C1. Project Description

PROJECT TITLE

Live coding of complex flood simulations with uncertainty quantification

AIMS AND BACKGROUND

Emergency services responding to environmental disasters (such as floods and bushfires) increasingly utilise computational simulations to model and influence critical decisions involving the deployment of resources. Such simulations involve elaborate mathematical models overlayed on realistic terrain at scales relevant to local communities. They need to incorporate field data (weather conditions, water levels etc) and they are very demanding computationally, requiring high-performance computing in order to run effectively. In order to be useful for decision makers, simulations need to accommodate rapidly changing scenarios and field data, and they need to be able to properly quantify and communicate the uncertainty in their predictions. Developing such simulations requires insights from applied mathematics, software engineering, high-performance computing and human-computer interaction.

Aims

This research addresses the need for real-time simulation of environmental disasters through a *live coding* (or 'live programming') approach to rapid scenario building including uncertainty. For the purposes of this project, we will specialise our concerns to environmental models of inundation with the specific objectives of:

1. **Developing new inundation models** (models of riverine floods, storm surges and tsunamis) which use sparse grids and reduced basis approaches to *quantify uncertainty* and to dramatically increase the speed and usefulness of model predictions. Live coding will be used to bring traditionally "offline" aspects of reduced basis models for uncertaintly "online" and able to be used and modified in an interactive manner.

2. **Prototyping these models** using live coding to accelerate software development and to provide an interactive interface to deployed software in a rapidly changing environment.

3. **Deploying and redeploying these models** on realistic, high-performance-computing (HPC) systems, including local compute clusters and the cloud. Live coding will be used to dynamically redeploy models across changing HPC systems configurations in order to optimise the efficiency of computations and to cope with the compute node failures expected in volatile emergency-management scenarios.

The outcomes of this research will enable decision makers to examine many different environmental disaster scenarios in real-time, even with computationally-intensive models. Through this, they will develop an intuitive understanding of the uncertainty relationships in the system—from uncertainties in input data through to representations of uncertainty in model outputs. Although the mathematical and computational tools we will employ in this project are generalizable to any modelling environment, our focus is on specific application domains where (a) the model is (computationally) complex, (b) uncertainty is significant and (c) decisions are time-sensitive.

Background

Uncertainty quantification describes a collection of mathematical techniques that allow the predictions of computational simulations to be bounded probabilistically. The area is important in HPC simulations of scientific and engineering systems where it is desired to know how likely the outcomes of a simulation will be when various assumptions underlying the simulations are open to doubt. When uncertainty is included in a model, the essential dimensionality of the problem is increased markedly and sophisticated mathematical techniques are then required to deal with the "curse of dimensionality" where the cost of computation increases exponentially with the dimension of the problem. This project will exploit new mathematical techniques that combine reduced order models (such as **sparse grids and reduced basis methods**) with uncertainty quantification. **Sparse grids** [5] are known to reduce the effects of the curse of dimensionality and recent work in our group has found new ways to incorporate gradient information and multi-fidelity models into sparse grid approximations [8, 13, 7]. **Reduced basis models** normally involve the computation of a large number of 'offline' simulations that are examined together with an 'online' simulation to quantify its uncertainty. With our live-coding approach, we plan to modify this approach so that the bounding simulations are also 'online' and 'live' in a way that allows them to be extended and interpolated and steered in real time.

Live coding describes software systems that support the direct intervention of the programmer in a program's run-time state. It can be thought of as an extreme version of agile programming [9], where code changes are hot-swapped into running programs, allowing for extremely fast exploration and iteration of new ideas and system updates. As the ambition of live-coding has grown, support systems and languages have evolved to, for example, create, modify and interact with music and hardware devices in real-time [refs]. Such an approach has been described as "with-time programming" [29] because it allows for timing constraints on a running system, including human-computer-interaction constraints, to be explicitly modelled and guaranteed. The present project will make use of the **Extempore live-coding software environment**[1] that can **harness and steer scientific simulations** (written in ABI compatible languages such as C, C++ and Fortran) and evaluate (and visualise) the outcomes of those simulations in real time. Such an intervention in the world of high-performance computer simulation radically changes the landscape and ambition of simulation codes; no longer do they need to be considered as hands-off batch processes running on supercomputers, but they can now be interacted with on-the-fly while a simulation is in progress. We envision that there will be several benefits of the application of live-coding to our problem: firstly, it will enable us to **rapidly prototype our simulation software** and to deliver systems which can deliver feedback on a myriad of demands of a disaster emergency response; secondly, live coding will allow us to **maintain and tune a set of, traditionally-offline simulations used to quantify uncertainty in real time**; and thirdly, the use of live coding will allow us to adjust and optimise our systems for better efficiency and to cope with compute node failure in the volatile HPC systems expected in disaster management situations.

