

Gene genealogies in a haploid population evolving according to sweepstakes reproduction – approximating $\mathbb{E}[R_i(n)]$ for the time-changed δ_0 -Poisson-Dirichlet($\alpha, 0$)-coalescent

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Fix $0 < \alpha < 2$ and $0 < \gamma \leq 1$. Let $\{\xi^n\} \equiv \{\xi^n(t) : t \geq 0\}$ be the continuous-time time-changed δ_0 -Poisson-Dirichlet($\alpha, 0$)-coalescent with time-change function $G(t) = \int_0^t e^{\rho s} ds$.

Write $\#A$ for the number of elements in a given finite set A , $L_i(n) \equiv \int_0^{\tau^{(n)}} \#\{\xi \in \xi^n(t) : \#\xi = i\} dt$ and $L(n) \equiv \int_0^{\tau^{(n)}} \#\xi^n(t) dt$ and $\tau(n) \equiv \inf\{t \geq 0 : \#\xi^n(t) = 1\}$ for $i \in \{1, 2, \dots, n-1\}$. We then have $L(n) = L_1(n) + \dots + L_{n-1}(n)$. Define $R_i(n) \equiv L_i(n) / \sum_j L_j(n)$ for $i = 1, 2, \dots, n-1$. Interpreting $\{\xi^n\}$ as ‘trees’ we may view $L_i(n)$ as the random total length of branches supporting $i \in \{1, 2, \dots, n-1\}$ leaves, with the length measured in coalescent time units, and n sample size. With this C++ code we sample the time-changed δ_0 -Poisson-Dirichlet($\alpha, 0$)-coalescent with $0 < \alpha < 2$ and exponential growth parameter $\rho \geq 0$ fixed, and approximate $\mathbb{E}[R_i(n)]$

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1 Copyright

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CTANGLE 4.12.1 (TeX Live 2025/Debian)
g++ (Debian 15.2.0-12) 15.2.0
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This is LuaHBTeX, Version 1.22.0 (TeX Live 2025/Debian) Development id: 7673
SpiX 1.3.0
GNU Awk 5.3.2, API 4.0, PMA Avon 8-g1, (GNU MPFR 4.2.2, GNU MP 6.3.0)
GNU Emacs 30.2

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2 compilation and output

This CWEB [KL94] document (the `.w` file) can be compiled with `cweave` to generate a `.tex` file, and with `ctangle` to generate a `.c` [KR88] C++ code file.

Use the shell tool `spix` on the script appearing before the preamble (the lines starting with `%$`); simply

```
spix /path/to/the/sourcefile
```

where `sourcefile` is the `.w` file

One may also copy the script into a file and run `parallel` [Tan11] :

```
parallel --gnu -j1 :::: /path/to/scriptfile
```

3 intro

We consider the continuous-time time-changed δ_0 -Poisson-Dirichlet($\alpha, 0$)-coalescent, with $A \equiv 1 / \left(\prod_{j=2}^n (\sum_i \mathbb{1}_{\{k_i=j\}})! \right)$, transition rates

$$\lambda_{n;k_1, \dots, k_r; s} = A \binom{n}{k_1 \dots k_r s} \left(\mathbb{1}_{\{r=1, k_1=2\}} \frac{C_\kappa}{C_\kappa + c(1-\alpha)} + \frac{cp_{n;k_1, \dots, k_r; s}}{C_\kappa + c(1-\alpha)} \right) \quad (1)$$

where $0 < \alpha < 1$, $\kappa \geq 2$, $c \geq 0$ all fixed, and

$$p_{n;k_1, \dots, k_r; s} = \frac{\alpha^{r+s-1} \Gamma(r+s)}{\Gamma(n)} \prod_{i=1}^r (k_i - \alpha - 1)_{k_i-1} \quad (2)$$

$$C_\kappa = \mathbb{1}_{\{\kappa=2\}} \frac{2}{m_\infty^2} + \mathbb{1}_{\{\kappa>2\}} \frac{c_\kappa}{2^\kappa (\kappa-2)(\kappa-1)}$$

and $\kappa + 2 < c_\kappa < \kappa^2$ for $\kappa > 2$.

4 code

¶ includes.

the included libraries

```
5 <includes 5> ≡  
#include <iostream>  
#include <cstdlib>  
#include <iterator>  
#include <random>  
#include <fstream>  
#include <iomanip>  
#include <vector>  
#include <numeric>  
#include <functional>  
#include <algorithm>  
#include <cmath>  
#include <unordered_map>  
#include <assert.h>  
#include <float.h>  
#include <fenv.h>  
#include <gsl/gsl_rng.h>  
#include <gsl/gsl_randist.h>  
#include <gsl/gsl_math.h>  
#include "headerfile.hpp"
```

This code is used in chunk 17.

