

Surrogate Modelling of the Tritium Breeding Ratio

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UK Atomic
Energy
Authority

Nuclear fusion – the energy of the future!

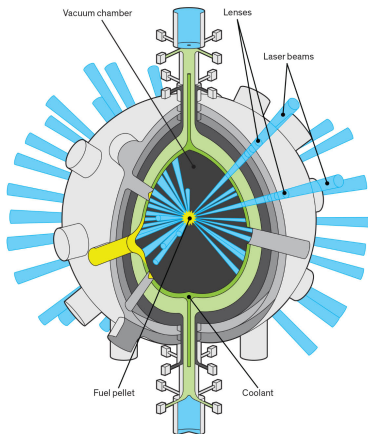
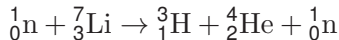
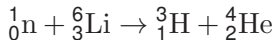


Illustration by Chris Philpot, courtesy of IEEE Spectrum.

- Designing next-generation Inertial Confinement Fusion (ICF) facility.
- Search for optimal reactor design.
- **Fueling** – important for viability.
- Require fuel of 2 varieties:
 - Deuterium ^2H – abundant in naturally-sourced water.
 - Tritium ^3H – **extremely rare**.
- Modern reactors can generate tritium during operation.

Tritium breeding blankets convert neutron radiation to ^3H fuel:



^3H balance described by **Tritium Breeding Ratio (TBR)** = $\frac{\text{fuel bred}}{\text{fuel consumed}}$

- Depends on numerous geometric and material parameters.
- Evaluated by *Paramak* – OpenMC neutronics simulation.
- Slow ... we want to consider as many reactor designs as possible!

Our Challenge

Produce a *fast* TBR surrogate that strongly approximates Paramak.

Produced datasets by sampling Paramak outputs over its 7 discrete and 11 continuous input parameters at random.

Deployed at UCL's

Hypatia cluster:

- Created **1M points**.
- **27 days** of runtime.

2 classes of runs:

- All parameters free.
- Discrete fixed, continuous free.

	Parameter name	Domain
Blanket	Breeder fraction [†]	[0, 1]
	Breeder ⁶ Li enrichment fraction	[0, 1]
	Breeder material	{Li ₂ TiO ₃ , Li ₄ SiO ₄ }
	Breeder packing fraction	[0, 1]
	Coolant fraction [†]	[0, 1]
	Coolant material	{D ₂ O, H ₂ O, He}
	Multiplier fraction [†]	[0, 1]
	Multiplier material	{Be, Be ₁₂ Ti}
	Multiplier packing fraction	[0, 1]
	Structural fraction [†]	[0, 1]
	Structural material	{SiC, eurofer}
First wall	Thickness	[0, 500]
	Armour fraction [†]	[0, 1]
	Coolant fraction [†]	[0, 1]
	Coolant material	{D ₂ O, H ₂ O, He}
	Structural fraction [†]	[0, 1]
	Structural material	{SiC, eurofer}
	Thickness	[0, 20]

Groups of parameters marked^{†‡} are required to sum to 1.

Conventional regression task – search for a cheap surrogate $\hat{f}(x)$ that **minimizes dissimilarity** with an expensive function $f(x)$:

- Regression performance: mean absolute error, σ of error, R^2 , R_{adj}^2 .
- Computational complexity: training & prediction time / sample

2 approaches to solution:

Decoupled Approach

- 1 Collect training dataset.
- 2 Use data to train a surrogate.

Adaptive Approach

- 1 Collect initial training dataset.
- 2 Use data to train a surrogate.
- 3 Collect more data in regions where surrogate performed poorly.
- 4 Repeat steps 2 and 3.

Decoupled Approach

Compared 9 state-of-the-art surrogate families:

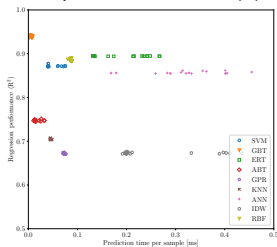
- Support vector machines,
- Gradient boosted trees,
- Extremely randomized trees,
- AdaBoosted decision trees,
- Gaussian process regression,
- k nearest neighbors,
- Artificial neural networks (MLP),
- Inverse distance weighting,
- Radial basis functions.

Performed 4 experiments:

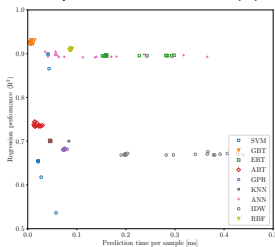
- 1 Hyperparameter tuning (simplified) – Bayesian optimization, discrete features fixed & withheld.
- 2 Hyperparameter tuning – same as #1 but with all features.
- 3 Scaling benchmark – increase training set size.
- 4 Model comparison – train surrogates for practical use.