This research is significant because it aims to unlock the power of sophisticated computational simulation incorporating uncertainty for *interactive* use. Although we concentrate our research on simulation support for disaster response, the ultimate potential of this work is to eventually empower domain experts from a broad range of areas to better use the high-performance computing power which is now available to them. We envision a future where performing a complex flood model or disaster simulation is as interactive and *alive* as flicking through photos on a tablet.

INVESTIGATORS

The personnel involved in this project will be CIs Gardner, Strazdins, Roberts and Hegland, two Post-doctoral Research Associates and four PhD students. This project is split equally between the ANU Research School of Computer Science and the ANU Mathematical Sciences Institute. The four CIs are senior academics with many years of experience in running projects and many years of experience working with each other. Although CI Gardner is the lead CI on this grant application, the management structure of the project will be flat and deeply collaborative.

CI Gardner will be responsible for the overall project. He is a senior academic with many years of experience in computational science, high performance computing, virtual reality, Human Computer Interaction and computer music. He was director and head of school of ANU Computer Science from 2008 to 2013 and is presently the Associate Dean of Higher Degree Research in the ANU College of Engineering and Computer Science. In recent years, CI Gardner has been leading a research group that has developed the live coding "Extempore" programming system. This system originated in the creative arts to support live computer music, but has now been shown to be able to harness and interactive with traditional computational science applications in real time with negligible performance overhead. CI Gardner has a 40% research allocation and his term as Associate Dean will expire in 2018 providing him with opportunity to provide the proposed 20% allocation to the present project. **CI Strazdins** will be responsible for the high performance and distributed computing components of the project, based on his expertise in high performance computing, where he has a number of significant and well cited publications [3, 33, 2]. CI Strazdins has a 40% research allocation, leaving sufficient research time to cover the proposed 15% allocation to this project. **CI Roberts** will lead the inundation modelling, and

[1] http://extempore.moso.com.au

uncertainty quantification components, based on his expertise in computational fluid dynamics and the use of sparse grid based uncertainty quantification [7, 15, 28, 24]. CI Roberts has a 40% research allocation, with no current grant obligations, leaving sufficient research time to cover the proposed 20% allocation to this project. **CI Hegland** will be responsible for the sparse grid and reduced model component of the project, based on his extensive expertise in computational mathematics, in particular his expertise in the analysis of the combination technique for sparse grids [3, 12, 2]. CI Hegland has a 60% research allocation. In 2018 will he contribute 20% of his research time to the DP150102345, and potentially a 20% contribution to LP160100624 leaving sufficient research time to cover the proposed 20% allocation to this project.

Our project is strengthened by a collaboration we are building with Dr Bert Debusschere and Dr John Jakeman both from Sandia National Laboratories, USA. They both have very strong records in uncertainty quantification research. Dr Jakeman has expertise on uncertainty quantification techniques based on his extensive experience in using adaptive sparse grids, having applied such techniques to complex modelling problems [15, 14, 13] and has already collaborated with CI Roberts (his former PhD supervisor) [15]. Dr Debusschere has extensive expertise in uncertainty quantification through to fault tolerant numerical solvers, having already collaborated with CI Strazdins [30].