¶ the random number generators.

the random number generators

```
6 <rngs 6> ≡  
    std::random_device randomseed;      /*  
     * Standard mersenne twister random number engine */  
    std::mt19937_64 rng(randomseed());  
    gsl_rng *rngtype;  
  
    static void setup_rng(unsigned long int s)  
    {  
        const gsl_rng_type*T;  
        gsl_rng_env_setup();  
        T = gsl_rng_default;  
        rngtype = gsl_rng_alloc(T);  
        gsl_rng_set(rngtype, s);  
    }
```

This code is used in chunk 17.

4.1 the coalescent rate

the coalescent rate $\lambda_{n;k_1,\dots,k_r;s}$

$$\langle \lambda_{n;k_1,\dots,k_r;s} \rangle \equiv$$

```

7   static double lambdanks (const double n, const std::vector<unsigned int> &v_k ) {
    assert(v_k[0] > 1);
    double d
    {
    ;
    double k
    {
    ;
    double f
    {1};
    const double r = static_cast<double>(v_k.size()); std::unordered_map<unsigned int ,
        unsigned int > counts
    {
    ;
    const auto descending_factorial = [] (const double x, const double m)
    {
        double p = 1;
        for (double i = 0; i < m; ++i) {
            p *= (x - i);
        }
        return p;
    }
    ;
    const auto veldi = [] (const double x, const double y)
    {
        feclearexcept(FE_ALL_EXCEPT);
        const double d = pow(x, y);
        return (fetestexcept(FE_UNDERFLOW) ? 0. : (fetestexcept(FE_OVERFLOW) ? FLT_MAX : d));
    }
    ;
    for (std::size_t i = 0; i < v_k.size(); ++i) {
        f *= descending_factorial(static_cast<double>(v_k[i]) - 1. - ALPHA,
            static_cast<double>(v_k[i]) - 1); /* 
            count occurrence of each merger size */
        ++counts[v_k[i]];
        k += static_cast<double>(v_k[i]);
        d += lgamma(static_cast<double>(v_k[i] + 1));
    }
    assert(k < n + 1);
    const double s = n - k;
    const double p = static_cast<double> ( std::accumulate (counts.begin(), counts.end(), 0,
        [] (double a, const auto &x)
    {
        return a + lgamma((double)x.second + 1);
    }
    ) );
}

```

```

const double l = ((v_k.size( ) < 2 ? (v_k[0] < 3 ? 1. : 0) : 0) * CKAPPA) + (CEPS * veldi(ALPHA,
    r + s - 1) * tgamma(r + s) * f / tgamma(n));
return (veldi(exp(1),
    (lgamma(n + 1.) - d) - lgamma(n - k + 1) - p) * l / (CKAPPA + (CEPS * (1 - ALPHA)))); }

```

This code is used in chunk 17.

