

# Implied Future Pricing Engine

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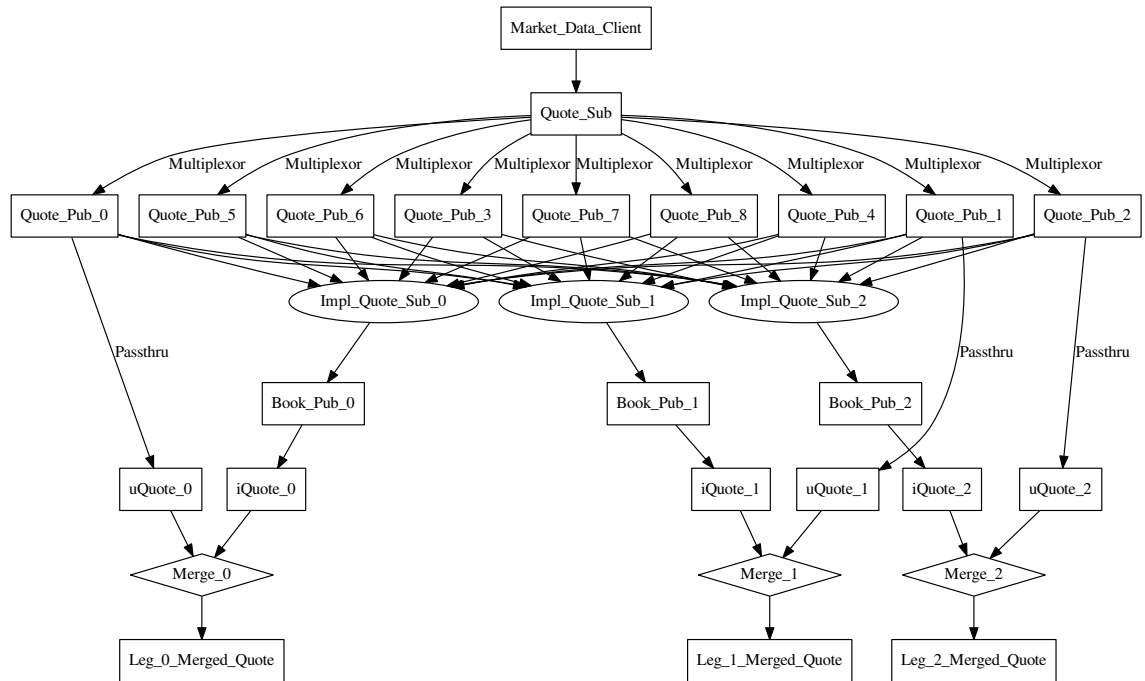
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## Abstract

We present the results of an application of the Implied Engine logic to a hypothetical market closely resembling CME WTI Crude (CL) futures, ICE/IPE Brent futures (B), or any one of the crude product markets. The algorithm as implemented here produces implied quote prices and sizes using only user-entered quote information in leg, calendar spread, and strategy (strips, packs, etc.) markets. The algorithm is modular, and each leg quote (size, price) can be computed on its own execution thread. We exploit this to test a distributed version of the code, using a typical consumer-producer queue with worker tasks consuming a user quote and generating multiple downstream implied quotes per input.

## Workflow

A high-level workflow is presented. The application subscribes to the user-only ('non-implied') quote feed for the respective exchange, and computes both top-of-book user-only and implied quotes for each leg. We present here a simple case in which 3 legs products are considered, and user quotes from the legs and 6 calendar spread products are consumed.



Notes

1. The initial multiplexor separates the flow of 3 leg and 6 spread products and forwards them to one of 9 quote publishers.
2. The main algorithm and most of the work is performed in the oval nodes. Here multiple leg, calendar spread quotes are consumed and an implied quote (price,size) is computed for the specified leg. There are 3 Impl\_Quote\_Sub nodes in this case. Care must be taken to ensure that these passes are threadsafe.
3. Separate user and implied quote objects (uQuote, iQuote) are maintained, and best-of or merged quotes are computed in a threadsafe fashion.