One post-doctoral fellow, to be situated in the Research School of Computer Science (RSCS), will develop large portions of the live programming tools and software interface which will interact with the scientific models and will conduct experiments on live scenarios where human actors mimic the interactions and information flows involved in the group dynamics of disaster response with simulation support. Due to the large skill set and responsibilities of this position it has been factored into the budget at level B3. One possible candidate for this position is Dr Ben Swift who is currently a post doc in the RSCS and has work extensively in HCI and has collaborated extensively with CI Gardner, on work relevant to this project [19, 20, 34, 35, 36].

A second post-doctoral fellow, to be situated in the Mathematical Sciences Institute (MSI), will need to have a very different skills set to the computer science research fellow. This research fellow will develop the numerical methods for computing sparse grid surrogates and reduced basis models which will be used to efficiently propagate uncertainties in model applications of tsunami and flood surge events. This position is budgeted at level B1 (raising to B2 in year 3). One possible candidate for this position is the current PhD student of CI Hegland, Mr Brendan Harding, who has has collaborated with CIs Hegland, Strazdins and Roberts, all on work relevant to this project [2, 3, 8, 12, 33].

We are requesting ARC funding for **four PhD students**, and we anticipate obtaining funding for another two PhDs from Australian Postgraduate Awards. Even though we have designated these PhD students to either computer science or mathematics, the projects will be inter-disciplinary, with all four CIs being on the supervisory panels of each of the students. The four PhD students will be split between the two departments—two in RSCS and two in MSI, focusing on specific aspects of the project, essentially aligned with the four CIs areas of responsibility. In RSCS, these will be the dynamic distributed computing infrastructure and the development of live interfaces for data visualisation. In the MSI, these will be the uncertainty quantification and the development of numerical methods for the sparse grid technique, and the reduced basis method, applied to our inundation model example.

PROJECT QUALITY AND INNOVATION

Significance

The January 2011 Brisbane River floods in south-east Queensland cost 32 lives and caused 2.5 billion dollars worth of damage [39]. In the days leading up to these events, a key issue facing authorities was incorporating their **uncertainty** about the preceding fortnight's rainfall and the forecast rainfall into their modelling. In their report on the causes, impacts and implications of the floods, [39] concluded:

> whilst the dam operators were acting in accordance with the operations manual for the dam, their modelling did not take account of forecast rainfall in determining the predicted dam water level, and this resulted in a sub-optimal water release strategy. Employing tools for decision making under uncertainty would have resulted in a different water release strategy.

At the other end of the environmental spectrum, bushfire model predictions are similarly 'fraught with uncertainty' [1, p375]. As Australia's climate changes and extreme weather events become more common, there is a significant need for better ways to gather timely insights from modelling in the presence of uncertainty and to communicate those insights to decision makers and emergency services.

Computational modelling and simulation is an invaluable support tool for disaster response, allowing emergency services personnel to explore what might happen in the immediate future under various scenarios. But these model simulations can be fraught with uncertainty: some of their *input parameters* may be well known (possibly from reliable sensor data), others may be known only approximately, and others still may only be guessed at. Even with perfect input data, the models themselves entail assumptions and numerical approximations which bound the reliability of their predictions.

A specific storm-surge example

Consider the problem of predicting the maximum storm surge water level at a location (or locations) along a coast threatened by a cyclone. We will denote the geographical area of interest by Ω (the region threatened by the cyclone) and consider only spatial points $(x, y) \in \Omega$. We will also restrict our interest to times t to an interval of time $T = [t_0, t_1]$ (the duration of the storm). A standard mathematical model for storm surge is provided by the shallow water wave equations [37]

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(uh) + \frac{\partial}{\partial y}(vh) - R = 0, \tag{1a}$$

$$\frac{\partial uh}{\partial t} + \frac{\partial}{\partial x}\left(u^2 h + \frac{1}{2} g h^2\right) + \frac{\partial}{\partial y}(vuh) + gh\frac{\partial b}{\partial x} - \frac{h}{\rho}\frac{\partial P}{\partial x} - S_{fx} - S_{wx} = 0, \tag{1b}$$

$$\frac{\partial vh}{\partial t} + \frac{\partial}{\partial x}(uvh) + \frac{\partial}{\partial y}\left(v^2 h + \frac{1}{2} g h^2\right) + gh\frac{\partial b}{\partial y} - \frac{h}{\rho}\frac{\partial P}{\partial y} - S_{fy} - S_{wy} = 0, \tag{1c}$$

where $h(x, y, t)$ is the depth of water, $u(x, y, t)$ and $v(x, y, t)$ are the x and y horizontal components of water velocity. In particular h, u and v are functions defined on $\Omega \times T = \mathcal{D}$.