4.2 partitions summing to a given number

generate the partitions of a given size summing to a given number $myInt$

```
8 <GenPartitions 8> ≡
static double GenPartitions (const unsigned int m, const unsigned int myInt, const
    unsigned int PartitionSize, unsigned int MinVal, unsigned int MaxVal,
    std::vector<std::pair<double, std::vector<unsigned int>>> &v_l_k, std::vector<double> &lrates_sorting ) {
    /* m is the given number of blocks; PartitionSize is the size of the partitions; the
     partitions sum to myInt */
double lrate
{
;
double sumrates
{
; std::vector<unsigned int> partition(PartitionSize);
unsigned int idx_Last = PartitionSize - 1;
unsigned int idx_Dec = idx_Last;
unsigned int idx_Spill = 0;
unsigned int idx_SpillPrev;
unsigned int LeftRemain = myInt - MaxVal - (idx_Dec - 1) * MinVal;
partition[idx_Dec] = MaxVal + 1;
do {
    unsigned int val_Dec = partition[idx_Dec] - 1;
    partition[idx_Dec] = val_Dec;
    idx_SpillPrev = idx_Spill;
    idx_Spill = idx_Dec - 1;
    while (LeftRemain > val_Dec) {
        partition[idx_Spill--] = val_Dec;
        LeftRemain -= val_Dec - MinVal;
    }
    partition[idx_Spill] = LeftRemain;
    const char a = (idx_Spill) ? ~((-3 >> (LeftRemain - MinVal)) << 2) : 11;
    const char b = (-3 >> (val_Dec - LeftRemain));
    switch (a & b) {
        case 1: case 2: case 3: idx_Dec = idx_Spill;
            LeftRemain = 1 + (idx_Spill - idx_Dec + 1) * MinVal;
            break;
        case 5:
            for (++idx_Dec, LeftRemain = (idx_Dec - idx_Spill) * val_Dec;
                (idx_Dec ≤ idx_Last) & (partition[idx_Dec] ≤ MinVal); idx_Dec++)
                LeftRemain += partition[idx_Dec];
            LeftRemain += 1 + (idx_Spill - idx_Dec + 1) * MinVal;
            break;
        case 6: case 7: case 11: idx_Dec = idx_Spill + 1;
            LeftRemain += 1 + (idx_Spill - idx_Dec + 1) * MinVal;
            break;
        case 9:
            for (++idx_Dec, LeftRemain = idx_Dec * val_Dec;
                (idx_Dec ≤ idx_Last) & (partition[idx_Dec] ≤ (val_Dec + 1));
                idx_Dec++) LeftRemain += partition[idx_Dec];
            LeftRemain += 1 - (idx_Dec - 1) * MinVal;
    }
}
}
```

```

break;
case 10:
    for (LeftRemain += idx_Spill * MinVal + (idx_Dec - idx_Spill) * val_Dec + 1, ++idx_Dec;
          (idx_Dec ≤ idx_Last) ∧ (partition[idx_Dec] ≤ (val_Dec - 1)); idx_Dec++)
        LeftRemain += partition[idx_Dec];
        LeftRemain -= (idx_Dec - 1) * MinVal;
        break;
    }
    while (idx_Spill > idx_SpillPrev) partition[--idx_Spill] = MinVal;
    assert(static_cast<unsigned int>(std::accumulate(partition.begin(), partition.end(),
        0)) ≡ myInt); /* § 4.1 */
    lrate = lambda(static_cast<double>(m), partition);
    assert(lrate ≥ 0);
    v_l_k.push_back(std::make_pair(lrate, partition));
    lrates_sorting.push_back(lrate);
    sumrates += lrate;
} while (idx_Dec ≤ idx_Last);
assert(sumrates ≥ 0);
return sumrates; }

```

This code is used in chunk 17.

4.3 all partitions summing to a given number

get all partitions (merger sizes) summing to a given number

```
9  ⟨allmergers_sum_m 9⟩ ≡
  static double allmergers_sum_m (const unsigned int n,const unsigned
    int m, std::vector < std::pair < double , std::vector < unsigned
    int >>> &v_l_k, std::vector < double >&v_lrates_sort ) { /*
      n is the number of blocks; the partitions sum to m */
  const std::vector < unsigned int > v_m
  {m}; /* § 4.1 */
  double sumr = lambdanks(static_cast<double>(n),v_m);
  v_l_k.push_back(std::make_pair(sumr,v_m));
  v_lrates_sort.push_back(sumr);
  if (m > 3) {
    for (unsigned int s = 2; s ≤ m/2; ++s) {
      assert(m > 2 * (s - 1)); /* § 4.2 */
      sumr += GenPartitions(n,m,s,2,m - (2 * (s - 1)),v_l_k,v_lrates_sort);
    }
    assert(sumr ≥ 0);
  }
  return sumr; }
```

This code is used in chunk 17.

¶ write mergers to file.

10 ⟨ratesmergersfile 10⟩ ≡

```
static void ratesmergersfile (const unsigned int n, const std::vector < unsigned
  int > &v_idx, const std::vector < std::pair < double , std::vector <
  unsigned int >>> &vk, const double s, std::vector < std::vector <
  double >> &a_cmf ) {
  assert(s > 0);
  double cmf
  {}
  ;
  std::ofstream f;
  f.open("gg_" + std::to_string(n) + ".txt", std::ios::app);
  a_cmf[n].clear();
  for (const auto &i:v_idx) {
    cmf += (vk[i].first)/s;
    assert(cmf ≥ 0);
    a_cmf[n].push_back(cmf);
    assert((vk[i].second).size() > 0);
    for (const auto &x:vk[i].second)
    {
      f << x << ' ';
    }
    f << '\n'; }
  f.close(); }
```

```
assert(abs(cmf - 1.) < 0.999999); }
```

This code is used in chunk 17.

