On Limits

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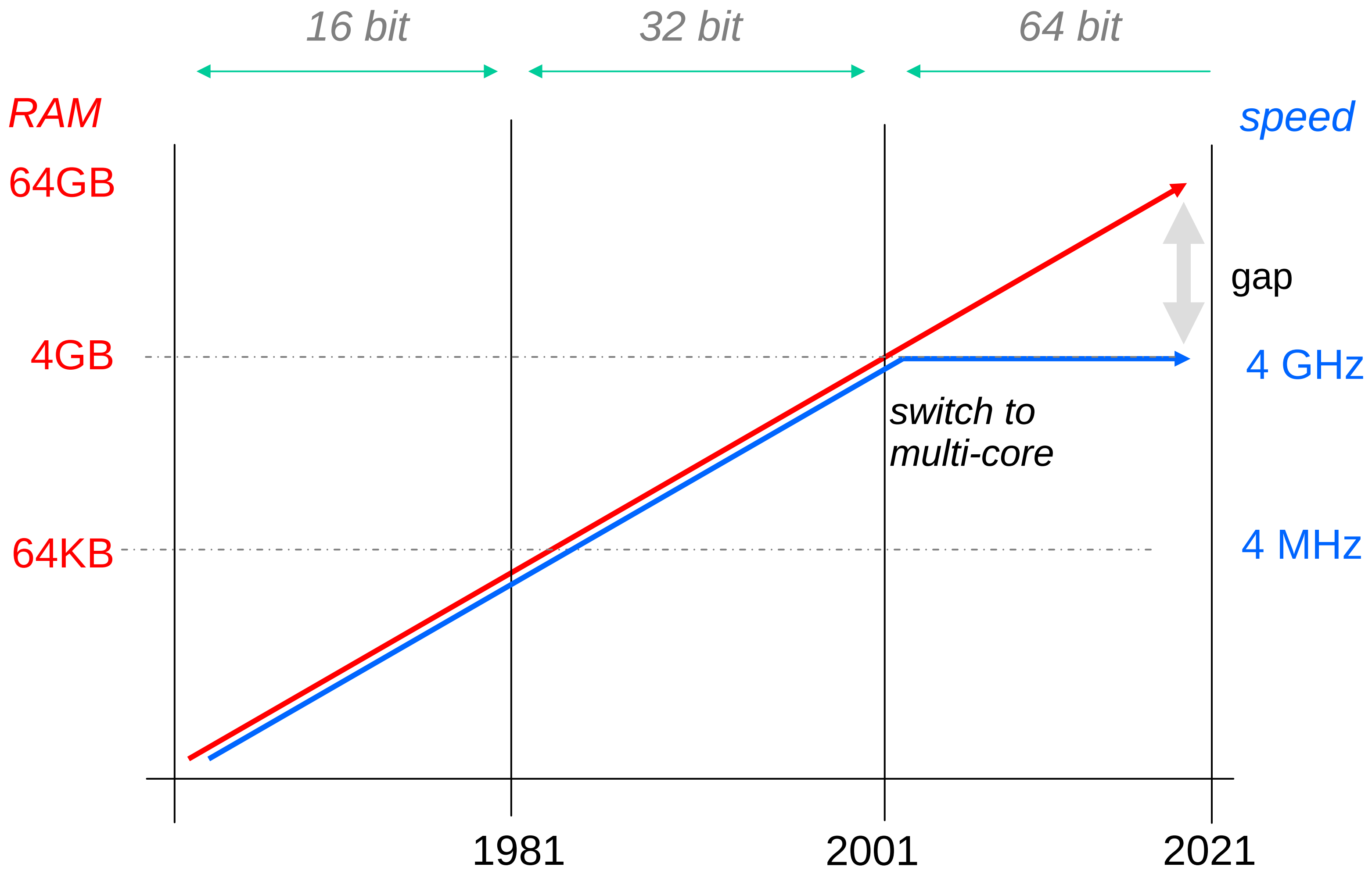