Here g is the gravitational constant (9.81) and ρ is the density of water. The other terms constitute input data to the model. The bathymetry $b(x, y)$, is the elevation of the ocean bed. The rate of rainfall on the region over time is R. The atmospheric pressure is given by P (which generates a surge due to spatial differences in atmospheric pressure associated with a large cyclone). The x and y components of the frictional force generated by the flow of the surge over the ocean bed (flow over sand is different than flow through mangroves) is given by S_{fx} and S_{fy}, respectively. The x and y components of the surface stress force (generated by the wind) is given by S_{wx} and S_{wy}, respectively. As is evident, there are many opportunities for uncertainty in the input data defining this model.

In our papers [28, 24] these equations and their approximation using the AnuGA package is shown to provide a reliable model of general flows associated with inundation due storm-surge as well as riverine flooding and tsunamis.

The parameter space $\mathcal{P}$ will represent the possible variation in the input data R, b, P, S_f, S_w, as well as design parameters describing actions such as raising or lowering flood barriers and releasing or diverting flow from upstream rivers, or flood basins, or indeed constructing emergency levees. The model solution

$$U_{\mathbf{p}}(\mathbf{x}) = (h(x, y, t), u(x, y, t), v(x, y, t))$$

represents the water depth and velocity fields obtained by solving the model problem for a choice of parameter $\mathbf{p}$ at a particular location and time $\mathbf{x} = (x, y, t)$. Equation (1) can be characterised as $M_{\mathbf{p}}(U_{\mathbf{P}}) = 0$.

In this case, the quantity of interest $Q(U_{\mathbf{p}})$ will be the maximum storm surge height at a particular location $(x_0, y_0) \in \Omega$,

$$Q(U_{\mathbf{p}}) = \max_{t_0 \le t \le t_1} \left(h(x_0, y_0, t) + b(x_0, y_0)\right).$$

The aim of uncertainty quantification is to obtain useful relationships between the variations in pressure, wind and rainfall (changes of $\mathbf{p} \in \mathcal{P}$) and $Q(U_{\mathbf{p}})$, including identifying which components of the inputs have the greatest influence on the result.

A completely general parameter space $\mathcal{P}$ may lead to an intractable problem. It is sensible to look for a lower dimensional manifold $\mathcal{C} \subset \mathcal{P}$. This can be done algorithmically. Or in this case $\mathcal{C}$ might represent a model of the pressure, wind and rainfall associated with a cyclone of specific intensity and location. This would still involve

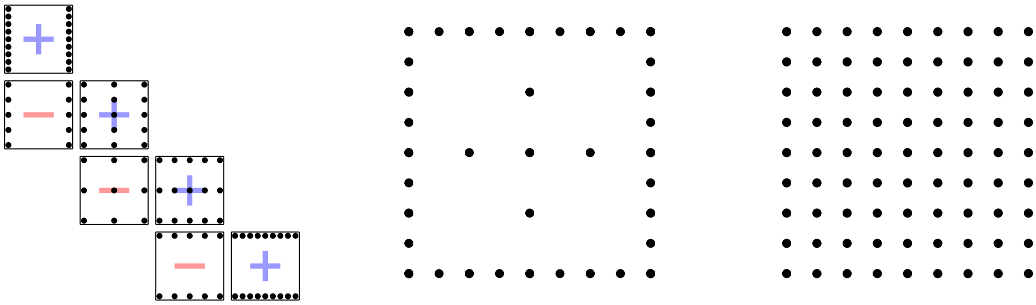

Figure 1: Combination grids on the left (with coefficients, marked with a blue plus for $+1$ and red minus for -1), sparse grid in the middle, full grid on the right. Note the marked reduction in the number of grid points for the sparse grid relative to the full grid. This is even more pronounced in higher dimensions.

uncertainty, and so would entail numerous solutions of our model problem to quantify the uncertainty in our quantity of interest. Finally, as we investigate our model, it might be advantageous to change the assumptions of our cyclone model, or incorporate updated forecasts or indeed play with adding different types of uncertainty to the various input data streams. This is where live programming and real time interaction with our model becomes paramount.