4.4 get all partitions

```

11 <allmergers_when_n_blocks 11> ≡
    static void allmergers_when_n_blocks (const unsigned int n, std::vector <
        double > &v_lambda, std::vector < std::vector < std::vector < double >> &a_cmf ) {
        std::vector < std::pair < double , std::vector < unsigned int >>> vlk
    {}
    ; std::vector < double > ratetosort
    {}
    ;
    ratetosort.clear();
    double lambda
    {}
    ;
    vlk.clear();
    assert(n > 1);
    for (unsigned int k = 2; k ≤ n; ++k) { /* the partition sums to k; the number of blocks is n */
        lambda += allmergers_sum_m(n, k, vlk, ratetosort);
    } /* record the total rate when n blocks */ /* use for sampling time */
    assert(lambda > 0);
    v_lambda[n] = lambda;
    std::vector < unsigned int > indx(ratetosort.size());
    std::iota(indx.begin(), indx.end(), 0);
    std::stable_sort (indx.begin(), indx.end(), [&ratetosort](const unsigned int x, const
        unsigned int y)
    {
        return ratetosort[x] > ratetosort[y];
    }
    ); /* merger rates sorted in descending order; print the cmf and rates to file */
    ratesmergersfile(n, indx, vlk, v_lambda[n], a_cmf); }
```

This code is used in chunk 17.

¶ get all partitions.

generate all mergers up to sample size

```

12 <all possible partitions 12> ≡
    static void allmergers ( std::vector < double > &vlmn, std::vector < std::vector <
        double >> &acmf )
    {
        for (unsigned int tmpn = 2; tmpn ≤ SAMPLE_SIZE; ++tmpn) { /* § 4.4 */
            allmergers_when_n_blocks(tmpn, vlmn, acmf);
        }
    }
```

This code is used in chunk 17.

4.5 tree modules

```
13 ⟨ updatetree 13 ⟩ ≡
    static void updatetree ( std::vector < unsigned int > &tre, const std::vector < unsigned
    int > &mergersizes ) {
        assert(mergersizes.size( ) > 0); std::vector < unsigned int > newblocks
        { }
        ;
        newblocks.clear();
        std::shuffle(tre.begin( ), tre.end( ), rng);
        std::size_t s = tre.size( ); for (const auto &k:mergersizes)
        {
            assert(k > 1);
            assert(k ≤ s);
            s -= k; /* record the size of the merging blocks */
            newblocks.push_back(std::accumulate(tre.rbegin( ), tre.rbegin( ) + k, 0)); /* remove the blocks that merged */
            tre.resize(s);
        }
        assert(newblocks.size( ) > 0);
        assert(static_cast<unsigned int>(std::accumulate(newblocks.begin( ), newblocks.end( ),
            0)) ≤ SAMPLE_SIZE);
        tre.insert(tre.end( ), newblocks.begin( ), newblocks.end());
        assert(static_cast<unsigned int>(std::accumulate(tre.begin( ), tre.end( ),
            0)) ≡ SAMPLE_SIZE); }
```

This code is used in chunk 17.

¶ read partitions.

```
14 ⟨ readmergersizes 14 ⟩ ≡
    static void readmergersizes (const unsigned int n, const unsigned int j, std::vector <
    unsigned int > &v__mergers ) {
        std::ifstream f("gg_" + std::to_string(n) + ".txt");
        std::string line { };
        ;
        v__mergers.clear();
        for (unsigned int i = 0; std::getline (f, line ) ∧ i < j; ++i ) { if (i ≥ j - 1) {
            std::stringstream ss ( line );
            v__mergers = std::vector < unsigned int > ( std::istream_iterator < unsigned int > (ss),
            { } ); }
        assert(v__mergers.size( ) > 0);
        assert(v__mergers[0] > 1);
        assert(v__mergers.back() > 1);
        f.close(); }
```

This code is used in chunk 17.

4.6 one experiment

```

15 <onexperiment 15> ≡
    static void onexperiment ( std::vector < double > &v__ri, std::vector < double > &vl,
        const std::vector < double > &v__lambda__n, const std::vector <
        std::vector < double >> &a__cmf ) {
        std::vector < unsigned int > v__tre(SAMPLE_SIZE, 1);
        std::fill(vl.begin(), vl.end(), 0);
        unsigned int lina
        {
        };
        double tau
        {
        };
        double new_time
        {
        };
        ; std::vector < unsigned int > v__merger_sizes(SAMPLE_SIZE/2);
        v__merger_sizes.reserve(SAMPLE_SIZE/2); auto newtime = [] (const double
            lambdam, const double tau)
        {
            return (RHO > DBL_EPSILON ? log1p(-(RHO * exp(-RHO * tau)/lambdam) * log(1. -
                gsl_rng_uniform_pos(rngtype)))/RHO : gsl_ran_exponential(rngtype,
                1./lambdam));
        }
        ; auto updatelengths = [&v__tre, &vl](const double t) {
            for (const auto &b:v__tre)
            {
                assert(b > 0);
                assert(b < SAMPLE_SIZE);
                vl[0] += t;
                vl[b] += t;
            }
            ;
            auto samplemerger = [] (const unsigned int n, const std::vector <
                double > &v__cmf )
            {
                unsigned int j
                {
                };
                ;
                const double u = gsl_rng_uniform(rngtype);
                while (u > v__cmf[j]) {
                    ++j;
                }
                return j;
            }
            ;
            while (v__tre.size() > 1) {
                new_time = newtime(v__lambda__n[v__tre.size()], tau);
                tau += new_time;
            }
        }
    }
}

