Muddy waters: Modifying reserve design algorithms for riverine landscapes

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EXTENDED ABSTRACT

The objective of systematic conservation planning is to select areas to protect or rehabilitate ecological assets in the most efficient way. After setting targets for ecological assets, heuristic algorithms or optimization techniques are employed to meet these targets.

This technique – traditionally only used in terrestrial and marine settings – has recently been adapted to river management, acknowledging spatial constraints arising from the connected nature of rivers. However, terrestrial heuristics and optimization techniques employed to solve the minimum-set or maximum-coverage problem in conservation planning scenarios have been designed to deal with non-connected systems. Therefore, different algorithms will perform better or worse in a riverine setting. In this study, we compare the performance of two different techniques to identify important cells for meeting ecological targets in terms of efficiency, congruence and computational effort.

The first technique is a heuristic algorithm, often used in classic conservation planning problem. Heuristics operate in a stepwise manner, selecting for the most taxa rich or the rarest feature first, then recalculate the selection matrix and run until all conservation targets are covered. To ensure connectivity of planning units is preserved, we modified the rules of the heuristic: Isolated planning units in the middle of a river system cannot be selected. Instead the entire catchment area upstream will have to be protected

The second method is an extension of the conservation software package MARXAN. After allocating a random initial reserve, planning units are randomly added to and taken out. Each step is evaluated against an objective function that considers the achieved conservation targets, as well as cost and compactness of the reserve system. The last measure – compactness of the reserve system – is used to accommodate MARXAN to lotic systems. Instead of penalising for all boundaries of a planning unit, only the planning units that are crossed by a river are counted.

We found that while the heuristic assigned a higher range of irreplaceability values, the areas of high conservation value were similar in both algorithms. When comparing the best solutions (also termed near-minimum sets), we found that an increasing boundary penalty in MARXAN also increases the reserve network. While a run without penalty only needs 27 out of 1854 planning units, this increases to 174 units at penalty 10 and 696 at penalty hundred. At boundary penalty 100, not all features were captured, as the penalty for compactness exceeded the penalty for not meeting targets.

The 174 units at penalty 10 take up a slightly smaller area than the best solution of the heuristic algorithm. Boundary penalty 10 seems to be the optimal penalty in the current dataset. While it is not as strict in the upstream protection as the modified heuristic, it still creates a network of compact reserves at a configuration that is easier to achieve. However, because of the lack in the strict upstream protection, the reserve network might not be adequate for some of the targets, depending on the strength of upstream disturbance.

While this is a great step forward to advance river conservation planning, more research into the tradeoffs between whole catchment protection and practicality will have to be conducted.

Currently, the node-based approach in the heuristic ensures to find a near-optimal set under the constraints that whole-catchment protection is needed. With a medium boundary penalty setting, MARXAN can deliver more efficient reserve designs, but this could lead to inadequate protection. As a future research direction, we recommend to include information about the downstream extent of disturbance to ensure adequacy.

1. INTRODUCTION

Historically, conservation areas to protect ecological assets have been selected based on rather unscientific criteria. The key criterion was simply lack of conflict with exploitative uses. In the last two decades, terrestrial and marine ecologists have begun developing more scientific approaches to the protection of ecological assets, measuring conservation value by irreplaceability and weighing this up against the risk of degradation.

The main difference between river and terrestrial/marine planning is the way in which rivers are connected to their environment. The two main influences on any planning unit in a freshwater setting are:

- Lateral connectivity: the influence of the catchment immediately surrounding the river. Since Hynes (1975) first described the influence of human land use in the contributing catchment, this has been a central theme in aquatic ecology.

- Longitudinal connectivity: Upstream disturbances that are influencing downstream habitat and biodiversity. Examples are chemical spills that are travelling downstream or sediment pulses caused by erosion events.

These unique properties of river systems are the reason why modern conservation planning techniques cannot be used in lotic systems without modification. While freshwater conservation tools are mainly index based (e.g. richness, rarity), modern terrestrial and marine conservation planning methods use complementarity-based algorithms - proven to be most efficient at protecting a large number of taxa for the least cost.

