

Julia Subtyping: A Rational Reconstruction

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VALIDATION OVER TRACES OF WIDELY USED PACKAGES

Table 1 summarizes the results of the validation of our reference implementation against a set of 100 popular Julia’s packages found on GitHub. The table consists of four columns (with a number of subcolumns) which reflect (1) package name and the abbreviation for the command that has been traced for the package (either U for use or T for test), (2) the numbers of types in the subtype queries parsed from the logs, (3) the results of the validation of our `typeof` implementation, (4) the results of validation of our subtype implementation. The mode in the first column (either U or T) corresponds to the program evaluated under instrumented Julia’s VM: either using `PkgName` or `Pkg.test(PkgName)`.

The second column reports on the number of logged types for each project and mode — in the `#types` subcolumn (since we log invocations to subtype, there are two types logged per invocation). The instrumentation relies on the Julia internal debug pretty-printer to dump types. Unfortunately, this pretty-printer may generate strings that cannot be reliably parsed by the Julia parser itself for a number of reasons¹. The subcolumn *not WF* counts the types in the log traces that are not well-formed: either cannot be parsed, or refer to names not in scope. The usual reason for the latter is the types for lambda functions which are VM-generated and can be different in every session. The subcolumn *unsupp* counts the types containing the `[[Vararg]]` construct, which we did not formalize and which is not supported by our implementation. We also sometimes cannot resolve names of types for lambda functions (the problem is already mentioned, but can show up on the later stages) and `eval` names — all these go in the same subcolumn.

Columns three and four of table 1 report on the validation of our `typeof` and subtype formalization-based implementations. For `typeof`, for each well-formed logged type, we compare the output of our implementation against the Julia one, reporting an error when they do not match. The ANY subcolumn refers to the ANY pseudo type of Julia. In fact, this is a globally defined type variable which behaves almost identically to Any type, but when used in a method signature, prevents the method from being specialized. This can be useful for various reasons which are not of concern in this paper: we do not test `typeof` on types containing ANY, and we substitute Any for ANY when testing subtype.

For the subtype column, likewise, we compare the outcome of each logged subtype test (ignoring those for which at least one type is not well-formed) with the result returned by our implementation. To speed up validation, some cases are resolved by a trivial subtyping function. The number of those is also reported.

¹E.g. sometimes the pretty-printer outputs nested `UnionAll`-types where the names of bound variables are all equal to `_`, making the type ambiguous. The other issue raises from the fact that the types in Julia can contain values (`Array{Int, 2}` being the simplest example), and the values can have somewhat complicated structure leading Julia’s pretty-printer to confusion. Example being a call to a constructor with so called keyword-arguments. These issues have semantic underpinning, but there are also those with purely syntactic nature, e.g. Unicode characters or characters with a special lexer behavior as `<` or `\`.

