistency.py*** : a static consistency checker which compares the XMML definition with C code and ensures that the number and usage of messages is consistent.

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Performance analysis tools

- ***Dynamic Analysis Tools:***
  - ***The MM Package*** : The MM package is a dynamic to monitor message tracing in the simulation. It is a set additional directives included in the FLAME Templates which embedded in the application code that monitor all message tracing and outputs to an SQL data base. The data base can be post processed by the developed to assess the message tracing in the model.
  - ***The Time Package*** : The Timer package is a collection of timing utilities which allow detailed timing analysis of any FLAME generated application. The Timer package has been used to measure elapsed CPU time for functions and message board synchronisations.

Tools for Performance Analysis

- We need to assess the performance overhead of the FLAME Framework: message management; iterator creation and use; data input and output.
- The Timer Package is used to monitor the main message board activities.
- A FLAME uses multiple threads for computation and communication. FLAME attempts to overlap computational and communication. We test non-overlapped and overlapping overheads.

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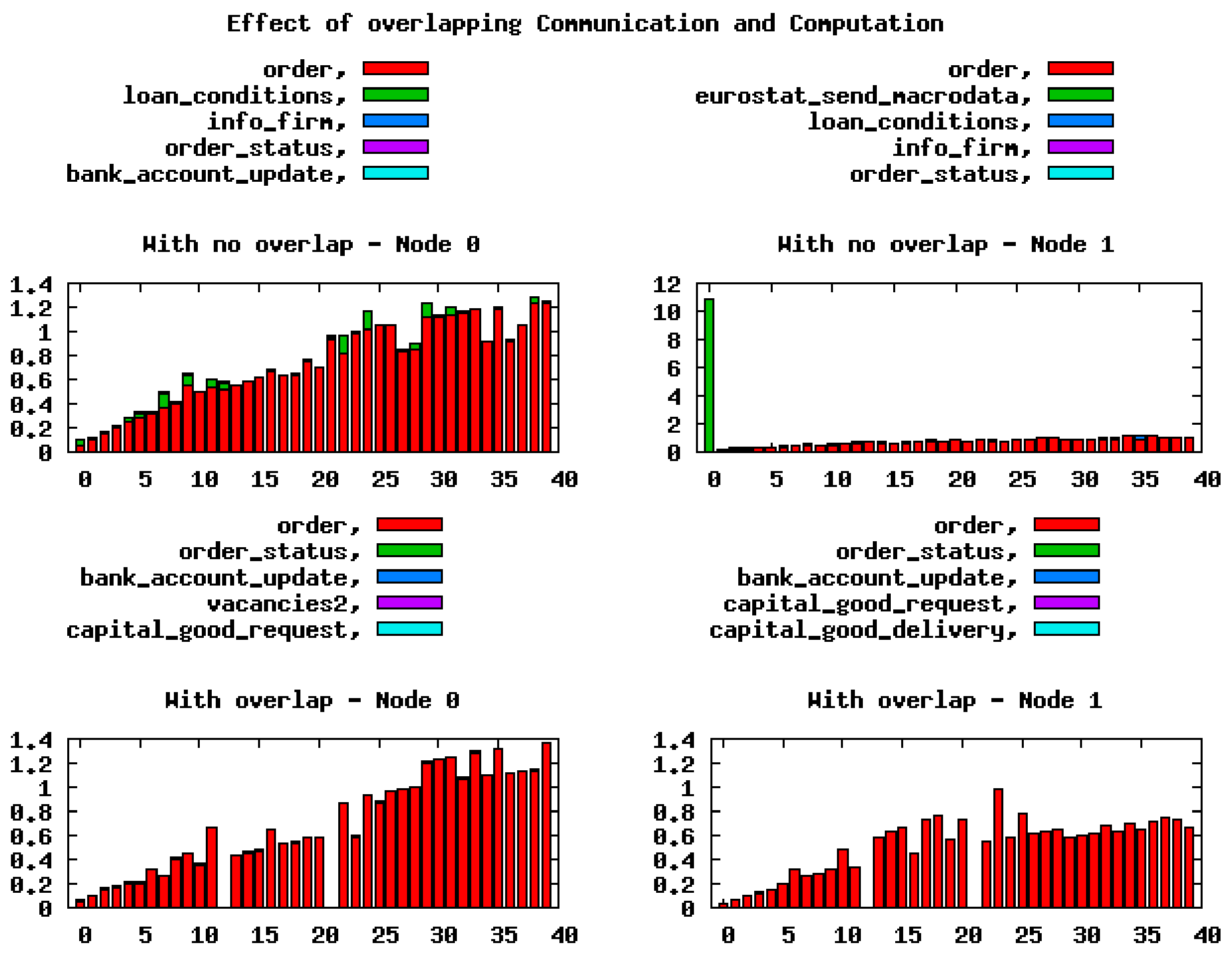
Static Analysis