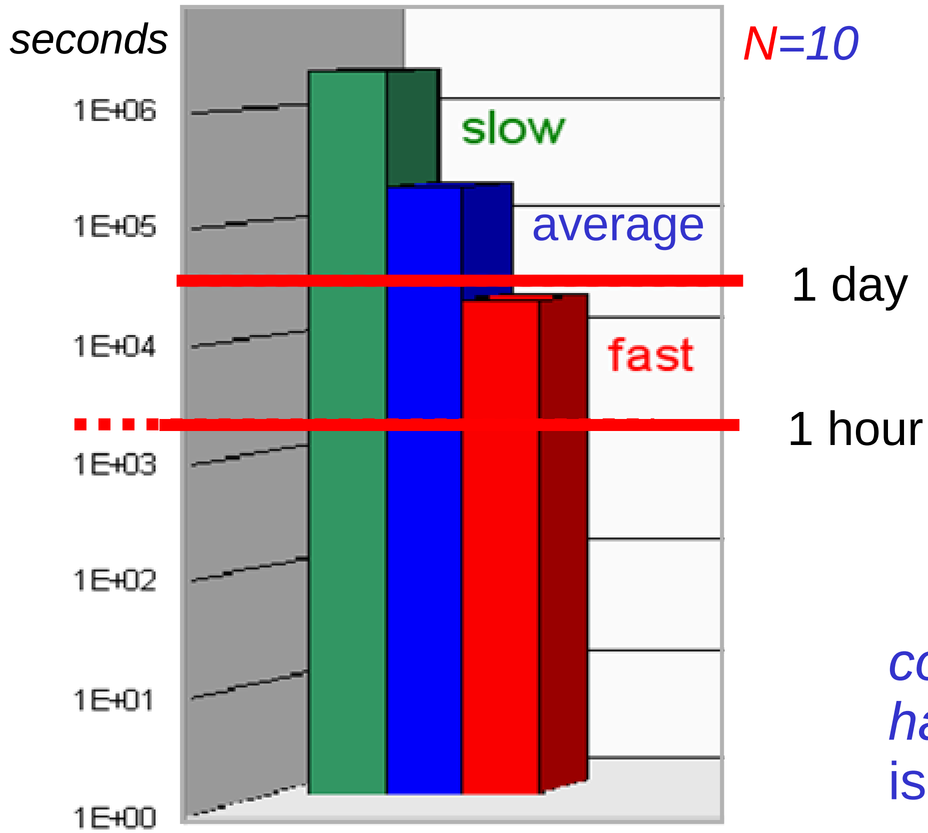
speed and memory trends