Sparse-Grids and Uncertainty Quantification

The mathematical component of this project will be based on new developments combining sparse grids [5], reduced basis methods [17, 26, 6, 25] and uncertainty quantification. One of the main difficulties in the study of current scientific models is the high dimensional spaces involved, often both in the parameter and domain spaces, $\mathcal{P}$ and $\mathcal{D}$ respectively. This is a significant barrier for the timely evaluation of models due to the 'curse of dimensionality' in which the cost scales exponentially with dimension. By using sparse grids and reduced basis models we will be able to compute *surrogates of the full problem* which have significantly fewer unknowns and are thus cheaper to compute whilst maintaining a high order of accuracy. For example, a general approach would be to find a lower dimensional manifold of the parameter space $\mathcal{Q} \subset \mathcal{P}$ over which the model is most sensitive using a proper orthogonal decomposition. A sparse grid surrogate of the model over $\mathcal{Q}$ can also be computed in an offline phase, so that in an online phase model solutions can be efficiently estimated using the surrogate model. For many problems sparse grids can also be used over $\mathcal{D}$ when computing solutions to the full model to speed up the construction of a reduced basis. We will compute sparse grid solutions via the 'combination technique' [11]. Figure 1 depicts the combination technique, the equivalent sparse grid and the corresponding full grid.

Propagating uncertainty in scientific models which are high dimensional and/or expensive to compute is a significant challenge. For models which are not stochastic in nature, and thus have no means of directly quantifying uncertainty, one must typically estimate statistical moments via Monte Carlo methods or quadrature rules. For high dimensional problems it has been shown that sparse grids can estimate these moments faster and more accurately than traditional Monte Carlo methods when the probability density functions are sufficiently smooth [15, 10]. Despite the advantages of reduced basis methods, the manifold $\mathcal{Q}$ is still sufficiently high dimensional that the quantification of uncertainty remains a challenge due to the sheer number of function evaluations required. This is particularly true when the quantification of uncertainty in a model is a component of an optimisation algorithm. As such it is important to continue to develop efficient numerical methods for uncertainty quantification for high dimensional problems. Replacing the full model with a reduced basis model also adds additional error and uncertainties. One needs to have some idea what the model outcomes may be for parameters not lying on the lower dimensional manifold $\mathcal{Q}$. An important part of developing reduced models is 'verifying' the model, by bounding the error of the surrogate for example. By using ensemble methods, multifidelity models [23] and gradient enhanced approximation [8, 13] we hope to improve the verification and propagation of uncertainties in models. Incorporating ideas from 'Kriging' (Gaussian process regression), a feature of which is having confidence intervals over an interpolant, together with sparse-grid interpolation, we will be able to express uncertainties explicitly in the surrogate model.

Live Coding of Scientific Simulation

This project will make use of the *Extempore* software environment[2] which has been used for live modification and real-time visualisation of particle-in-cell (PIC) plasma physics simulation codes, with negligible performance overhead compared to batch-mode execution in C [34]. This allows the scientist to modify the domain size/shape, the initial and boundary conditions, and various other parameters while the simulation is running, with live visual feedback.

The Extempore software environment is a key tool for this project as it allows us to fine tune our suite of simulation software for the specific requirements of the task domain.

Live Coding for Uncertainty Quantification

The ability to stop, modify, or restart computations 'in flight' has the potential to significantly improve the efficiency of an uncertainty analysis. There exist many algorithms, for example adaptive Markov chain Monte Carlo methods [40], which attempt to choose the best samples based on the sampling history. For complex problems however, a domain expert may often have a better idea about the region of the parameter domain where function evaluations should be concentrated. Through live programming within a tight feedback loop a domain expert can incrementally guide the current sampling strategy being used for uncertainty quantification, and in turn be guided by real time information derived from the reduced order model (such as surpluses provided by sparse grid approximation to identify important parameter dimensions and regions of interest), to improve the end result. The resulting strategies are expected to be more aggressive in nature as they are better targeted to the specific problem at hand. The result of this is more efficient quantification of uncertainty.