		0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Firm	*0*	0.000	0.000	**2.857**	1.429	1.464	**10.000**	**2.143**	1.464	**4.286**
Central_Bank	*1*	0.000	0.000	0.000	0.000	0.036	0.000	0.000	0.000	0.036
Clearinghouse	*2*	**2.143**	0.000	0.000	0.000	1.429	0.714	0.000	0.000	0.000
IGFirm	*3*	1.429	0.000	0.000	0.000	0.036	0.714	0.000	0.000	0.714
Government	*4*	0.714	**2.143**	1.429	0.714	0.000	1.464	0.000	0.000	0.714
Household	*5*	**6.464**	0.000	0.714	0.000	**2.179**	0.000	1.429	0.036	0.714
Mall	*6*	0.714	0.000	0.000	0.000	0.000	**2.857**	0.000	0.036	0.000
Eurostat	*7*	0.036	0.036	0.000	0.000	0.714	0.000	0.000	0.000	0.000
Bank	*8*	1.429	1.429	0.000	0.000	0.036	0.714	0.000	0.000	0.000

Weighted Communications Matrix

Effects of multi-threading



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Information from MM Package

Writing	
Message Name	***Counts***
order	57,557
bank_account_update	1,551
job_application	666
job_application2	552
order_status	337
accepted_consumption_1	274
consumption_request_1	274
tax_payment	62
hh_subsidy_notification	60
hh_transfer_notification	60

Reading	
Message Name	***Counts***
order	2,935,407
quality_price_info_1	13,700
info_firm	7,850
accountInterest	6,000
dividend_per_share	3,000
bank_account_update	1,551
job_application	666
vacancies	666
job_application2	552
vacancies2	552

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Serial Performance

Initial performance analysis

Function	Time (s)	%
ClearingHouse_receive_orders_and_run	**82.81**	**72.00**
Household_stock_beliefs_formation	**25.32**	**22.00**
Household_send_orders	2.06	1.70
Household_bond_beliefs_formation	0.44	0.38
Household_rank_and_buy_goods_1	0.42	0.36
Firm_read_job_applications_send_job_offer_or_rejection	0.37	0.32
Household_update_its_portfolio	0.16	0.14
Household_receive_dividends	0.11	<0.10
Household_receive_info_interest_from_bank	0.09	<0.10
Household_send_account_update	0.09	<0.10

Performance analysis after initial optimisation

Function	Time (s)	%
Household_stock_beliefs_formation	**245.78**	**61.00**
Household_send_orders	46.44	11.00
ClearingHouse_receive_orders_and_run	**41.76**	**10.00**
Household_bond_beliefs_formation	4.98	1.20
Household_update_its_portfolio	1.48	0.30
Household_rank_and_buy_goods_1	1.04	0.28
Household_rank_and_buy_goods_2	0.90	0.22
Household_receive_dividends	0.80	0.20
Household_receive_info_interest_from_bank	0.79	0.20
Firm_read_job_applications_send_job_offer_or_rejection	0.62	0.15