(we will soon have very large amounts of memory and relatively slow processors)



the time needed to fill *N* GB of RAM



conclusion:
having more memory
is not always useful

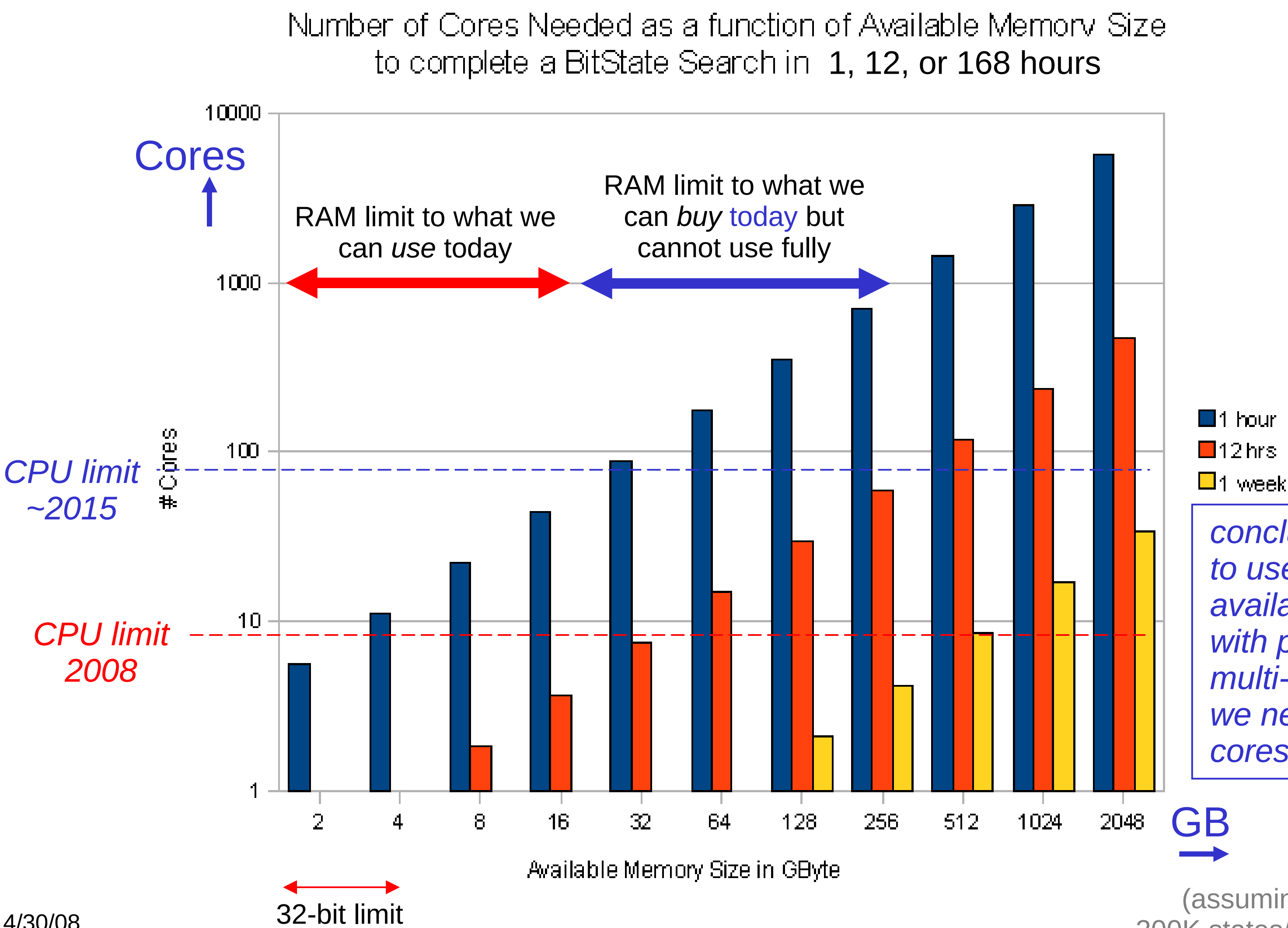
[Spin in bitstate mode]
storing a relatively large number of system states
into memory at a rate of 10^4 to 10^6 states/second

what are the limits?

- at a fixed clock-speed, there is a limit to the largest problem size we can handle in 1 hour (day / week)
  - no matter how much memory we have (RAM or disk)
  - even a machine with “infinite memory” but “finite speed” will impose such limits

- we can increase speed by using multi-core algorithms
  - but do 10^n CPUs always get a 10^n x speedup?
  - it will depend on the CPU architecture (NUMA/UMA)
  - do we know what the CPU architecture will be for large multi-core machines (think 1,000 CPUs and up)?
- isn’t there an easier way?
  - can’t we find a way to use N x as many CPUs, and get a result that is always “N x better” (by some definition of “better”)

at fixed speed how many CPUs does it take to fill up *N* GB of RAM in 1 hour?

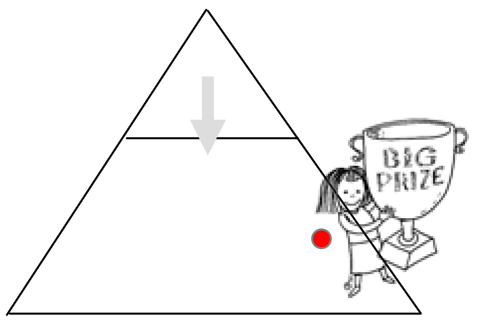


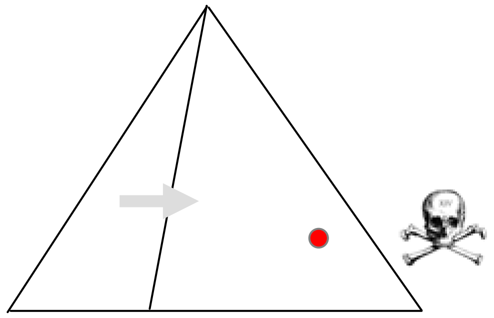
conclusion:
to use all GB of RAM available in year Y, with perfect multi-core scaling we need the nr of CPU cores from year Y+7