Most modern terrestrial and marine reserve design algorithms have two outputs:

1. A minimum set which identifies the single most efficient solution to protect a set of conservation targets

2. A measure of irreplaceability: usually defined by has two aspects (Pressey et al., 1993): 1. the likelihood that an area will be required as part of a conservation system that achieves all conservation targets; and 2. the extent to which the options for achieving all targets are reduced if the area is unavailable for conservation.

Minimum sets and irreplaceability maps are commonly calculated using two groups of techniques. The first group consists of heuristic algorithms (used in the software packages C-Plan and ResNet), which take a stepwise approach to reserve selection. The second group are optimisation methods, such as branch-and-bound algorithms or simulated annealing – the latter is used in the package MARXAN.

The few complementarity-based lotic conservation efforts all use broad river classifications instead of biota as targets, a method heavily disputed in the literature. Additionally, up to this year, none of the riverine approaches included acknowledging the connectivity issues outline above. In 2007, three publications detailing ‘real’ systematic conservation planning approaches were published, one in South Africa (Nel *et al.*, 2007), one in the USA (Sowa *et al.*, 2007) and one in Australia (Linke *et al.*, 2007).

It is the aim of this paper to present two ways of dealing with connectivity in lotic systems and compare their performance, efficiency and computational demands. These approaches are derived from the two groups above. The first approach is a bootstrapped heuristic, the second approach is an adoption of MARXAN which considers longitudinal connectivity.

2. METHODS

2.1. Study area and data used

Victoria is about 227 600 km^2 and covers a wide variety of landforms and climatic conditions. To account for the connected nature of rivers, 1854 subcatchments derived from a 3 arcsecond digital elevation model (DEM) were used as planning units.

Targets for conservation planning were 1065 macroinvertebrate taxa collected within 222 subcatchments. Taxa distributions for the remaining subcatchments were predicted using generalized additive models (GAMs) as described by Yuan (2004). Predictor variables were derived from spatial data layers that included the subcatchments location in the landscape, local climate, landform, geology and vegetation. After autocorrelated predictors were removed using principal components analysis (PCA), the six predictors remained.After removing macroinvertebrate taxa with less than 10 occurrences, 400 taxa were successfully modeled according to the criteria set by Yuan (2004, Criterion=ROC AUC>0.6).

2.2. Modified heuristic algorithm

Data pre-processing

To deal with the connected nature of rivers, we restricted the selection process. An isolated mid-order subcatchment that may have disturbances upstream does not make much sense in a conservation framework and is hence a forbidden configuration (Fig. 1a). Instead, to protect the target features in the greyed out subcatchment, the entire region upstream needs to be protected. (Fig.1b)

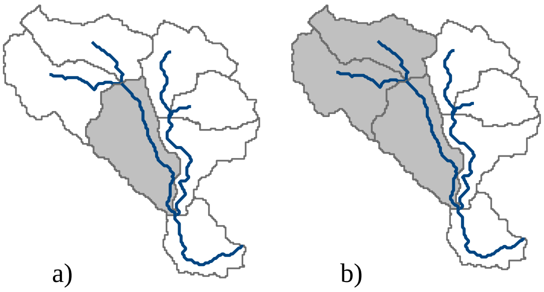


Figure 1. a) Isolated mid-order subcatchments that have possible disturbances upstream are forbidden b) whole catchments have to be selected instead

Technically, we solved this by prioritising for nodes instead of planning units. Nodes are hereby defined as the outflow points of a subcatchment. Using a propagation algorithm on the river network constructed within ArcHydro, we determined all the targets upstream of a node and the cost associated with the node (Fig. 2). With no actual land costs available, we use the area upstream of the node as the cost surrogate. Figure 2 illustrates the tradeoff in the algorithm. While selecting a node further downstream will increase the cost, it will also protect more targets.

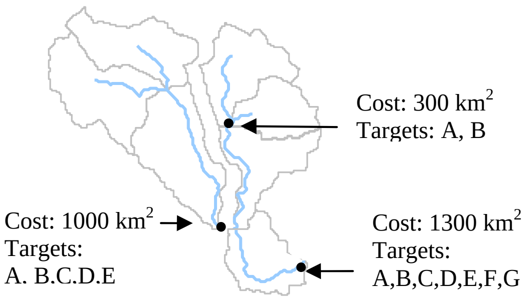


Figure 2. The structure of the spatial database after pre-processing. Every node has a set of targets upstream, as well as an associated cost.