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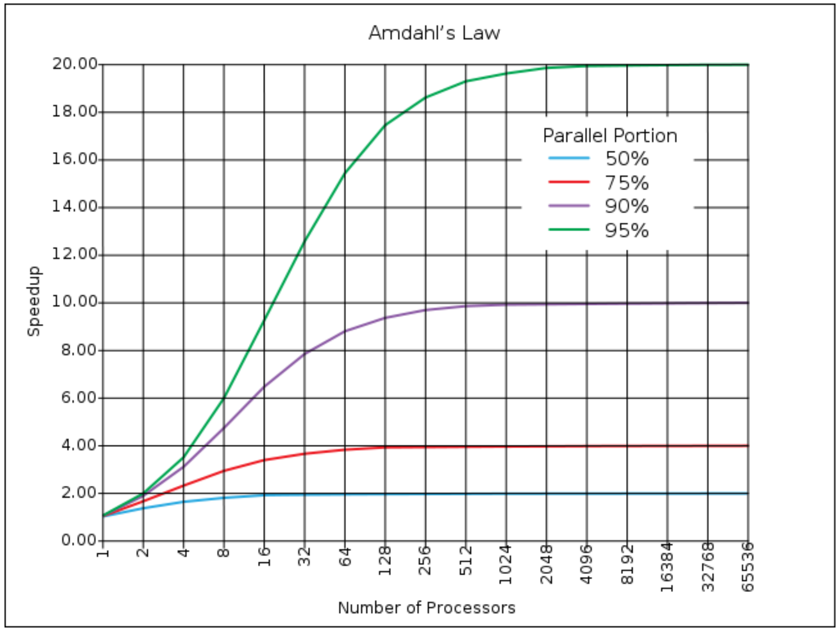
Amdahl's Law



$$\frac{1}{(1-P) + \frac{P}{N}}$$

Where *N* is the number of processors and *P* the fraction of the code that can be parallelised.

As *N*->∞ *P/N* -> 0 and the (1-*P*) term dominates.
The proportion of serial code dominates the parallel performance.

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Parallel Performance

Node 0: Performance analysis of agent functions

Function	Time (s)	%
Household_send_orders	**2083.30**	**14.2**
Household_stock_beliefs_formation	211.14	1.4
order	137.02	0.9
Household_receive_dividends	104.89	0.7
Household_receive_data	43.66	0.3
Household_receive_info_interest_from_bank	37.16	0.3
Household_update_its_portfolio	34.56	0.2
Firm_read_stock_transactions	17.74	0.1
Household_rank_and_buy_goods_1	16.10	0.1

Node 1: Performance analysis of agent functions

Function	Time (s)	%
ClearingHouse_receive_orders_and_run	**5125.29**	**35.0**
Household_send_orders	2067.41	14.1
Household_stock_beliefs_formation	222.10	1.5
Household_receive_dividends	104.26	0.7
order	75.31	0.5
Household_receive_data	43.50	0.3
Household_receive_info_interest_from_bank	37.06	0.3
Household_update_its_portfolio	34.41	0.2
Household_rank_and_buy_goods_1	16.49	0.1

Gustafson’s Law

- Gustafson's law addresses scaling to match availability of computing power as the machine size increases.

  $$S(N) = N - \alpha \bullet (N - 1)$$

  where α is the serial fraction and *N* the number of processors.
- It removes the fixed problem size or fixed computation load on the parallel processors: instead, he proposed a fixed time concept which leads to scaled speed up for larger problem sizes (i.e. weak or soft scaling).