(assuming: ~200K states/second bitstate search)

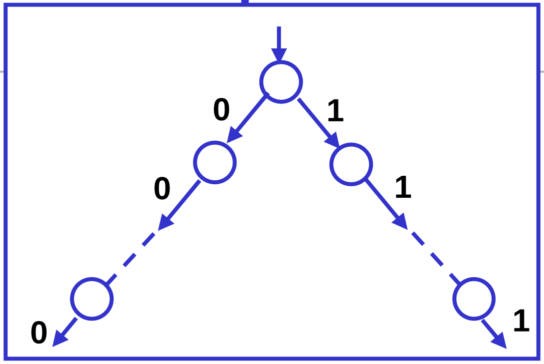
the infinitely large problem and the infinitely large machine

- there will always be problems that require more *time* to verify than we are willing (or able) to wait for
  - how do we best use finite time to handle large problems?
- example of an “infinitely large problem:” a Spin Fleet Architecture model from Ivan Sutherland & students (courtesy Sanjit Seshia)
  - known error state is just beyond reach of a breadth-first search (and symbolic methods) – error is too deep
  - error is on “wrong” side of the DFS tree
  - a bitstate search either fills up memory or exhausts the available time before the error state is reached
  - how do we maximize our chances of finding errors like this?





measurement:
define a simple, large search problem




```
byte pos = 0;
int val = 0;
int flag = 1;

active proctype word()
{    /* generate all 32-bit values */
end: do
     :: d_step { pos < 32 -> /* leave bit 0 */ flag = flag << 1; pos++ }
     :: d_step { pos < 32 -> val = val | flag; flag = flag << 1; pos++ }
     od
}

never {/* check if some user-defined value N can be matched */
    do
    :: assert(val != N)
    od
}
```

2^{32} reachable states, 24 byte per state

100 GB to store the full state space

what if we only have 64 MB to do the search?

0.06 % of what is needed

a sample search query

- 2^{32} reachable states, 24 bytes per state
  - 100 GB to store the full state space
  - 64 MB available (0.06 % of 100 GB)

- question:
  - seed *100* randomly chosen numbers
  - how many of these numbers can be found (matched)?
    - using different search techniques

- one obvious candidate: bitstate hashing with depth-first search
  - assume 0.5 byte per state on average: $2^{32} \times 0.5 \sim 2$ GB
  - 64MB (2^{26}) is now 3% (1/32) of what is needed to represent all states
  - should find matches for ~ 3 of the 100 numbers

bitstate dfs –w29

2^{29} bits = 2^{26} bytes = 64 MB

```
$ spin -DN=-1 -a word.pml
$ cc -O2 -DSAFETY -DBITSTATE -o pan pan.c
$ ./pan -w29
...
1.4849945e+08 states, stored  (3.46% of all 2^32 states)
...
hash factor: 3.61531 (best if > 100.)
bits set per state: 3 (-k3)
...
pan: elapsed time 127 seconds
$
```

this search does not find a match for the target number -1
if we repeat this 100x for each of the randomly chosen numbers
we should expect 3 or 4 matches

checking 100 numbers

```
$ > out
$ for r in `cat ../numbers`
$ do
   spin -DN=$r -a word.pml
   cc -O2 -DSAFETY -DBITSTATE pan.c
   ./pan –w29 >> out
done
$ grep “assertion violated” out | sort –u | wc -l
8
```

we were “entitled” to 3 or 4 matches, and we got 8 (i.e., we were lucky)

numbers matched:
234, -3136, 3435, 19440, 6985, 12435, 4915, 27246
(note: 52 of our targets are negative numbers, we matched only 1 in this subset)

using iterative search refinement [HS99]

(using 128KB, 256KB, … 64 MB)

```
$ > out
$ for w in 20 21 22 23 24 25 26 27 28 29
do
   for r in `cat ../numbers`
   do
        spin -DN=$r -a word.pml
        cc -O2 -DSAFETY -DBITSTATE pan.c
    ./pan –w$w >> out
   done
done
$ grep “assertion violated” out | sort –u | wc -l
15
```

-w	dfs
20	1
21	1
22	2
23	2
24	2
25	3
26	6
27	8
28	11
29	15

we increased the number of matches from 8 to 15
can we do still better?