## Implementation

The main entry point is the ImpliedServer class template, consisting of 3 components: a Client object for reading of quote information via socket, an ImpliedEngine<sub>N<sub>i</sub></sub> object which is the computation engine, and a threadpool object for asynchronous calculations off of the main calc thread. Appropriate serialization and barriers are implemented within the ImpliedEngine<sub>N<sub>i</sub></sub> class to ensure thread safety. The interface can be found on <https://github.com/pehlivanian/ImpliedPriceEngine/>

```
template<int N>
class ImpliedServer
{
public:
    ImpliedServer(bool process_feed=true) :
        p_(std::make_unique<impl<ImpliedServer<N>>>()) { init_(); }
    void process() { preload_tasks_(); profiled_process_tasks_(); };

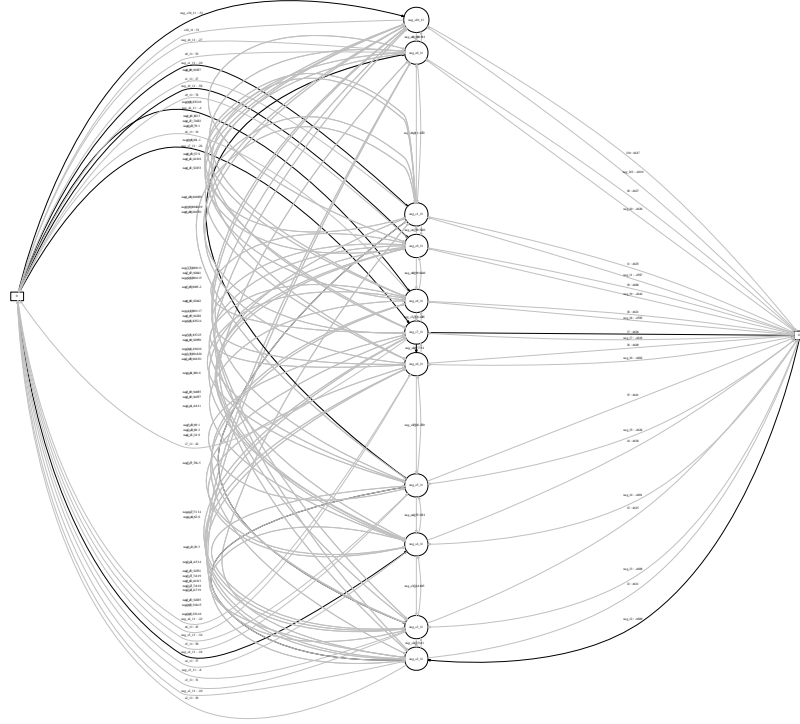
    //...
private:
    void preload_tasks_();
    void process_tasks_();

    void init_();
    std::unique_ptr<impl<ImpliedServer>> p_;
};

template<int N>
struct impl<ImpliedServer<N>>
{
    impl() :
        IE_(std::make_unique<ImpliedEngine<N>>()),
        C_(std::make_unique<Client>(8008, (char*)"0.0.0.0")),
        pool_(std::make_unique<threadpool>())
    {}

    std::unique_ptr<ImpliedEngine<N>> IE_;
    std::unique_ptr<Client> C_;
    std::unique_ptr<threadpool> pool_;
};
```

Within the `ImpliedEngineN` class, the main calculation algorithm makes use of some notions from linear algebra and graph theory. A typical graph for a 12-leg problem is shown, without explanation.