Experiments 1 & 2: Hyperparameter Tuning

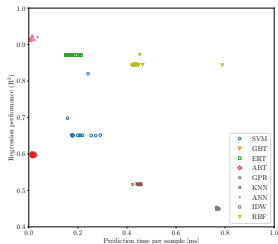
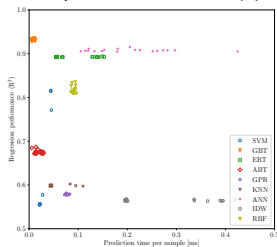
Experiment 1, slice (a)



Experiment 1, slice (b)



Experiment 1, slice (c)

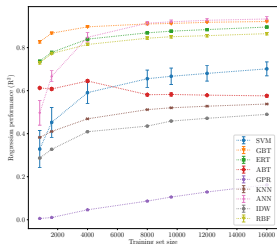


Experiment 2

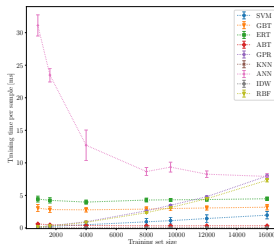
- Showing $\bar{t}_{\text{pred.}}$ vs. R^2 for the 20 best surrogates per family (top left \Leftrightarrow fastest, most accurate).
- Omit discrete features \rightarrow negligible performance improvement.
- Dominated by **trees** (GBTs, ERTs) and **neural networks**.

Experiment 3: Scaling Benchmark

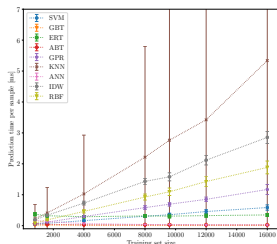
- We observe a hierarchy.
- **Trees** and **neural networks** scale the best in $\bar{t}_{\text{pred.}}$.
- Maximizing training set size, **neural networks** dominate.
- Instance-based surrogates (KNN, IDW) train trivially but have slow lookup.
- Neural networks show inverse scaling due to parallelization.



Regression performance



Training time / sample



Prediction time / sample

Experiment 4: Model Comparison

Trained **8 surrogates** for practical use.

Model 1, best regression performance

- ANN (4-layer MLP), 500K samples.
- $R^2 = 0.998$, $\sigma = 0.013$,
- $\bar{t}_{\text{pred.}} = 1.124 \mu\text{s}$, speedup $6\,916\,416\times$

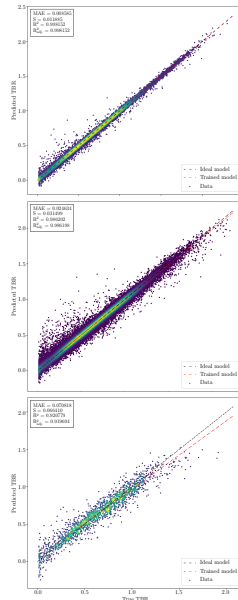
Model 2, fastest prediction[†]

- ANN (2-layer MLP), 500K samples.
- $R^2 = 0.985$, $\sigma = 0.033$,
- $\bar{t}_{\text{pred.}} = 0.898 \mu\text{s}$, speedup $8\,659\,251\times$

Model 4, smallest training set[†]

- GBT, **10K samples**.
- $R^2 = 0.913$, $\sigma = 0.072$,
- $\bar{t}_{\text{pred.}} = 6.125 \mu\text{s}$, speedup $1\,269\,777\times$

[†] with acceptable regression performance.

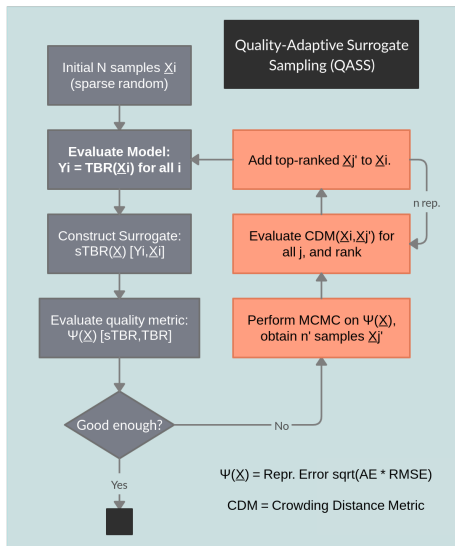


Adaptive Approach

How to use information *during training* to reduce sample quantity?

Our **novel technique**:

- 1 Construct surrogate quality distribution by nearest-neighbour interpolation.
- 2 Draw candidate samples by quality using MCMC.
- 3 Include samples with greatest separation from neighbours.
- 4 Repeat!