Heuristic to calculate near-minimum set and irreplaceability

The most efficient heuristic selection procedure (based on trials detailed in Linke et al. (accepted)) selects for nodes for which upstream protection ensures the most and rarest protected taxa at the least cost (area).

The mathematic formulation of the prioritisation parameter is therefore

$$c = \sum \frac{1}{f} / area \qquad \text{(Equation 1)}$$

where c = contribution to targets, summed across all taxa upstream of node, corrected for area
f = frequency of the taxon in the entire dataset
$area$ = hectares covered by subcatchment or group of subcatchments

The first step of the algorithm was to select the node with the highest c upstream. The area upstream and the taxa it contained were then removed from the dataset and c was re-calculated. Tied values of c did not occur so we did not have to resort to tie-breaking rules (Pressey et al., 1997). Selections, removals, and recalculations were repeated until every taxon in the dataset was represented at least once.

To estimate irreplaceability, the algorithm was run 1000 times with 90% of the planning units randomly removed at each run. Irreplaceability was defined as the frequency of selection in the randomisations.

2.3. Simulated annealing with a boundary length modifier

The second method is simulated annealing, an optimisation method popularised in the conservation planning field through its use in the software package MARXAN (Possingham *et al.*, 2000). After allocating a random initial reserve, planning units are randomly added to and taken out. Each step is evaluated against an objective function

$$\sum_{sites} cost + \sum_{features} feature\ penalty + \sum boundary\ length$$

Hereby *cost* represents the cost of the reserve network. *Feature penalty* is a penalty for not representing conservation targets in the network (at 0 feature penalty, all targets are covered) and *boundary length* is a measure how fragmented the reserve system is. As the goal of the algorithm is to produce spatially compact reserves that cover all targets, steps that lower the objective function are more likely to be accepted than steps that increase the objective function.

The boundary length penalty is used to modify MARXAN for the connected nature of rivers. First, a script within ArcView 3.3 will identify subcatchment (or planning unit) boundaries that are crossed by a streamline. These boundaries are earmarked and are set to incur a boundary length penalty if not both adjoining planning units are selected. This is demonstrated in Figure 3.

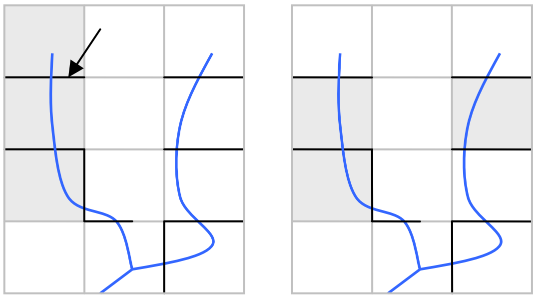


Figure 3. Construction of the boundary length file. Relevant boundaries are marked in bold lines. Reserve design A is favourable to reserve design B, because the boundary in the left upper corner does not incur a penalty.

The strength of the boundary effect can be adjusted by multiplying the term $\sum$*boundary length* by a constant. We used the weights of 0 (no boundary effect), 1 (small boundary effect), 10 (increased clumping) and 100 (strong clumping). Irreplaceability was determined by running the algorithm 500 times and summing the selection frequency analogous to the heuristic.

2.4. Analysis

Multiple runs were conducted using both approaches.

- Bootstrapped heuristic without data pre-processing (isolated subcatchments are allowed)
- Bootstrapped heuristic with pre-processing
- MARXAN with four levels of boundary penalties

We expect that at a penalty weighting of zero, the solution would resemble the minimum set in the heuristic without an upstream rule. As the penalty weighting increases, the solutions should resemble the minimum set of the heuristic when using the upstream protection rule.

3. RESULTS

3.1. Comparison of algorithms

When running the algorithms on the non-processed data, correlation is relatively low (r=0.47). However, while the heuristic algorithm displays a wider spread, it is obvious in Figure 4 that highly irreplaceable subcatchments are selected frequently in both methods.