Table 1. Validation results

PROJECT	PARSER			TYPEOF			SUBTYPE				
	#types	unsupp	not WF	#tests	passed	fail	ANY	#tests	trivial	passed	fail
AutoGrad/U	12980	1942	0	11038	11037	0	1	4716	1559	3157	0
AutoGrad/T	462818	56438	3845	406415	399301	0	3234	173944	43402	130542	0
AxisArrays/U	5096	451	0	4645	4643	0	2	2148	173	1975	0
AxisArrays/T	376396	37766	7510	331223	329448	0	1688	146082	24498	121583	1
BayesNets/U	32820	1738	2	31082	31079	0	3	14775	1330	13445	0
BayesNets/T	305490	19816	2419	283651	281724	0	1539	131586	22375	109211	0
BenchmarkTools/U	1486	387	0	1099	1097	0	2	385	157	228	0
BenchmarkTools/T	119352	9136	795	110307	108411	0	1010	50241	9117	41124	0
Bio/U	55466	2253	2	53213	53210	0	3	25625	1965	23660	0
Bio/T	129030	9198	592	119551	118779	0	471	55161	9690	45470	1
BlackBoxOptim/U	18898	910	2	17988	17985	0	3	8592	689	7903	0
BlackBoxOptim/T	193686	10814	1260	181619	180448	0	1168	85361	14291	71063	7
Blink/U	19188	2525	159	16504	16488	0	16	7005	2439	4566	0
Blink/T	37920	3548	305	34067	33877	0	190	15263	4037	11226	0
BuildExecutable/U	7286	628	86	6572	6549	0	23	2980	771	2209	0
BuildExecutable/T	30982	2832	155	27995	27736	0	259	12674	3001	9673	0
Calculus/U	1380	380	0	1000	998	0	2	339	135	204	0
Calculus/T	36446	2552	254	33688	33317	0	323	15601	3610	11991	0
Clustering/U	15314	1218	0	14096	14093	0	3	6569	708	5861	0
Clustering/T	147714	8907	1067	137802	136932	0	808	64486	11461	53024	1
Compose/U	22382	1377	104	20901	20899	0	2	9773	1753	8020	0
Compose/T	146936	11859	2419	132745	132030	0	628	59985	10510	49475	0
Cubature/U	1376	380	0	996	994	0	2	337	133	204	0
Cubature/T	21566	1088	247	20270	20060	0	171	9516	2511	7001	4
Cxx/U	47310	3397	7127	37563	36529	0	257	14346	3506	10839	1
Cxx/T	82024	6321	16788	60825	58088	0	827	20843	5484	15359	0
DSGE/U	116336	6315	463	109560	109174	0	386	51750	8689	43061	0
DSGE/T	709594	44703	9779	655399	651107	0	4007	302540	62995	239542	3
DSP/U	2518	424	0	2094	2092	0	2	864	152	712	0
DSP/T	232400	18880	2439	211135	209594	0	1487	96491	20651	75836	4
DataFlow/U	14046	1784	89	12173	12171	0	2	5182	1921	3261	0
DataFlow/T	70164	6860	662	62642	62011	0	631	27800	6982	20818	0
DataFrames/U	28756	1929	101	26726	26722	0	4	12462	3334	9128	0
DataFrames/T	433244	26149	2508	404609	401479	0	3130	189122	34868	154254	0
DataFramesMeta/U	44190	2474	207	41509	41345	0	164	19554	4621	14933	0
DataFramesMeta/T	137140	8391	3205	125544	124606	0	938	57638	11552	46086	0
DataStructures/U	15436	1345	89	14002	14000	0	2	6330	1621	4709	0
DataStructures/T	211232	15020	669	198361	194378	0	1165	90693	12861	77831	1
DecisionTree/U	1454	380	0	1074	1072	0	2	376	153	223	0
DecisionTree/T	70860	4881	359	65676	65028	0	592	30461	6687	23774	0
Devectorize/U	2154	384	0	1770	1768	0	2	722	197	525	0
Devectorize/T	22754	1688	136	20930	20775	0	155	9661	1890	7771	0
DifferentialEquations/U	68518	3868	300	64352	64296	0	56	30409	4435	25974	0
DifferentialEquations/T	209138	18745	9454	188030	180132	0	809	78403	15605	62798	0
Distances/U	1528	380	0	1148	1146	0	2	413	177	236	0
Distances/T	103174	9292	1263	92825	91877	0	742	42005	10633	31372	0
FastGaussQuadrature/U	1838	418	0	1420	1418	0	2	530	134	396	0
FastGaussQuadrature/T	122686	13450	635	108657	107875	0	726	48085	14291	33794	0
Flux/U	35584	2298	284	33002	32960	0	42	15388	1897	13491	0