Toy functional TBR theory with wavenumber n , and qualitatively comparable ANN performance to Paramak:

$$\text{TBR}_{\text{toy}} = \frac{1}{|C|} \sum_{i \in C} [1 + \sin(2\pi n(x_i - 1/2))] \quad (\text{where } C \text{ enumerates all continuous variables})$$

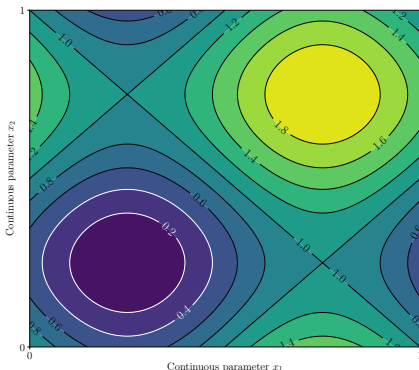
Evaluation set:

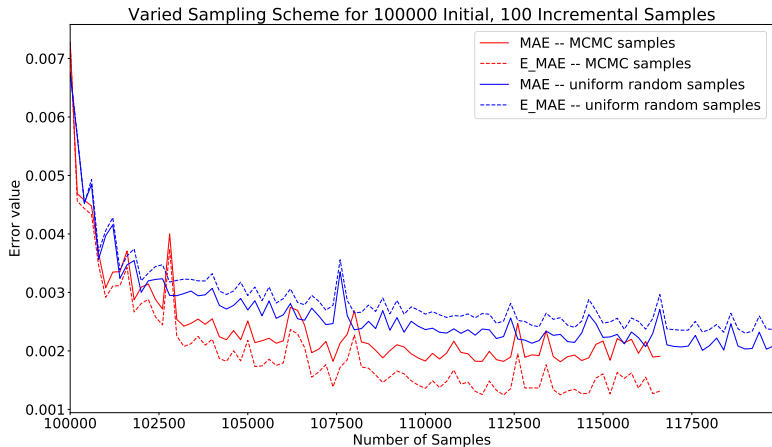
- Adaptive samples
- Generated during runtime

Validation set:

- Uniform random samples
- Generated independently

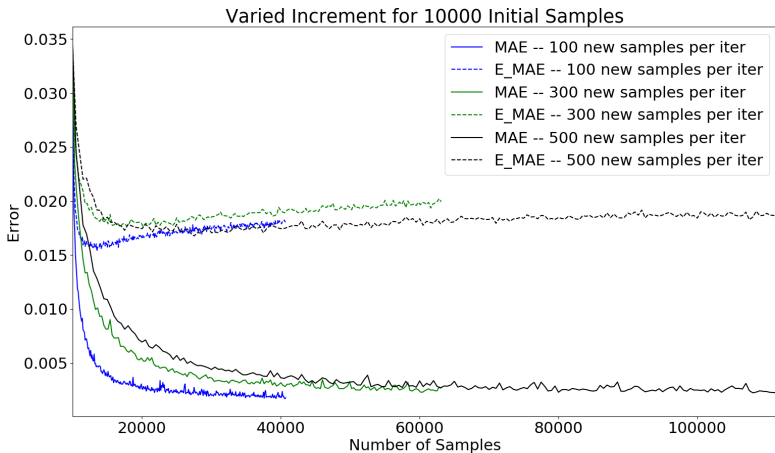
Placebo comparison – incremental uniform-random samples, no MCMC.





60% decrease in MAE for validation set (dashed)

Equivalently, 6% decrease in samples needed for same accuracy



Fewer incremented samples can lead to better accuracy!

But depends on initial samples, specific model – further study needed.

Decoupled Approach

- Heuristic: **GBTs** for $< 10^4$ samples, **ANNs** for $\geq 10^5$ samples.
- Fastest found surrogate evaluates TBR in $0.898 \mu\text{s}$ with error 0.033. This is roughly $8 \cdot 10^6 \times$ **faster** than Paramak.
- Found surrogates with comparable properties with $\approx 10\text{K}$ **samples**.

Adaptive Approach

- New theoretical approach **QASS** developed, based on MCMC.
 - **60% decrease** in evaluation MAE demonstrated.
 - **6% decrease** in expensive TBR samples needed.
-
- **Portable** methods \rightarrow cheap approximation of any simulation.
 - Article in IOP **Journal of Nuclear Fusion** (pending).
 - Included as a benchmark in the **SciML Collaboration**.

Thank you for listening!

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Further Reading

- Single page abstract (available online).
- Journal article, currently in internal pre-submission review (available online):
Fast Regression of the Tritium Breeding Ratio in Fusion Reactors.
- Industry group project final report (available online).
- All models, plots, training data, source code and technical documentation.
<https://github.com/ucl-tbr-group-project>