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Parallel Performance

Model	Regions per Processor	No. of Agents	Time (0.02)	Time (0.01)	Time (0.005)	Time (0.0)
10R_10P	1	16,844	9.790	3.716	1.840	0.232
20R_10P	2	33,684	61.712	33.914	9.671	0.682
30R_10P	3	50,524	453.321	144.203	59.872	1.344
40R_10P	4	67,364	854.781	254.785	107.772	1.707
50R_10P	5	84,204	2083.108	578.451	305.411	2.605
60R_10P	6	101,044		262.061	107.489	3.535
70R_10P	7	117,884		101.094	55.440	4.504
80R_10P	8	134,724		76.171	30.587	5.739
90R_10P	9	151,564		73.339	41.525	6.660
100R_10P	10	168,404		97.151	96.784	8.174
200R_10P	20	336,804			361.985	25.716
300R_10P	30	504,712				64.041

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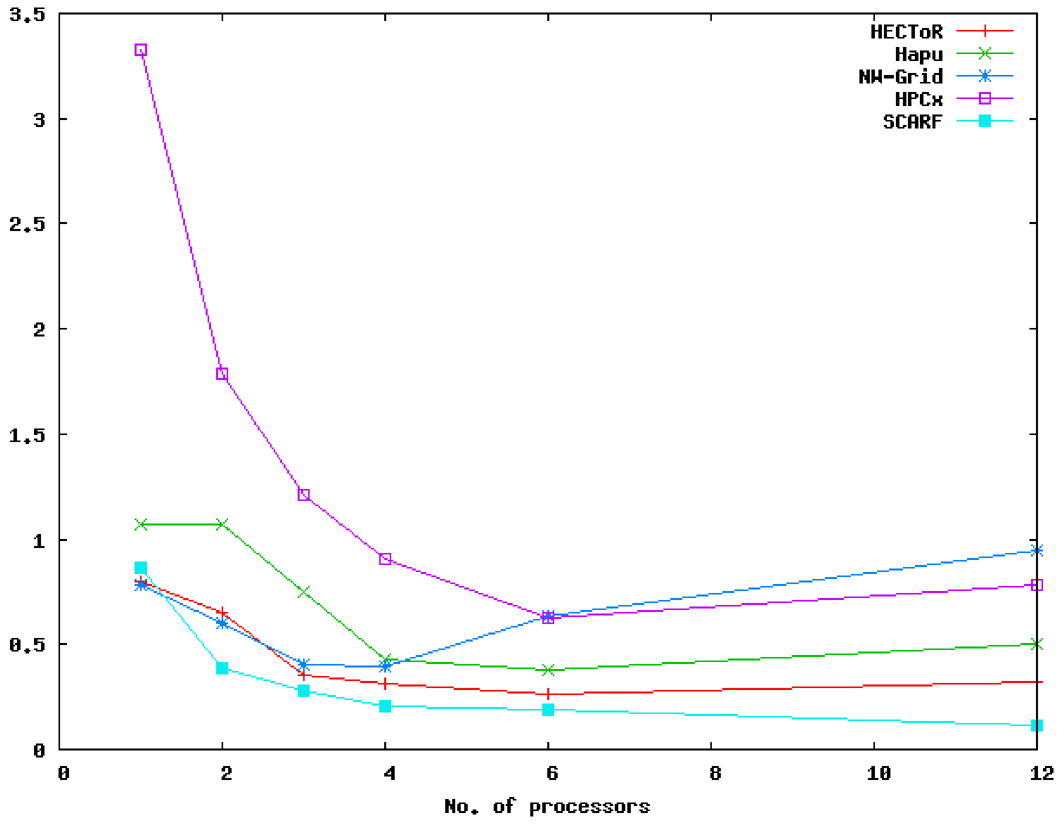
Serious Parallel Performance