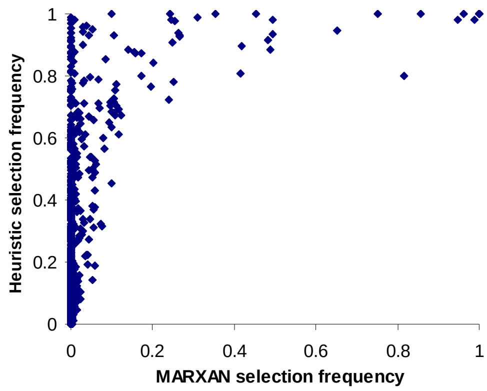


Figure 4. MARXAN selection frequency only coincides with the selection frequency of the heuristic algorithm for high selection frequencies.

3.2. Minimum sets and irreplaceability maps

Figures 5 a-c illustrate the increasing influence of the boundary penalty factor in MARXAN. While only 27 subcatchments are required for the near minimum set when the boundary penalty is switched off (similar at boundary penalty 1, map omitted), this increases to 174 subcatchments at boundary penalty 10. In contrast to the This increases to 696 subcatchments at boundary penalty 100. At boundary penalty 100, not all features were captured, as the penalty for compactness exceeded the penalty for not meeting targets.

Figure 6 shows the minimum set created by the heuristic. With 10.3% of the entire study area, it occupies a slightly larger area compared to the configuration at boundary penalty 10.

The irreplaceability map in Figure 7 displays a wide geographical spread of areas of high irreplaceability. These are roughly centered around the large areas in the minimum sets at boundary penalty 10 and the heuristic minimum set respectively.