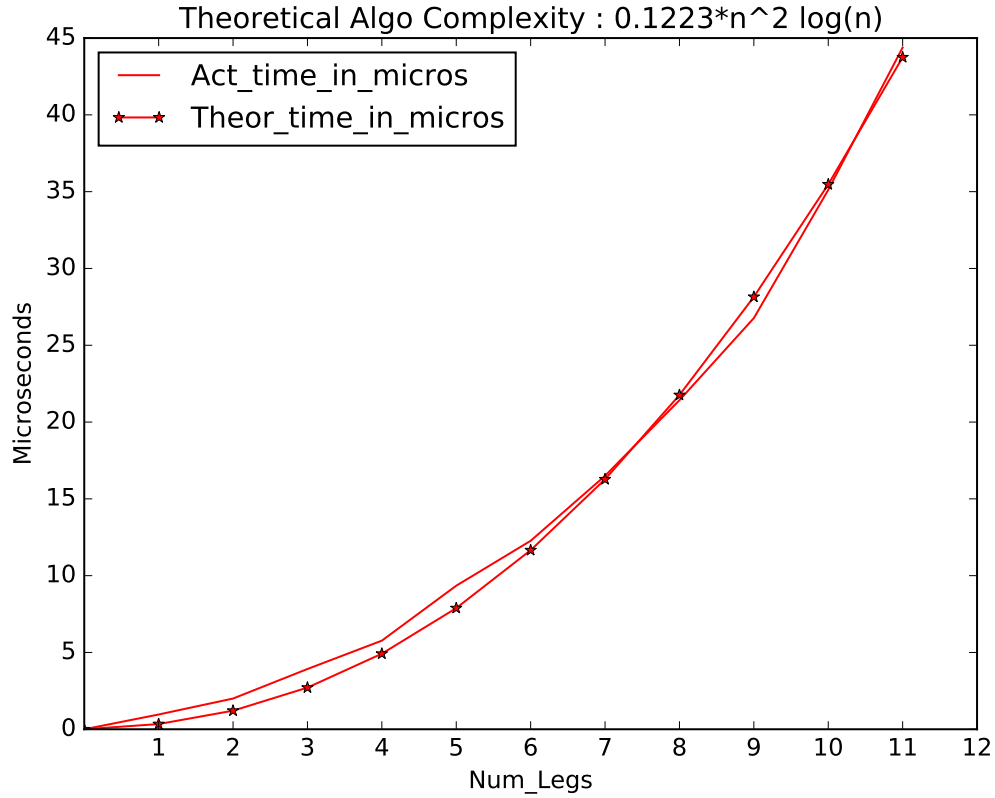
## Benchmarks

The theoretical complexity of the algorithm is  $O(n^2 \log(n))$ , where  $n$  is the number of legs to calculate. I don't believe we can do any better than this, for theoretical reasons, unless we constrain the problem based on ad-hoc market structure considerations (no liquidity in certain markets, so we eliminate them from the calculation, etc.). In any case, the algorithm is highly configurable and will allow for most such constraints.

We first empirically verify the algorithmic complexity by plotting empirical (single-core, single-threaded) CPU times with a theoretical fit. The times given are for a single update step consisting of

1. publishing parsed quote update to `ImpliedEngineN` class;
2. updating user quote object for this market;
3. calculating *all* implied leg quotes affected by this update (usually  $N$  legs);
4. merging user, implied quotes into single quote object.

The qualitative fit is good, with constant  $C = .1223$ . The fit was performed using the scipy orthogonal directions regression library.



We also can calculate the update time (time start: immediately after incoming quote is parsed, time end: full update of quote objects and task returns success). The following tables show times for a single update step (defined above) on a 4-core CentOS linux commodity machine. Times are in microseconds. Note that this time includes an update of the user quote object with the incoming quote, a step that would have to be performed in any case whether we were computing implied prices or not.

N	Average	Min	Max	Stddev	Num
0	14.563158	11	31	3.567040	9500
1	14.295474	11	30	3.323515	9500
2	14.150211	11	29	3.369054	9500
3	14.012737	11	28	2.926719	9500
4	14.050211	11	29	3.124248	9500
5	13.997158	11	28	3.082419	9500
6	13.974526	11	27	2.821791	9500
7	14.220842	11	29	3.148978	9500
8	13.908105	11	27	2.767451	9500
9	13.945158	11	27	2.911735	9500