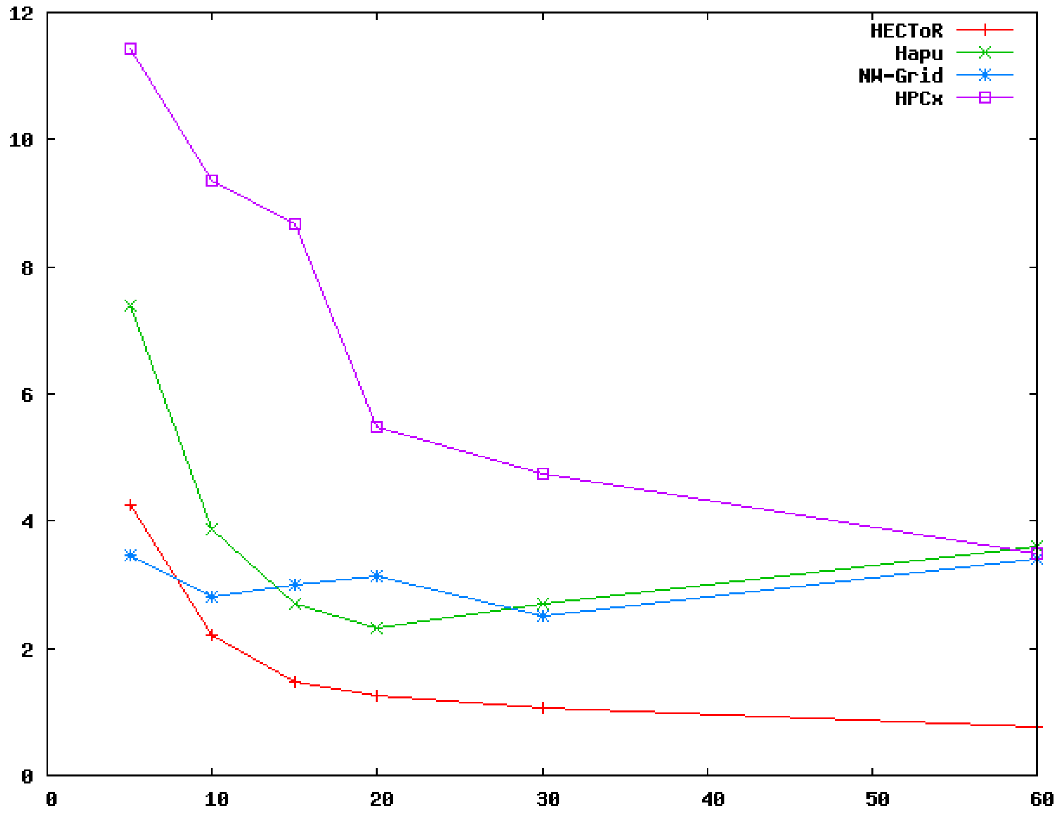
- We have used two test models each with two different populations in our testing:
  - Population 1:
    - → 20,212 agents, 12 regions
    - → Run on 1, 2, 3, 4, 6 and12 processors
  - Population 2:
    - → 101,044 agents, 60 regions
    - → Run on 5, 10, 15, 20, 30 and 60 processors
- The value of *trading_activity* also been varied.

EURACE Results – Pop1



Pop1: 20,212 agents, 12 regions

EURACE Results – Pop2



Pop2: 101,044 agents, 60 regions

Some observations

- We do get limited improvement of performance
- The performance is very model dependent
  - the serial component of the model
  - the *weight* of each agent task
- Performance is very architecture dependent
  - the speed of the processors
  - the speed of the interconnect
  - the size of the available memory
- It is difficult for modellers to express the parallelism in their applications

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Research Issues

A short list of research subjects:

- definition and use of message filtering
- optimisation of scheduling from task graph
- generating communications overlap
- maintaining load balance over the system
- detecting serialism in the model and transforming
- coupling models with computational steering
- Use of multi-core processors and GPUs using OpenMP or OpenCL/CUDA
- Verification and Validation methods and tools
- Use of in-complete data – try to carry on regardless!