adding search diversification

- dfs: standard depth-first search (the default)
- dfs_r: reverse order in which non-deterministic choices within a process are explored
  - using compiler directive –D_TREVERSE (Spin 5.1.5).
- r_dfs: use search randomization on the order in which non-deterministic choices within a process are explored
  - using compiler directive –DRANDOMIZE (Spin 4.2.2)

    randomly selects a starting point in the transition list, and checks transitions for executability in round-robin order from that point

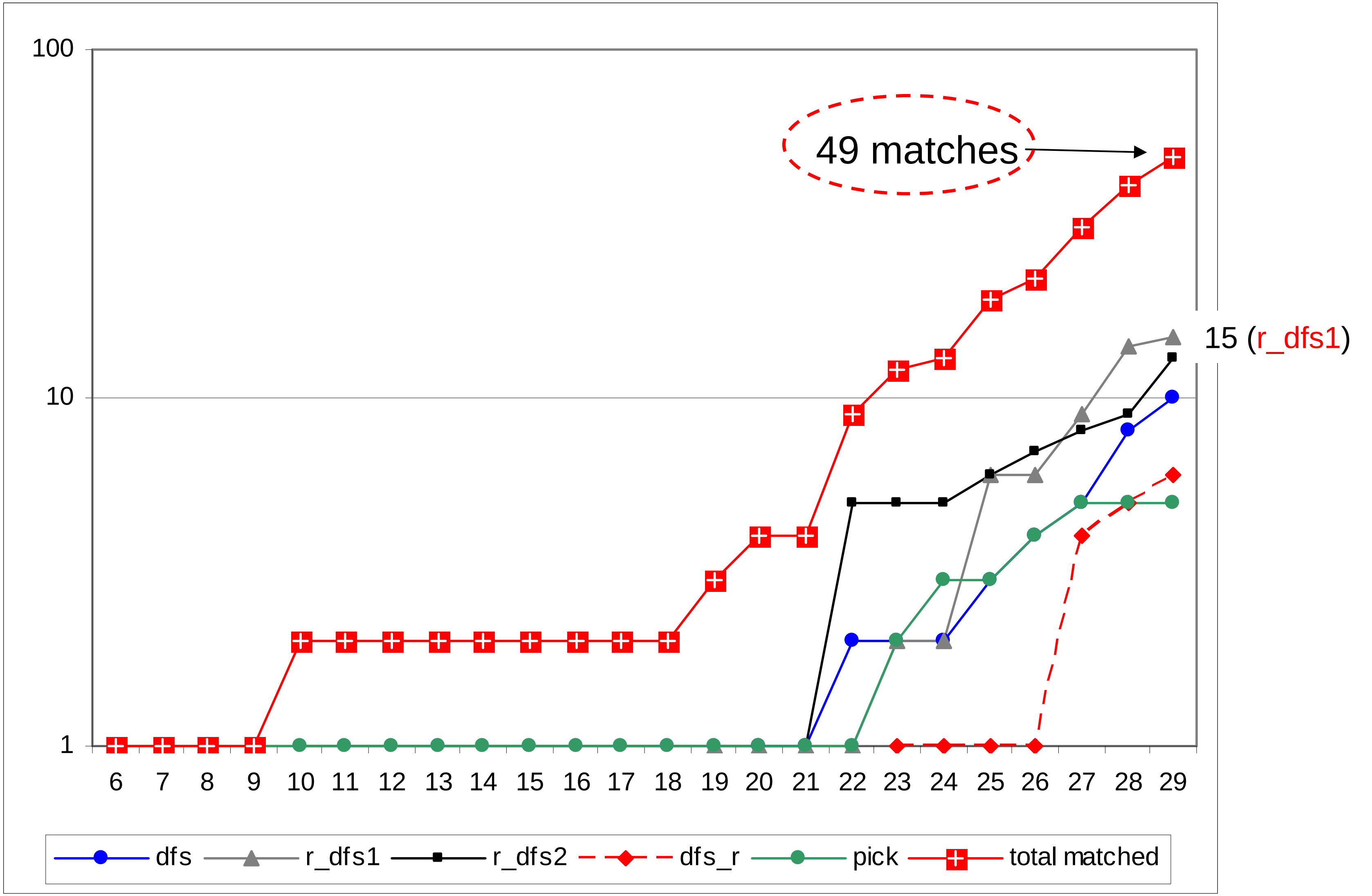
    use different seeds to create multiple variants (r_dfs1, r_dfs2)
- pick: use embedded C code to define a user-controlled selection method to permute the transitions in a list of non-deterministic choices within a process