Figure 5a. MARXAN near-minimum set using no boundary penalty

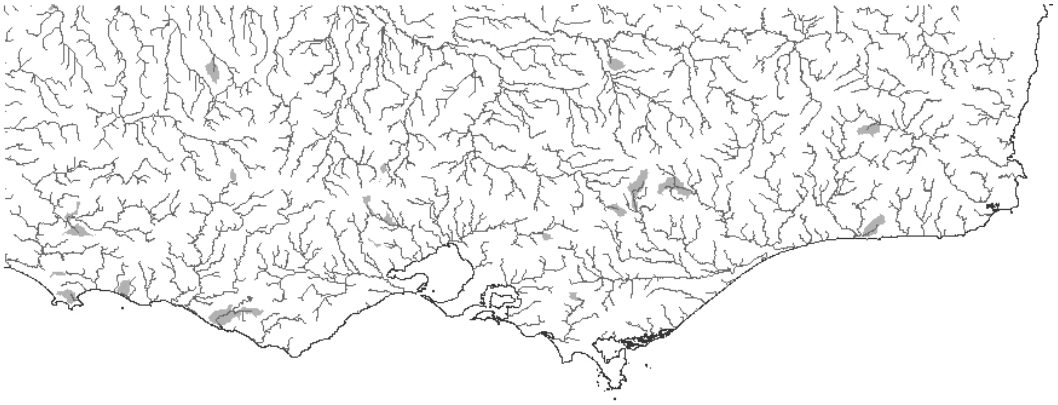


Figure 5b. MARXAN near-minimum set using a boundary penalty of 10

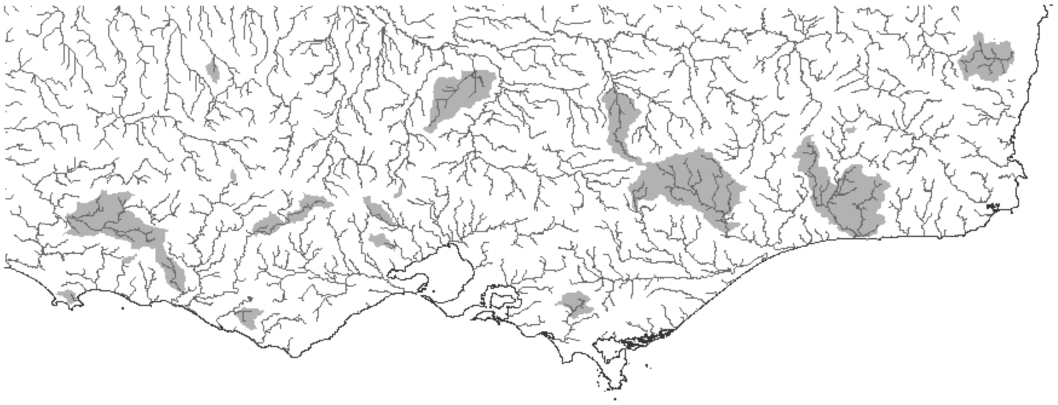


Figure 5c. MARXAN near-minimum set using a boundary penalty of 100

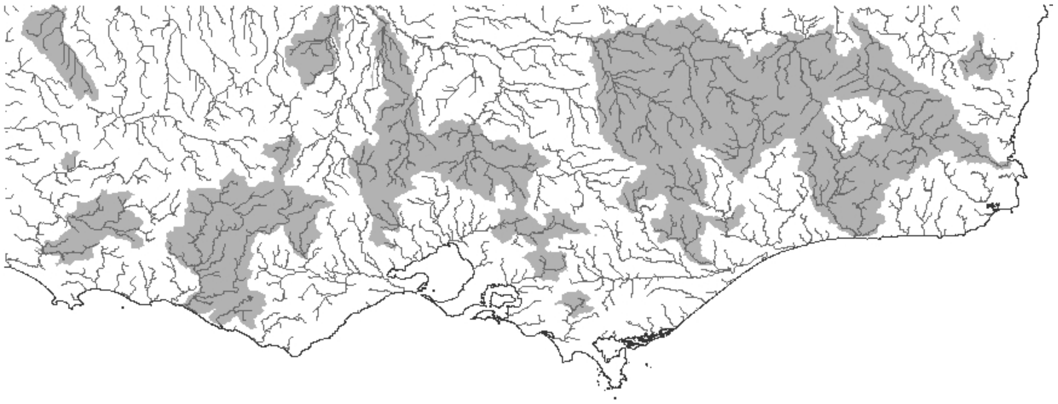


Figure 6. Heuristic near-minimum set restricted to only include entire catchments

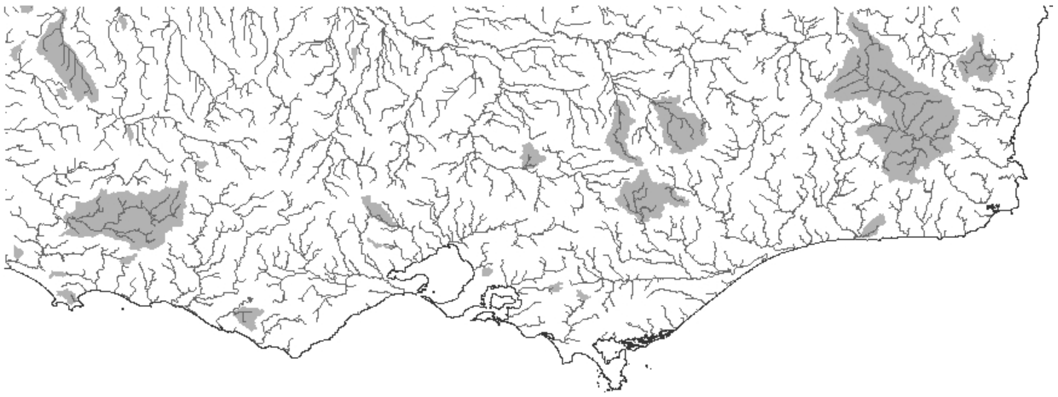
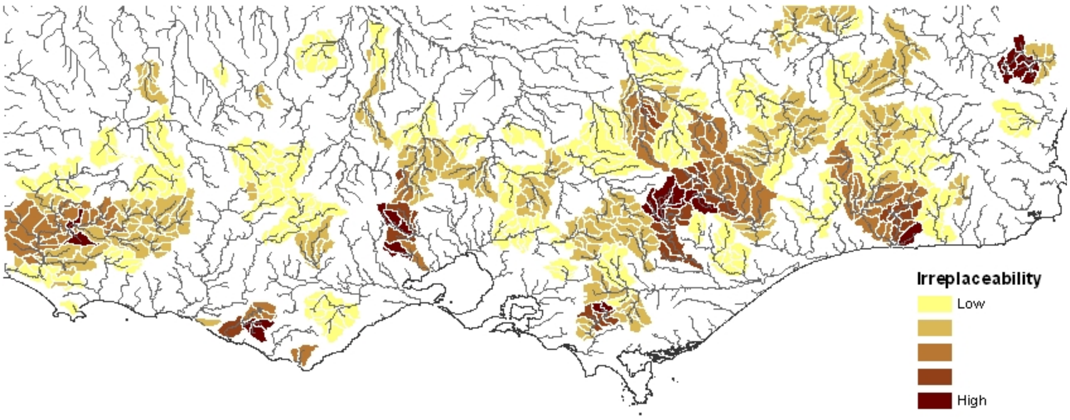


Figure 7. Summed irreplaceability calculated by MARXAN at boundary penalty 10



4. DISCUSSION

The two approaches presented in this paper are the first modifications undertaken to fit reserve design algorithms into a catchment framework. This is crucial to address issues of adequacy in freshwater conservation planning (Pringle, 2001; Linke *et al.*, 2007) as upstream influences need to be considered just as much as the disturbances in the surrounding catchments.