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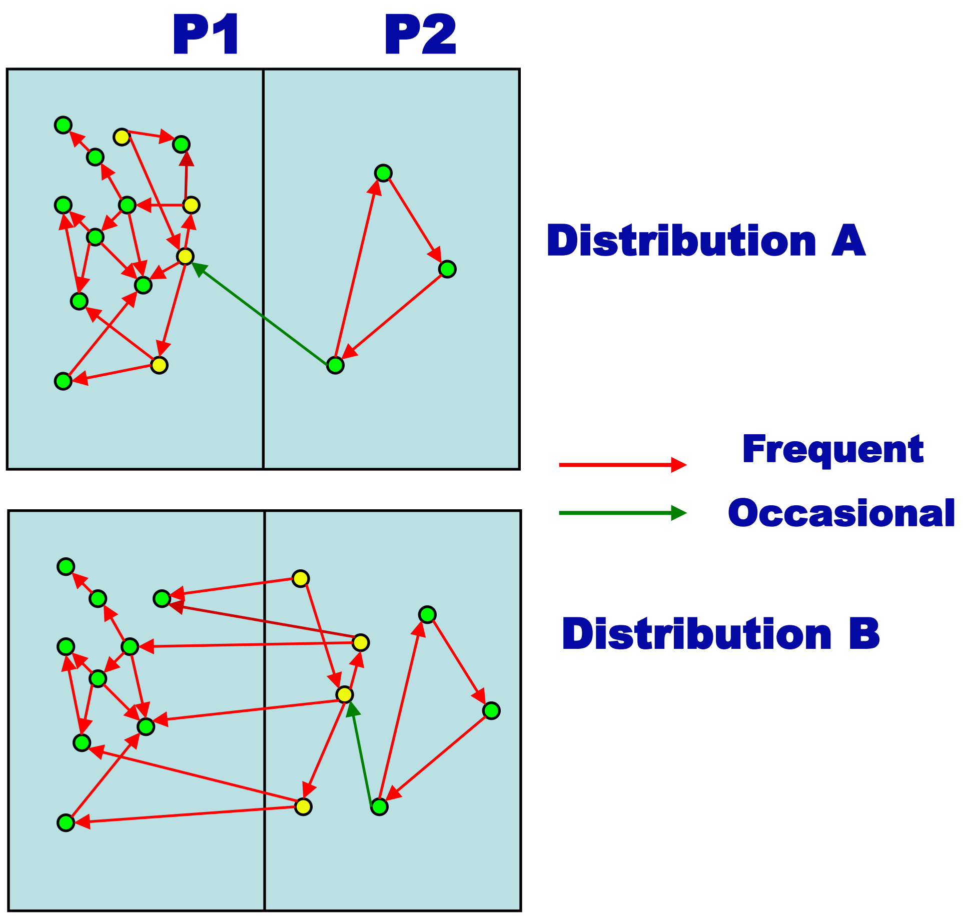
Dynamic Load Balancing

- Goal to move agents between compute nodes:
  - reduce overall elapsed time
  - increase parallel efficiency
- There is an interaction between computational efficiency and overall elapsed time
- The requirements of communications and load may conflict!

Balance - Load vs. Communication

- Distribution A
  - P1: 13 agents
  - P2: 3 agents
  - P2 <--> P1: 1 channel
- Distribution B
  - P1: 9 agents
  - P2: 7 agents
  - P1 <--> P2: 6 channels