pick: user-defined randomization

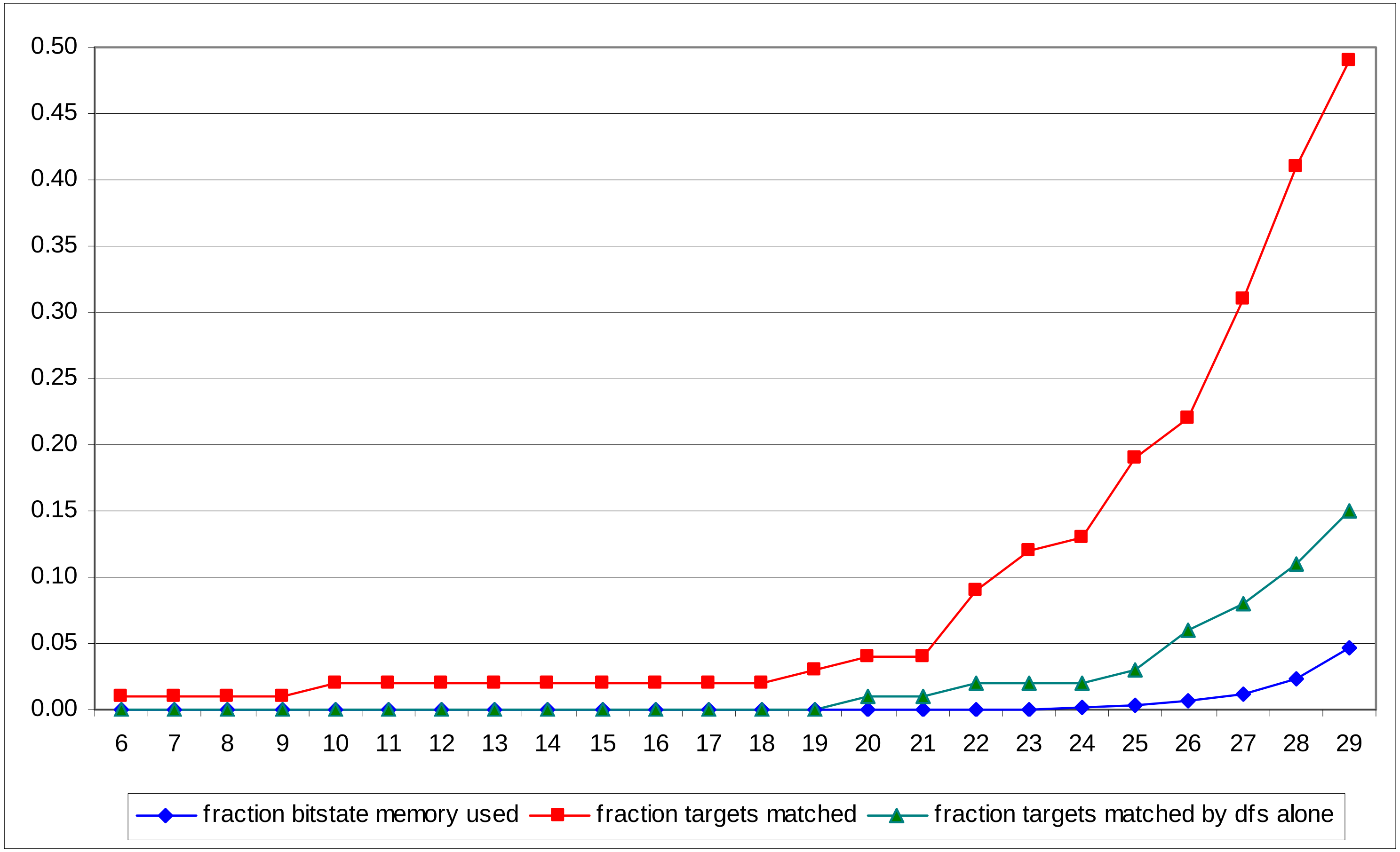
(courtesy of rajeev joshi & alex groce)

```
c_decl {
        \#define MAX_CHOICES  32   /* max nr of choices in calls to "pick" */

        int choices[MAX_CHOICES];
        int last_seed = 3;
};

c_track "choices"     "sizeof(int) * MAX_CHOICES"   "UnMatched";
c_track "&last_seed"  "sizeof(int)"                 "UnMatched";

inline pick(v, min, max) {
        tmp = max-min+1 ;
        c_code {
                int i, j, t;     /* temporary C vars */

                srandom(last_seed) ;
                for (i = 0; i < now.tmp; i++)
                {       choices[i] = i;
                }
                for (i = 0; i < now.tmp-1; i++)
                {       j = (random() % (now.tmp - i));
                        t = choices[i];
                        choices[i] = choices[i+j];
                        choices[i+j] = t;
                }
                now.tmp = 0;
        };
        /* randomize search order each time a node is revisited */
        do      /* cover all choices */
        :: d_step { tmp < max-min -> tmp++ }
        :: d_step {
                v = min + c_expr { choices[now.tmp] };
                c_code { last_seed += now.tmp; now.tmp = 0; }
           }; break
        od
}

int n, x, y, tmp;

active proctype main()
{
        do
        :: n < 3 -> n++;
                pick(x, 1, 3);
                pick(y, 7, 9);
                printf("n=%d, x = %d, y = %d\n", n, x, y)
        :: else ->
                break
        od
}
```