Table 1: 12-Leg Problem, 10 Iterations

N	Average	Min	Max	Stddev	Num
0	11.265895	8	26	3.154317	9500
1	10.876737	8	24	2.717391	9500
2	10.807263	8	23	2.611048	9500
3	10.714737	8	23	2.612919	9500
4	10.792737	8	23	2.466470	9500
5	10.839158	8	23	2.601639	9500
6	10.902632	8	24	2.816397	9500
7	10.886947	8	25	2.793006	9500
8	10.790632	8	23	2.615368	9500
9	10.914737	8	24	2.721616	9500

Table 2: 11-Leg Problem, 10 Iterations

N	Average	Min	Max	Stddev	Num
0	10.218000	8	25	2.835815	9500
1	9.975474	8	23	2.480480	9500
2	9.948947	8	24	2.475615	9500
3	9.834000	8	22	2.142498	9500
4	10.079263	8	24	2.683880	9500
5	9.976737	8	24	2.604584	9500
6	10.039368	8	22	2.475212	9500
7	9.976737	8	22	2.221967	9500
8	9.970211	8	23	2.303404	9500
9	9.810105	8	22	2.097212	9500

Table 3: 10-Leg Problem, 10 Iterations

N	Average	Min	Max	Stddev	Num
0	8.095368	6	20	1.988481	9500
1	8.238316	6	18	2.100899	9500
2	8.033263	6	20	1.907523	9500
3	8.079474	6	21	2.086936	9500
4	7.972211	6	17	1.614646	9500
5	7.932211	6	18	1.664525	9500
6	8.004211	6	20	1.844572	9500
7	8.142632	6	21	2.089525	9500
8	8.077263	6	21	2.061618	9500
9	8.084421	6	20	2.041992	9500

Table 4: 9-Leg Problem, 10 Iterations

N	Average	Min	Max	Stddev	Num
0	6.198421	5	15	1.519532	9500
1	6.165895	5	15	1.528084	9500
2	6.145053	5	17	1.666477	9500
3	6.159158	5	15	1.467598	9500
4	6.061684	5	15	1.484377	9500
5	6.272000	5	17	1.800889	9500
6	6.078842	5	16	1.576353	9500
7	6.072632	5	16	1.454141	9500
8	6.256316	5	15	1.591008	9500
9	6.163158	5	15	1.569364	9500

Table 5: 8-Leg Problem, 10 Iterations

N	Average	Min	Max	Stddev	Num
0	4.422737	3	12	1.067384	9500
1	4.415579	3	12	1.096525	9500
2	4.411895	3	10	0.936406	9500
3	4.397053	3	12	1.036156	9500
4	4.316632	3	12	0.947155	9500
5	4.356000	3	12	1.034819	9500
6	4.353895	3	12	0.960325	9500
7	4.664421	3	13	1.448348	9500
8	4.301895	3	12	0.919325	9500
9	4.434211	3	12	1.131518	9500

Table 6: 7-Leg Problem, 10 Iterations

N	Average	Min	Max	Stddev	Num
0	3.025474	2	7	0.816572	9500
1	3.023053	2	7	0.795552	9500
2	2.967789	2	7	0.788788	9500
3	3.022316	2	7	0.803408	9500
4	3.050737	2	7	0.852258	9500
5	2.963895	2	7	0.751642	9500
6	2.983474	2	7	0.791071	9500
7	3.108421	2	8	0.966451	9500
8	3.275158	2	8	1.100045	9500
9	2.990526	2	7	0.799854	9500

Table 7: 6-Leg Problem, 10 Iterations

# 1 Curve Evolution

This is a typical snapshot of the user vs. implied price (no size) for a simulated data set. The simulator produces prices in legs and calendar spread contracts, maintaining no-arbitrage conditions across the curve, and producing realistic bid-ask spreads and shape throughout the curve. This snapshot represents the market at sequence number 1350.

The implied quote curve gives a more comprehensive, arguably better notion of fair value across the curve.

A full evolution for a randomly selected interval of sequence numbers is given in the file *quote\_evolution.pdf*.