```

```

updateLengths(new_time);
lina = sampleMerger(v_tre.size(), a_cmfs[v_tre.size()]);
readMergersizes(v_tre.size(), 1 + lina, v_merger_sizes); /* § 4.5 */
updateTree(v_tre, v_merger_sizes);
}
assert(v_tre.back() == SAMPLE_SIZE);
assert(vl[0] > DBL_EPSILON);
const double d = vl[0]; std::transform (vl.cbegin(), vl.cend(), v_ri.begin(),
v_ri.begin(), [&d](const auto &x, const auto &y)
{
    return y + (x/d);
}
) ; }

```

This code is used in chunk 17.

¶ go ahead – approximate $\mathbb{E}[R_i(n)]$.
approximate $\mathbb{E}[R_i(n)]$

16 ⟨approximate 16⟩ ≡

```

static void approximate() {
    std::vector < double > vri(SAMPLE_SIZE);
    vri.reserve(SAMPLE_SIZE); std::vector < double > v_l(SAMPLE_SIZE);
    v_l.reserve(SAMPLE_SIZE); std::vector < double > v_l_n(SAMPLE_SIZE + 1);
    v_l_n.reserve(SAMPLE_SIZE + 1); std::vector < std::vector < double >> a_cmfs
        (SAMPLE_SIZE + 1, std::vector < double > { } );
    allmergers(v_l_n, a_cmfs);
    int r = EXPERIMENTS + 1;
    while (--r > 0) { /* § 4.6 */
        oneExperiment(vri, v_l, v_l_n, a_cmfs);
    }
    double x
    {}
    ;
    for (unsigned int i = 1; i < SAMPLE_SIZE; ++i) {
        x = vri[i]/static_cast<double>(EXPERIMENTS);
        std::cout << log(x) - log1p(-x) << '\n';
    }
}

```

This code is used in chunk 17.

¶ main.
the *main* module

17 ⟨includes 5⟩

```

⟨rngs 6⟩      /*
§ 4.1 */
⟨λn;k1,...,kr;s 7⟩      /*
§ 4.2 */
⟨GenPartitions 8⟩      /*
§ 4.3 */
⟨allmergers_sum_m 9⟩
⟨ratesmergersfile 10⟩      /*
§ 4.4 */
⟨allmergers_when_n_blocks 11⟩
⟨all possible partitions 12⟩      /*
§ 4.5 */
⟨updatetree 13⟩
⟨readmergersizes 14⟩      /*
§ 4.6 */
⟨onexperiment 15⟩
⟨approximate 16⟩
int main(int argc, const char *argv[])
{
    setup_rng(static_cast<unsigned long>(atoi(argv[1])));
    /* § 4.6 */
    approximate();
    gsl_rng_free(rngtype);
    return GSL_SUCCESS;
}

```

5 conclusions and bibliography

We approximate $\mathbb{E}[R_i(n)]$ when the coalescent is the time-changed δ_0 -Poisson-Dirichlet($\alpha, 0$)-coalescent. An example in Figure 1

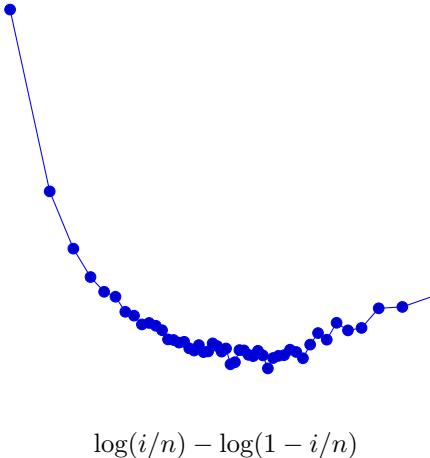


Figure 1: An example approximation of $\mathbb{E}[R_i(n)]$ for the given parameter values and graphed as logits against $\log(i/n) - \log(1 - i/n)$ for $i = 1, 2, \dots, n - 1$ where n is sample size

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