In this project, using live coding to accelerate the feedback loop between $\mathbf{p}$ and $Q(U_{\mathbf{p}})$, together with estimates of its uncertainty, will give a scientist the ability to interactively *explore* the connection (and the associated uncertainty) between the different dimensions of $\mathbf{p}$ and the overall response of the system. This will be used to **rapidly prototype software** with a view to identifying the necessary interactive controls needed to modify and interact with the final, relased and running, software in real-time. By understanding the human-factors and systems-level time constraints on the delivery of useful information in disaster-response settings, we will also be able to specify timing requirements on our model simulations as in the next section.

High-Performance Computing Systems Support

A reliance on high performance computing for the evaluation of scientific models provides additional challenges to the technical side of the project. Specifically, our algorithms must be highly scalable and robust to errors and faults in the computer system layer. There have been many recent developments in both highly-scalable algorithms for the sparse grid combination technique [32, 31] which will be of use for this and, additionally, it has been recently shown that such computations can be made robust [12, 3, 2]. By leveraging and continuing to develop these algorithms we can ensure that the offline components of our software system that require high performance computing resources will be both scalable and robust.

In this project we will leverage on-demand compute resources, such as the Amazon AWS cloud [4] and the National Compute Infrastructure NCI Cloud [22]. Using these cloud services will further improve the project's ability to deliver timely results in high-pressure and time-critical decision making scenarios.

Once again, we emphasise that our approach to live coding of test software is a novel aspect of our methodology. The *Extempore* tool that we have developed has been shown to be able to harness and steer scientific simulation in real time. In this part of the project, we will apply this tool to the real-time steering of the computer systems layer itself.

This will involve developing code libraries to assist the developer in the live performance evaluation and tuning of these complex and highly parallel simulations. For example, groups of processes will be allocated to different parts of the simulation. If some parts are delayed relative to others, processes can be 'stolen' from the faster group to improve load balance [30]. Communication bottlenecks can be identified and alternate communication algorithms can be employed to rectify this. Different computational kernels can be selected depending on the current memory system and floating point performance. It should be noted that this fine-tuning is not only application-dependent, but within an application, it depends on the workload selected, and even

[2] http://extempore.moso.com.au

Figure 2: The overall system context of the project

within that, may depend on the current phase of the simulation. Only Live Programming by *Extempore* has the flexibility and agility to facilitate such a degree of performance tuning.

Live coding of the systems layer of our project will, once again, allow rapid prototyping and performance-tuning of our software so that it can be run on realistic (cluster and cloud) HPC computer support. Most importantly, live-coding will allow a computer support expert to optimise the execution of those running simulations under conditions where the computer systems may be unreliable or subject to rapid change.

The overall context of our project is shown in Figure 2. . In the application layer, the project is concerned with developing and delivering simulations with quantified uncertainty in a time-bound manner under conditions of rapidly changing human demands. At the systems layer, the project is concerned with managing large and ambitious simulations, and their associated data, in emergency disaster management settings where the very existence of such systems may be volatile. Both of these layers of concern will be supported by a novel live-coding approach to software development and prototyping as well as the use of live-coding for delivered simulations in order to modify and tune them, and their computational systems in real time.

Expected Outcomes

This project will provide the following discoveries:

1. a suite of interactive, real-time modelling tools for surge-tsunami flood disasters which combine high fidelity simulations (fine grids) with low fidelity (coarse grid) simulations to quantify uncertainty, optimised for human exploration

2. a 'live software engineering' approach to the development, deployment and optimisation of these interactive software systems

3. models of group interaction scenarios for decision-making with expert modelling support; from these models, we will obtain empirical estimates of the time constraints that such scenarios impose on software and computer system requirements and the live controls needed to run them effectively in volatile contexts

4. interactive information visualisation of simulation predictions together with uncertainties

BENEFITS

This research is aims to unlock the power of sophisticated computational simulation incorporating uncertainty for *interactive* use. Although we concentrate our research on simulation support for disaster response, the ultimate potential of this work is to eventually empower domain experts from a broad range of areas to better use the high-performance computing power which is now available to them. We envision a future where performing a complex flood model or disaster simulation is as interactive and *alive* as flicking through photos on a tablet.