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PROJECT	PARSER			TYPEOF			SUBTYPE				
	#types	unsupp	not WF	#tests	passed	fail	ANY	#tests	trivial	passed	fail
Flux/T	243028	19135	2041	224240	220053	0	1799	101616	20633	80978	5
ForwardDiff/U	13164	1052	0	12112	12110	0	2	5645	535	5110	0
ForwardDiff/T	260434	12455	4732	244939	243885	0	1054	114493	18823	95670	0
FunctionalCollections/U	12654	696	124	11834	11795	0	39	5564	1009	4555	0
FunctionalCollections/T	98796	6461	2109	90475	89746	0	480	41135	7239	33886	10
GLM/U	34470	1915	103	32454	32450	0	4	15342	3419	11923	0
GLM/T	273988	18166	2950	252881	251199	0	1675	117177	24259	92916	2
GPUArrays/U	6930	1154	0	5776	5774	0	2	2457	566	1891	0
GPUArrays/T	346384	27161	1360	317863	316618	0	1245	146469	42149	104320	0
GR/U	1388	390	0	998	997	0	1	304	94	210	0
GR/T	33472	1487	2279	29782	29514	0	192	13145	2475	10670	0
Gadfly/U	69316	4058	180	65080	65055	0	25	30659	5061	25598	0
Gadfly/T	86524	5122	329	81145	80928	0	147	38114	6716	31398	0
Gallium/U	1170	182	0	988	984	0	4	403	69	334	0
Gallium/T	5706	424	0	5282	5239	0	43	2439	475	1964	0
GitHub/U	13440	1494	156	11790	11784	0	6	5106	2196	2910	0
GitHub/T	127334	7552	833	119080	118223	0	726	55775	11443	44331	1
GraphLayout/U	44296	2963	285	41048	41046	0	2	19065	3555	15510	0
GraphLayout/T	203608	13415	7919	182274	181418	0	856	81727	16519	65207	1
Graphs/U	16116	1414	89	14613	14611	0	2	6601	1638	4963	0
Graphs/T	92314	6070	960	85912	84775	0	509	39392	7024	32368	0
HDF5/U	4092	784	0	3308	3304	0	4	1299	415	884	0
HDF5/T	71756	6369	305	65150	64561	0	521	29529	6619	22909	1
HttpServer/U	2218	650	0	1568	1566	0	2	488	228	260	0
HttpServer/T	59070	5122	420	53979	53111	0	417	24259	5769	18490	0
HypothesisTests/U	32566	1534	2	31032	31029	0	3	14888	1077	13811	0
HypothesisTests/T	179680	12438	1322	165929	165048	0	874	76982	13102	63880	0
IJulia/U	15316	1470	132	13714	13688	0	26	6108	2223	3885	0
IJulia/T	47422	3344	466	43623	43249	0	363	20055	4340	15715	0
Interact/U	18032	1505	89	16438	16434	0	4	7468	2184	5284	0
Interact/T	57202	4510	402	52290	51830	0	460	23921	6302	17619	0
Interpolations/U	3756	511	0	3245	3243	0	2	1414	259	1155	0
Interpolations/T	249098	19102	8472	221529	220147	0	1377	99891	20411	79480	0
IterativeSolvers/U	1064	93	0	971	970	0	1	440	40	400	0
IterativeSolvers/T	281758	21892	5620	254786	252512	0	1734	115544	27096	88445	3
Iterators/U	996	0	0	996	995	0	1	498	18	480	0
Iterators/T	51686	1438	225	50029	49843	0	180	24225	3562	20659	4
JLD/U	13566	1569	92	11905	11899	0	6	5169	1995	3174	0
JLD/T	215382	12522	14508	188419	185990	0	2362	82770	15801	66969	0
JSON/U	1410	380	0	1030	1028	0	2	354	139	215	0
JSON/T	77850	7807	645	69438	68918	0	480	31099	6660	24439	0
JuMP/U	31266	2442	116	28708	28706	0	2	13223	2318	10905	0
JuMP/T	469228	37334	8361	425152	421266	0	2267	191369	36021	155333	15
JuliaFEM/U	92292	5375	908	86009	85408	0	601	40309	8684	31625	0
JuliaFEM/T	440312	29898	29855	380624	377974	0	2585	164375	36737	127634	4
JuliaParser/U	28136	1998	139	25999	25997	0	2	11962	6505	5457	0
JuliaParser/T	101450	9676	605	94393	90667	0	502	41107	12919	28188	0
Knet/U	17386	2929	0	14457	14455	0	2	6228	1955	4273	0
Knet/T	495318	77100	2696	420737	412812	0	2710	172070	62104	109966	0