iterative search refinement + search diversification: nr matches increases to 49



fraction of memory used
compared with fraction of targets matched



(the memory reference is minimal amount of memory needed for full bitstate storage)

swarm

$ swarm –F config.lib –c6 > script
swarm: 456 runs, avg time per cpu 3599.2 sec
$ sh ./script

sample configuration file:

```
# ranges
w       20      32      # min and max -w parameter
d       100     10000   # min and max search depth
k       2       5       # min and max nr of hash functions

# limits
cpus            2               # nr available cpus
memory          513MB           # max memory to be used; recognizes MB,GB
time            1h              # max time to be used; h=hr, m=min, s=sec
vector          500     # bytes per state, used for estimates
speed           250000          # states per second processed
file            model.pml       # file with spin model

# compilation options (each line defines a search mode)
-DBITSTATE                      # standard dfs
-DBITSTATE -DREVERSE# reversed process ordering
-DBITSTATE -DT_REVERSE          # reversed transition ordering
-DBITSTATE -DRANDOMIZE=123              # randomized transition ordering
-DBITSTATE -DRANDOMIZE=173573   # ditto, with different seed
-DBITSTATE -DT_REVERSE -DREVERSE        # combination
 -DBITSTATE -DT_REVERSE -DRANDOMIZE # combination

# runtime options
-n
```

swarm verification of some large models

Verification Model	State vector size	System states reached in standard bitstate dfs (-w29)	Time for bitstate dfs (in minutes using 1 cpu)	Number of swarm jobs (1 hour limit 6 cpus)
EO1	2736	320.9M	43	86
Fleet	1440	280.5M	58	228
DEOS	576	22.3M	2	456
Gurdag	964	86.2M	17	231
CP	344	165.7M	18	451
DS1	3426	208.6M	159	100
NVDS	180	151.2M	6	516
NVFS	212	139.5M	45	265

performance

Verification Model	Number of Control States			% of Control States Reached	
	Total	Unreached			
		standard dfs	dfs + swarm	standard dfs	dfs + swarm
EO1	3915	3597	656	8	83
Fleet	171	34	16	80	91
DEOS	2917	1989	84	32	97
Gurdag	1461	853	0	41	100
CP	1848	1332	0	28	100
DS1	133	54	0	59	100
NVDS	296	95	0	68	100
NVFS	3623	1529	0	58	100

synopsis

- there is a growing performance gap
  - memory sizes continue to grow
  - but cpu speed no longer does (for now)
  - the standard approaches to handling large problem sizes have stopped working
  - we have to get smarter about defining incomplete searches in very large state spaces
- the best use of currently available computational resources (and *human time*)
  - may be to switch to the use of embarrassingly parallel methods, in combination with search diversification