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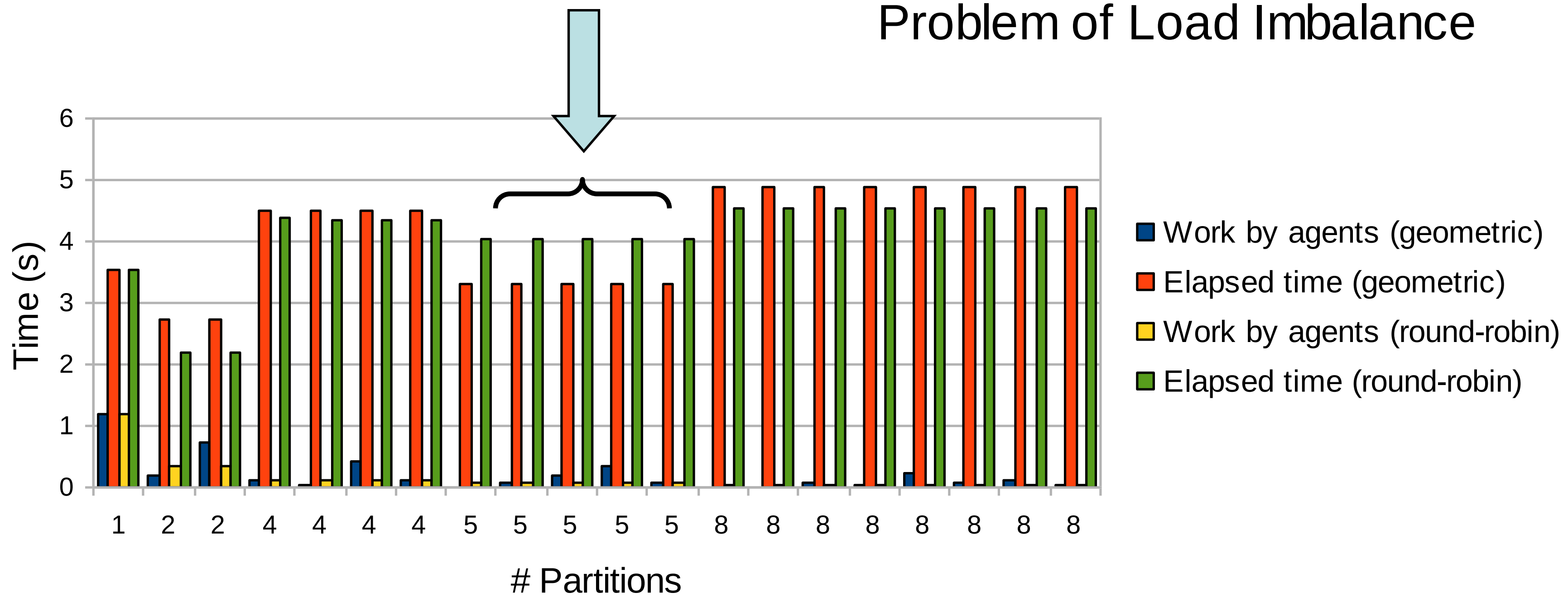
Moving Wrong Agents

Moving wrong agents could increase elapsed time

Problem of Load Imbalance



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Conclusions

- FLAME has proven to be a very versatile program generator for agent-based applications
- The FLAME overhead in both the serial and parallel implementations of FLAME applications is acceptably small - ~5% of total elapsed time
- The parallel performance of the FLAME application is very dependent of the inherent locality expressed in the model and the architecture of the target hardware
- By using parallelisation techniques we have successfully run populations of 500,000 agents
- To gain the best possible performance the modeller must understand and exploit the nature of parallel computing

Contacts

Prof Chris Greenough
Software Engineering Group
Computational Science & Engineering Dept
STFC Rutherford Appleton Laboratory
Harwell Science & Innovation Campus
DIDCOT
Oxfordshire OX11 0QX

Tel: +44 1235 445307
Email: christopher.greenough@stfc.ac.uk
Web: http://www.cse.scitech.ac.uk/seg

Based on Publications/Reports

- C. Greenough, DJ Worth, LS Chin: **An approach to the parallel implementation for multi-agent systems,** Rutherford Appleton Laboratory Technical Report, Jul 2010
- C. Greenough, DJ Worth, LS Chin: **Parallel Optimisation of the EURACE**
- **Agent-Based Economic Model, R**utherford Appleton Laboratory Technical Report, Jul 2010
- C. Greenough, DJ Worth, LS Chin, M. Holcome and S Coakley, **Exploitation of High Performance Computing in the FLAME Agent-Based Simulation Framework (CCEF 2008),** Rutherford Appleton Laboratory Technical Report RAL-TR-2009-022, Jul 2009
- C. Greenough, DJ Worth, LS Chin: **Porting of agent models to parallel computers,** Deliverable D1.4, EURACE Project, 2006
- C. Greenough, DJ Worth, LS Chin: **Porting of agent models to parallel computers,** Deliverable D8.4, EURACE Project, 2009