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PROJECT	PARSER				TYPEOF			SUBTYPE			
	#types	unsupp	not WF	#tests	passed	fail	ANY	#tests	trivial	passed	fail
Lazy/U	12528	1722	89	10717	10715	0	2	4484	1764	2720	0
Lazy/T	34298	3461	146	30961	30464	0	227	13653	3778	9875	0
LightGraphs/U	19988	1631	95	18262	18260	0	2	8316	1978	6338	0
LightGraphs/T	537206	29702	7570	500908	495312	0	4622	233225	49508	183710	7
Lint/U	20264	1931	110	18223	18207	0	16	8122	3061	5061	0
Lint/T	170320	14121	1861	154416	153034	0	1304	70458	16888	53563	7
LowRankModels/U	31724	2194	0	29530	29527	0	3	13856	1343	12513	0
LowRankModels/T	158818	8895	1172	148909	147744	0	1007	69922	11119	58803	0
Luxor/U	16678	1578	83	15017	15015	0	2	6715	1714	5001	0
Luxor/T	120812	10082	935	110902	108725	0	1070	49822	11769	38053	0
MAT/U	4370	795	0	3575	3571	0	4	1427	430	997	0
MAT/T	103500	8317	438	94745	94072	0	673	43369	8969	34399	1
MLBase/U	29774	1908	180	27686	27637	0	49	12877	2541	10336	0
MLBase/T	86176	7067	1382	77758	77226	0	501	35250	7622	27628	0
MXNet/U	12980	1660	83	11237	11233	0	4	4850	1873	2977	0
MXNet/T	215688	18465	933	196435	194956	0	1334	89555	20194	69361	0
Merlin/U	41506	3082	309	38115	37823	0	292	17521	3880	13641	0
Merlin/T	112518	10656	671	101434	100441	0	750	45713	12354	33359	0
MixedModels/U	42840	3407	86	39349	39345	0	4	18240	2877	15363	0
MixedModels/T	400670	30399	5823	364497	362232	0	2252	166761	33877	132870	14
Mocha/U	37528	3094	228	34206	34031	0	175	15607	3648	11959	0
Mocha/T	129018	9542	1163	118314	117442	0	871	54418	11690	42728	0
MultivariateStats/U	19234	1407	89	17738	17735	0	3	8169	1740	6429	0
MultivariateStats/T	126694	9875	1108	115825	114962	0	749	53081	11931	41148	2
Mustache/U	1376	380	0	996	994	0	2	337	133	204	0
Mustache/T	35006	2064	196	32787	32570	0	176	15307	2721	12586	0
Mux/U	27500	3131	229	24140	24051	0	89	10544	3319	7225	0
Mux/T	56678	4387	444	51847	51511	0	336	23705	5905	17800	0
NMF/U	33956	2545	245	31166	31077	0	89	14343	3313	11030	0
NMF/T	81530	6769	430	74364	73836	0	495	34212	7872	26340	0
OnlineStats/U	48150	2921	386	44843	44552	0	291	20968	4139	16829	0
OnlineStats/T	242202	16323	2902	222980	221291	0	1686	102579	19741	82835	3
Optim/U	19318	1185	0	18133	18131	0	2	8608	691	7917	0
Optim/T	424346	29804	17853	379946	374478	0	2333	167565	47669	119892	4
POMDPs/U	26880	1638	93	25151	25148	0	3	11764	2217	9547	0
POMDPs/T	57022	3922	204	52898	52422	0	476	24533	4882	19651	0
PackageCompiler/U	6786	836	0	5950	5949	0	1	2557	1121	1436	0
PackageCompiler/T	116230	6995	9879	99356	98517	0	839	42969	10302	32666	1
Parameters/U	15590	1365	89	14136	14134	0	2	6387	1645	4742	0
Parameters/T	56518	4018	441	52147	51619	0	440	23986	4357	19629	0
ParserCombinator/U	23828	1976	153	21699	21581	0	118	9919	2157	7762	0
ParserCombinator/T	32038	2815	153	29070	28850	0	220	13226	2880	10346	0
Playground/U	14664	1207	107	13350	13315	0	35	6048	1884	4164	0
Playground/T	55422	4058	297	51067	50391	0	676	23586	5239	18346	1
Plots/U	51628	4042	375	47211	47147	0	64	21570	5040	16530	0
Plots/T	187640	13876	1614	172152	171217	0	935	79530	15994	63533	3
ProgressMeter/U	1430	380	0	1050	1048	0	2	364	135	229	0
ProgressMeter/T	30826	2079	117	28902	28239	0	391	13319	3135	10184	0
ProtoBuf/U	1776	380	0	1396	1394	0	2	537	277	260	0