The initial comparison between the heuristic and MARXAN confirms that catchments of very high conservation value are recognised by both methods. The wider spread of the heuristic is attributable to the fact that MARXAN tries to optimise for the entire dataset in every run. However, the wide spread of the heuristic is a desirable attribute, especially in highly modified landscapes such as south-east Australia (Norris *et al.*, 2007). The irreplaceability map (Fig.7) is very similar to the one in Linke *et al.* (2007) that was created by the heuristic.

The strict upstream selection rule in the boostrapped heuristic ensures that the entire catchment upstream is protected. As discussed in Linke *et al.* (2007), this can lead to situations in which the catchment area upstream is too large to schedule efficient protection – which might not even be completely needed if the disturbance is metabolised within a short range.

The differences in the algorithms is demonstrated best in Victoria's largest catchement, the Snowy River (Fig. 8). The total catchment area is 15,500 km^2 at a stream length of 350 km from source to mouth. While the bootstrapped heuristic selects about half of the catchment upstream before it can include some taxa endemic to the lower reaches (Fig. 8a), MARXAN chooses a mixture of lower reach side-arms and a smaller section of the main stem – about 80 kilometres (Fig. 8b).

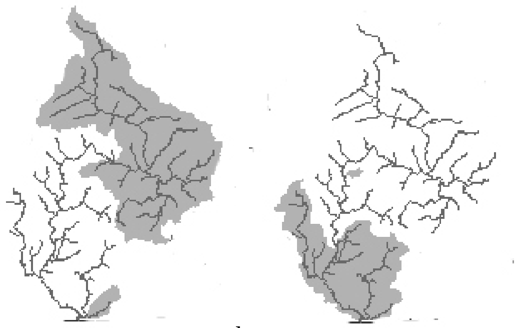


Figure 8. The Snowy River in eastern Victoria. a) is the minimum set created by the heuristic, b) is created by MARXAN

This flexibility in MARXAN can both be an advantage and a disadvantage. While it can select for a smaller area that is more realistic to manage (Fig. 8b), persistence of the targets is not guaranteed if upstream disturbances are too strong. On the other hand, the more realistic conservation plans could help to engage stakeholders.

Future research in applying MARXAN to rivers is still needed: As the sequence of Figures 5 a-c shows, the boundary penalty and the taxa penalty have to be well balanced to ensure a comprehensive and efficient conservation plan. Although the boundary penalty of 10 seems optimal in this situation, there is no obvious rule of thumb on how to balance the increased flexibility and smaller cost of a low penalty with the increased adequacy of higher penalties. The penalty weighting of 100 (Fig. 5c) demonstrates that an excessive boundary penalty creates inflated reserves and -because boundaries become more important than targets- even prevents comprehensiveness.

While it is beyond the scope of this paper, a cost-benefit analysis, in which the algorithms are cost-restricted would be a logical next step. This would show which algorithm is more efficient under a priori constraints.

5. CONCLUSION

The presented modifications to river conservation planning algorithms are the only explicit approaches to deal with the connected nature of rivers so far. While this is a great step forward to advance river conservation planning, more research into the tradeoffs between whole catchment protection and practicality will have to be conducted.

Currently, the node-based approach in the heuristic ensures to find a near-optimal set under the constraints that whole-catchment protection is needed. With a medium boundary penalty setting, MARXAN can deliver more efficient reserve designs, but depending on the nature of the disturbance this could lead to inadequate protection.

We recommend that future systems will include a measure of the disturbance at a site, as well as an estimate of the extent of the downstream effect. Considering this downstream effect of potential degradation would direct the aggregation needed for adequate conservation planning

6. ACKNOWLEDGEMENTS

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