There are several benefits arising from the successful completion of this project. They include, economic, societal as well as environmental along with the generation of new knowledge:

- Reduced economic losses from disasters such as flooding

- Reduced property damage from disasters

- Reduced loss of life from disasters

- New knowledge in the understanding of disaster modelling, and hence forecasting.

FEASIBILITY

The project is feasible due to the rigorous design with distinct tasks and timelines which address the identified, well understood challenges in this discipline. The project brings together a multi-disciplinary team comprising maths, software development, visualisation and high performance computing expertise, enabling the team to address the entirety of the challenges identified.

The Australian National University is a research-intensive university of high international standing. The quality of the research at ANU has been reflected in every one of the ERA evaluation exercises where, relevant to the current proposal, both Information and Computing Sciences (08) and Mathematical Sciences (01) have been assessed as being at the highest level of 5. At ANU, the Research School of Computer Science and the Mathematical Sciences Institute have a long and deep collaboration in numerical and applied mathematics, notably in a number of "Area" projects linked to the supercomputing facilities on campus. Indeed, since the early 1980s ANU has housed the largest supercomputers in Australia and the present National Computational Infrastructure is located on campus.

Over the next year, a new building will be constructed at ANU to locate the Mathematical Sciences Institute with part of the Research School of Computer Science. This co-location of academics in these two areas will be particularly fruitful for the present project. Indeed, it is possible that this project will become a showcase of cooperation between these two Schools and that some of the more visible and interactive components of the project will be strongly featured in outreach activities.

Furthermore, the cloud computing facilities at the NCI National facilities will provide an ideal testbed for the project. Virtualization is necessary for tuning Extempore, and the size of the clusters will permit large-scale simulations by project staff.

COMMUNICATION OF RESULTS

The ANU expects publications at the highest levels of international journals and conferences. We will communicate the results of this project by publishing in top venues such as the "SIAM Journal of Scientific Computing","Parallel Computing", and the "Journal of Computational Science". In computer science, refereed publications associated with the top conferences are more prestigious than journals. Our publication targets will be the ACM Conference on Human Factors in Computing Systems (CHI), OOPSLA, ICSE, VL/HCC, Supercomputing (SC), IEEE International Parallel and Distributed Processing Symposium (IPDPS), Computer Supported Cooperative Work (CSCW) and IEEE Information Visualisation. In both disciplines, we also value the community and high quality of Australian conferences, and we will be submitting work to OzCHI, ASWEC, Computational Techniques and Applications Conference (CTAC) and the International Congress on Modelling and Simulation (MODSIM). We will present our work at the International SIAM conferences in Computational Science and Engineering and Uncertainty Quantification.

In addition, the source code contributions of this project will be released to the public. Both the Extempore live programming system (`https://github.com/digego/extempore`) and the AnuGA [28, 24] shallow water simulation package (`https://github.com/GeoscienceAustralia/anuga_core`) are available on GitHub under MIT and GPLv2 licences respectively. Parallel Sparse Grid Combination codes (ParSGCT) are available from CI Strazdins' website. We are committed to accessible and reproducible computational science, and support these goals by using free software licences and developing our code in the open on GitHub.

MANAGEMENT OF DATA

All research output will be stored on the ANU Data Commons and ANU Digital Collections. Data Commons is a central data repository for ANU research data which has been designed to securely store data and ensure that data are immune to format and media changes. This repository enables data to be accessed and reused with full open-access functionality to the public. Digital Collections accepts journal articles, conference papers, book chapters, working or technical papers and other forms of scholarly communication. It is also a repository for digital images of manuscripts and photographs in other university research collections.

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