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PROJECT	PARSER			TYPEOF			SUBTYPE				
	#types	unsupp	not WF	#tests	passed	fail	ANY	#tests	trivial	passed	fail
ProtoBuf/T	46388	2707	195	43553	43018	0	468	20439	3426	17013	0
PyCall/U	26028	2928	223	22877	22780	0	97	9956	2903	7053	0
PyCall/T	133938	11086	780	122493	121068	0	1004	55724	9820	45903	1
QuantEcon/U	43714	2514	91	41111	41108	0	3	19397	2673	16724	0
QuantEcon/T	493768	36867	4568	453203	449907	0	2428	208050	41768	166280	2
QuantumOptics/U	53398	3398	257	49743	49688	0	55	23257	3842	19415	0
QuantumOptics/T	6250	440	47	5767	5713	0	50	2649	513	2136	0
Query/U	28758	2143	291	26324	26231	0	93	12150	2558	9592	0
Query/T	187972	11320	14878	162413	160404	0	1370	69264	11837	57425	2
Reactive/U	15966	1317	89	14560	14556	0	4	6623	1705	4918	0
Reactive/T	91788	9326	1428	83978	80183	0	851	35830	9514	26316	0
ReadStat/U	5684	402	0	5282	5236	0	46	2450	480	1970	0
ReadStat/T	5684	402	0	5282	5236	0	46	2450	480	1970	0
Requests/U	11656	1296	83	10277	10267	0	10	4478	1935	2543	0
Requests/T	100888	5304	487	95097	94507	0	590	44837	9588	35248	1
ReverseDiff/U	41254	1081	0	40173	40171	0	2	19671	584	19087	0
ReverseDiff/T	132396	7280	1282	123834	123261	0	573	57991	7527	50464	0
Revise/U	15464	1376	118	13975	13967	0	3	6293	1566	4727	0
Revise/T	63714	5895	5475	52447	51923	0	431	22945	6046	16899	0
SIUnits/U	2740	425	2	2315	2313	0	2	973	142	831	0
SIUnits/T	54494	2742	742	51015	50678	0	334	23932	3547	20385	0
SQLite/U	28474	1876	101	26497	26493	0	4	12379	3306	9073	0
SQLite/T	108506	5835	2917	99754	98886	0	868	45819	9299	36519	1
ScikitLearn/U	42982	3487	222	39273	39175	0	98	17939	3139	14800	0
ScikitLearn/T	40006	3803	497	35706	35505	0	201	15909	4226	11683	0
Sims/U	91230	5938	729	84563	84165	0	398	39388	7183	32205	0
Sims/T	117886	7447	861	109578	108996	0	582	51129	9798	41331	0
StaticArrays/U	5570	1005	0	4565	4563	0	2	1891	432	1459	0
StaticArrays/T	666260	31470	2545	632616	626991	0	5254	300406	43228	257177	1
StatsBase/U	11318	553	0	10765	10762	0	3	5154	457	4697	0
StatsBase/T	241260	20269	1681	219817	216952	0	2358	100287	24161	76126	0
Sundials/U	41966	2776	261	38929	38879	0	50	18161	3052	15109	0
Sundials/T	164924	10306	5689	149023	148300	0	631	67130	12915	54215	0
TSne/U	1588	380	0	1208	1206	0	2	443	182	261	0
TSne/T	173654	12141	1747	159811	158355	0	1411	73845	18328	55515	2
TensorFlow/U	61882	4833	236	56815	56713	0	102	26100	6117	19983	0
TensorFlow/T	82718	5914	367	76439	76039	0	400	35366	7858	27508	0
TensorOperations/U	1038	76	0	962	961	0	1	451	50	401	0
TensorOperations/T	134032	15486	1112	117437	115965	0	1469	51796	9155	42641	0
TextAnalysis/U	47926	2844	202	44880	44562	0	318	21082	6027	15055	0
TextAnalysis/T	82922	4587	307	78028	77351	0	677	36808	8559	28249	0
TimeSeries/U	7736	985	0	6751	6750	0	1	2905	1213	1692	0
TimeSeries/T	145960	11727	784	133713	132395	0	1054	61046	15229	45817	0
UnicodePlots/U	19230	1421	89	17720	17717	0	3	8153	1730	6423	0
UnicodePlots/T	59916	3283	269	56364	56068	0	296	26512	5343	21169	0
Unitful/U	3958	465	53	3456	3454	0	2	1514	317	1197	0
Unitful/T	279584	9342	98108	172152	168108	0	4044	39515	7699	31816	0
VoronoiDelaunay/U	6536	395	0	6141	6139	0	2	2905	239	2666	0
VoronoiDelaunay/T	24966	1713	144	23109	22907	0	202	10729	2159	8570	0

Table 1. Validation results

PROJECT	PARSER				TYPEOF			SUBTYPE			
	#types	unsupp	not WF	#tests	passed	fail	ANY	#tests	trivial	passed	fail
Wavelets/U	670	89	0	581	580	0	1	246	66	180	0
Wavelets/T	74152	4785	219	69157	68796	0	352	32445	6507	25938	0
Weave/U	3636	722	0	2914	2912	0	2	1125	538	587	0
Weave/T	61284	4804	434	56046	55707	0	339	25774	6558	19216	0
PROJECT	#types	unsupp	not WF	#tests	passed	fail	ANY	#tests	trivial	passed	fail
PROJECT	PARSER				TYPEOF			SUBTYPE			

Total numbers are:

- Parser
 - Types: 18 559 110
 - Unsupported: 1 385 570
 - Not well-formed: 104 643
- Typeof
 - Types: 16 831 502
 - Passed: 16 675 370
 - Fail: 0
 - ANY: 109 192
- Subtype
 - Tests: 7 612 469
 - Trivial: 1 597 871
 - Passed: 6 014 476
 - Fail: 122